ЗДРУЖЕНИЕ ЗА ЕЛЕКТРОНИКА ТЕЛЕКОМУНИКАЦИИ АВТОМАТИКА И ИНФОРМАТИКА НА РЕПУБЛИКА МАКЕДОНИЈА
SOCIETY FOR ELECTRONICS TELECOMMUNICATIONS AUTOMATICS AND INFORMATICS OF THE REPUBLIC OF MACEDONIA

ФАКУЛТЕТ ЗА ЕЛЕКТРОНИКА И ИНФОРМАЦИСКИ ТЕХНОЛОГИИ
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ЗБОРНИК НА ТРУДОВИ
CONFERENCE PROCEEDINGS

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З Д Р У Ж Е Н И Е З А
Е Л Е К Т Р О Н И К А
Т Е Л Е К О М У Н И К А Ц И И
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S O C I E T Y F O R
E L E C T R O N I C
T E L E C O M U N I C A T I O N S
A U T O M A T I C S A N D
I N F O R M A T I C S
O F T H E R E P U B L I C
O F M A C E D O N I A

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XVI МЕЃУНАРОДНА КОНФЕРЕНЦИЈА

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ЗДРУЖЕНИЕ ЗА ЕЛЕКТРОНИКА ТЕЛЕКОМУНИКАЦИИ АВТОМАТИКА И ИНФОРМАТИКА НА РЕПУБЛИКА МАКЕДОНИЈА

SOCIETY FOR ELECTRONIC TELECOMMUNICATIONS AUTOMATICS AND INFORMATICS OF THE REPUBLIC OF MACEDONIA

СОДРЖИНА
TABLE OF CONTENTS

Предговор **16**

Preface **19**

Пленарни предавања / Invited Plenary Lectures **21**

Highlights of Lane-Free Automated Vehicle Traffic with Nudging 22
Prof. Markos Papageorgiou, PhD

Securing Academic Records: Where Blockchain Meets AI 24
Prof. Fisnik Dalipi, PhD

Unlocking the Potential of Digital Therapeutics: Exploring Technologies and Intervention Opportunities 25
Prof. Oscar Mayora, PhD

Theory and Inference of Coupling Functions: Neural Delta-alpha Coupling in Resting State, Anaesthesia and Sleep 26
Tomislav Stankovski, PhD

Dedication to prof. Mile Stankovski 27

ЕТАИ сесии / ETAI Sessions **29**

Metrology and Electronics – ME **30**

Determination of the Maximum Clock Frequency of 8-bit Serial Converters for Maximum Length Sequence to Natural Binary Code 31
Milan Dinčić, Goran Miljković, Milica Stojanović, Dragan Denić and Ivana Ranđelović

Performance Evaluation of the 24-bit Floating Point Format in Different Variance Ranges for Digital Representation of Measurement Data 37
Milan Dinčić, Zoran Perić, Dragan Denić, Sofija Perić, Jelena Jovanović and Aleksandar Jocić

DC-DC Converters in GaN Technology – Measurements and SPICE Simulations 41
Marko Kamilovski and Katerina Raleva

Dixon Outlier Detection Approach Implemented in Sensor-to-Microcontroller Interface 47
Zivko Kokolanski, Mare Srbinovska, Kiril Demerdziev and Vladimir Dimcev

Ultra-low Power Wrapper of the Ethos-U55 AI Accelerator in the PSOC™ Edge E84 MCU 51
Aleksandar Simevski, Henrik Hostalka and Bernd Waschneck

Comparison of the Properties and Efficiency of Photovoltaic Cells 52
Filip Bojadjievski, Katerina Raleva, Marija Kalendap, Meita Asami and Depu Ma

Image Processing and Recognition - ImProc **58**

PointFEIT – Point Feature Extraction with Image PreTraining for 3D Semantic Segmentation 59
Dimitar Dimeski, Hristijan Gjoreski and Gorjan Nadzinski

Siamese Neural Network Architectures for Efficient Person Re-identification 65
Elena Vasileva, Tatjana Petkovska and Zoran Ivanovski

Siamese Networks for Vehicle Re-Identification 71
Monika Todevska, Elena Vasileva and Zoran Ivanovski

Automatic Private Parking System Using License Plate Recognition and Car Make and Model Recognition 76
Darko Pajkovski, Ilija Jolevski and Nikola Rendevski

System for Visual Graphic Animation and Recognition of Macedonian Sign Language Using Machine Learning and 3D Visualisation Tools 82
Teodora Kochovska, Marija Kochovska, Bojana Velichkovska and Marija Kalendar

Smart Biomedicine - SmartBioMed 86

Assistive Keyboard for Children with Ataxia 87
Martin Milanoski, Vladimir Kitanovski, Marko Zajkov, Nikola Jovanovski, Danche Todorovska and Branislav Gerazov

Open-ended Acoustic Obstacle Avoidance Interface for Visually Impaired People Based on Consumer Grade Mobile Device 91
Ana Sofronievska, Piotr Walas Daniela Stojceska, Hristijan Slavkoski, Kristijan Lazarev and Branislav Gerazov

Exploring Pigmented Skin Mole Borders: Minkowski Dimensions in Malignancy Detection 95
Mia Darkovska, Ilija Mizhimakoski, Ana Ristovska Dimitrovska and Vesna Andova

Health Risk Prediction for Children Built on a Combination of Heterogeneous Datasets.................. 101
Sebastjan Kramar, Marko Jordan, Marcel Založnik, Nina Reščič and Mitja Lustrek

Recognizing Finger Flexions from EMG Signals Using Wavelet Transform and Machine Learning 107
Klimentina Paunkoska, Gorjan Nadzinski, Blagoj Hristov and Vesna Ojleska Latkoska

Gesture Control Robotic Arm Using Flex Sensors 112
Hristijan Ivanoski and Katerina Raleva

Process Control in Industry and Manufacturing - ProcCont 116

Design and Implementation of a Laboratory-scale Photobioreactor 117
Jovan Kamchev, Bojan Glushica, Martin Milanoski, Toni Atanasovski, Bojan Ginoski, Nikola Jovanovski, Mario Makraduli, Darko Dimitrovski and Branislav Gerazov

Integrated Hybrid Manufacturing: Design, Control and Implementation of a Dual-Function CNC Machine 123
Nikola Jovanovski and Josif Kjosev

Modern SCADA Solution for Mitigation of Water Losses in Water Distribution Network 129
Stefan Boshkovski, Gorjan Nadzinski, Goce Taseski and Mile Stankovski

Model Predictive Control of a 2-DOF Robotic Arm and Comparative Analysis with Fuzzy Logic Control........... 135
Marija Bikova, Dushko Stavrov, Vesna Ojleska Latkoska and Blagoj Hristov

Optimal Control Algorithm for Electrical Load Management in Touring Buses and Comparative Analysis with Fuzzy Logic Control 141
Boris Butevski, Vesna Ojleska Latkoska, Dushko Stavrov and Gorjan Nadzinski

Information and Communications Technology - ICT 147

Segment Routing IPv6 for Future Networks 148
Toni Janevski and Darko Koloski

Technical Aspects of Using SRv6 Compared to MPLS for a Telecom Operator 154
Toni Janevski and Olivera Koteska

The impact of SD-WAN on the Quality of Services compared to Traditional WAN.............................. 160
Mitko Jankuloski and Stojan Kitanov

Optimization and Testing of Smart Contracts for Generation and Verification of Academic Diplomas 166
Avni Rustemi, Fisnik Dalipi, Vladimir Atanasovski and Aleksandar Risteski

AI Strategies for Reducing Carbon Footprint in the ICT Sector: An Evaluation through the Science-Based Targets Initiative 172
Jelena Gjorgjev, Nexhibe Sejfuli-Ramadani, Valentina Angelkoska, Valentin Rakovic and Aleksadar Risteski

Machine Learning 1 - ML1 177

Static, Dynamic, and High-Order Functional Connectivity Analysis in Schizophrenia and Bipolar Disorder Differentiation 178
Daniela Janeva, Martin Breyton, Spase Petkoski and Branislav Gerazov

Comparative Sentiment Analysis and Semantic Meaning in Text Using Sentiment Models from Hugging Face and Power Automate 182
Aneta Trajkovska and Ilija Jolevski

Optimizing Sensor Configuration on OCOSense for Accurate Detection of Facial Gestures 188
Ana Sofronievska, Daniela Stojceska, Jovana Angelovska, Sandra Shukleva, Borjan Sazdov and Hristijan Gjoreski

A System for Real-Time Voice Control of Robots in Macedonian 193
Marija Neceva, Zoran Ivanovski, Nikola Jovanovski, Tomislav Kartalov, Dimitar Taskovski, and Branislav Gerazov

Optimizing Chewing Rate Estimation: Insights from Sensor Data using OCOsense glasses and Machine Learning 199
Mia Darkovska, Kristina Kalamukoska, Damjan Mihajloski, Ognen Sekuloski, Filip Panchevski, Borjan Sazdov, Simon Stankoski, Charles Nduka and Hristijan Gjoreski

Performance Comparison Between PPG and ECG Based Heart Rate Detection 206
Marko Petrov, Branislav Gerazov, Nikola Jovanovski and Tomislav Kartalov

Cyber Security Applications - CybSec 212

GPU-Accelerated Password Hacking: Analyzing Performance Across Varied Password Lengths 213
Bisera Naumovska, Aleksandar Cvetanov, Bojana Velichkovska, Goran Jakimovski and Danijela Efnusheva

Web Application for Web Attack Detection Through Network Traffic Analysis 219
Ivana Dineva, Goran Jakimovski and Danijela Efnusheva

Analysis of Models for Detection of Cyberattacks in Computer Systems and Networks 224
Georgi Kamchevski, Dimitar Gugucheski and Hristijan Gjoreski

Binary Classification of VPN Proxy IP Address 230
Teodora Kochovska, Marija Kochovska, Ana Cholakoska Cilakova and Danijela Efnuseva

A Review on Machine Learning Based Intrusion Detection System:Techniques, Public Datasets and Challenges 236
Goce Stevanoski, Marko Porjazoski, Ivo Paunovski, Monika Kachurova and Aleksandar Risteski

Internet of Things - IoT 242

An IoT System for Detection and Displaying of PM Particles Concentrations in the Air 243
Josif Kjosev, Nikola Jovanovski, Marko Petrov, Filip Petkovski, Tijana Petkovska, Andrej Ilievski

Ethical Aspects in Building a Short-Range Object Detection Radar System with Arduino Mega 2560 247
Rexhep Mustafovski, Aleksandar Risteski and Tomislav Shuminoski

The use of Digital Development Board for Development of Ultrasonic Radar System for Short Distance Detection in a 360-degree 252
Rexhep Mustafovski, Aleksandar Risteski and Tomislav Shuminoski

Ambient CO2 and Temperature IoT Monitoring Solution 258
Aleksandar Kormushoski, Marija Kalendar, Ana M. Lazarevska and Valentina Gecevska

Design and Implementation of a Cloud-based System for IoT Sensor and Security Metrics Analysis 264
Marija Andonovska, Marija Kalendar and Daniel Denkovski

Enhancing Music Genre Classification: A Divide and Conquer Approach 272
Alek Pachemski, Ivan Jovanovski and Hristijan Gjoreski

Control and Control Applications - Cont 281

Complex Networked Time-delay Systems: Synchronization by Variable-structure Control Coordinator 282
Mile J. Stankovski, Yuanwei Jing, Boban Temelkovski and Georgi M. Dimirovski

Modelling, Simulation and Development of a Test Rig for Comparative Analysis of Temperature Controllers ... 290
Ana Sofronievska, Filip Donchevski

Quality control with real-time data analysis using intelligent algorithms 295
Aleksandar Arsovski, Vesna Ojleska Latkoska, Dushko Stavrov and Mile Stankovski

Designing Haptic Interfaces for the Internet of Things: An Open-Source Experimentation Platform 301
Alper Başaran and Dilek (Bilgin) Tükel

A Fuzzy Systems Approach to Discrete-time Sliding-mode Control for Uncertain Nonlinear Plant Systems 307
Yuanwei Jing and Yan Zheng, Gorjan Nadzinski and Georgi M. Dimirovski

Machine Learning 2 - ML2 315

Artificial Intelligence Architectural, Regulatory and Business Framework for Telecom Networks........................ 316
Dimitar Tanevski, Toni Janevski and Venceslav Kafedziski

Bitcoin Price Prediction Using Machine Learning Algorithms 322
Teodora Kochovska, Marija Kochovska, Valentina Angelkoska, Pero Latkoski and Aleksandar Risteski

A Comparison of Gradient Boosting Algorithms: XGBoost, CatBoost, and LightGBM 327
Ognen Pendarovski, Kristijan Milosheski and Hristijan Gjoreski

Analyzing Telecom Customer Churn using Machine Learning 333
Stefan Shipinkoski and Hristijan Gjoreski

Special Session Dedicated to prof. Mile Stankovski 339

Dynamic Graphs, Networks-of-Networks with Faulty Inter-network Connections, Pinning-control Synchronization Coordinator: Coincidences and Confluences 340
Georgi M. Dimirovski, Jinde Cao, Tao Ren, Lin Lin and Mile J. Stankovski

Програма на конференцијата / Conference Program.. 352

Предговор

Почитувани читатели, учесници и истражувачи,

Со голема чест и задоволство ви го претставувам зборникот на трудови од 16-та Конференција за електроника, телекомуникации, информатика и автоматика – ЕТАИ 2024. Овој зборник не претставува само збир на научни трудови и презентации, туку и особено значајно сведоштво за нашата посветеност кон иновациите и напредокот во овие динамични и клучни области на технологијата. Здружението ЕТАИ преку своите годишни активности и редовните конференции продолжува да биде водечка платформа, која ги обединува најновите истражувања и најзначајните достигнувања во особено актуелните технолошки области кои ги покрива.

Од своето прво издание во 1981 година, конференциите на Здружението ЕТАИ имаат за цел да го поттикнат развојот на науката и технологијата, да овозможат размена на знаења и да ја поттикнат соработка меѓу истражувачите, практичарите и индустријата. Токму затоа, конференциите организирани од ЕТАИ стануваат особено важен настан кој на секои две години ја отвора вратата за бројни иновации и значајни достигнувања, и привлекува најдобри умови и стручњаци од целиот свет.

Како и секогаш, и оваа година конференцијата ЕТАИ 2024 опфаќа повеќе теми кое се особено актуелни и важни: примената на машинското учење и вештачката интелигенција во сите сфери на нашето живеење, дигиталната трансформација и ИКТ системите, комуникациите, напредокот во електрониката, материјалите и технологиите за дизајн, прецизните мерења и модерните текови во метрологијата, кибер-безбедноста и нејзините нови предизвици. Сите овие технологии влијаат на секој аспект од нашиот живот – од начинот на кој комуницираме, управуваме со податоците, па се до нашите секојдневни активности и индустриски процеси. Како што технологијата напредува, така и нашите истражувања мора да ги следат овие промени и да одговорат на новите предизвици.

Зборникот на трудови за ЕТАИ 2024 вклучува широк спектар на теми, кои покриваат значајни аспекти од сите овие технологии:

Напредни електронски системи и компоненти: Овие трудови се фокусирани на новите технологии, иновации во дизајнот и производството на електронски компоненти, и нивната примена во различни области.

Нови текови во комуникациските мрежи и ИКТ системи: Изложени се најновите истражувања во областа на комуникациските мрежи разгледувајќи ги предизвиците на новото време и новите мрежи, како и новините во модерните ИКТ системи за управување со податоци преку актуелните „паметни договори”, базирани на актуелните блок-ланец технологии.

Кибер-безбедноста и новите предизвици: Ова е една од најактуелните теми каде постојаното учество на луѓето и сѐ поголемиот број на уреди во глобалниот поврзан свет, носи особено значајни предизвици. Токму затоа, покрај во трудовите, на ЕТАИ 2024 неа ѝ е посветена и засебна панел дискусија – „Emerging Trends and Challenges in Cyber Security” со актуелни панелисти од сите значајни чинители во државата.

Вештачка интелигенција и машинско учење: Трудовите во оваа категорија разгледуваат како вештачката интелигенција и машинското учење се применуваат за решавање на комплексни секојдневни проблеми и овозможуваат оптимизација на процесите. Особен фокус е ставен на трудовите каде технологиите за МУ и ВИ, обезбедуваат подобрувања во рамките на секојдневниот живот на човекот и подобрувањето на неговото здравје.

Управување на системи, автоматизација и роботика: Овие трудови се фокусирани на напредокот и новите методи во управувањето на системите, автоматизацијата и роботските технологии, и нивната примена во различни индустрии.

Информатика, анализа на големи податоци и облак системи: Истражувањата во оваа област ги разгледуваат новите методологии и технологии за обработка и анализа на големи количини на податоци, додека новите можности на облак системите значително го поедноставуваат и забрзуваат процесот на дизајн, развој и ставање во употреба на нови апликации, обезбедувајќи модуларност, скалабилност и управливост со целокупните системи.

Одржливост и енергетска ефикасност: И конечно, целокупниот технолошки развој значително влијае на сè околу нас. Како можеме да ги направиме нашите технологии поодржливи, а исто времено и да го намалиме нивното влијание врз животната средина? Оваа тема се истражува преку иновации и практични решенија.

Секоја од овие области носи со себе уникатни предизвици и можности. Како што ќе видите во трудовите, истражувањата и решенијата кои се презентирани покажуваат како се применуваат најновите теоретски и практични пристапи за да се одговори на потребите на современата технологија и индустрија. Тие не само што го осветлуваат напредокот во нашите области, туку и ја истакнуваат важноста на продолжената соработка и иновација меѓу индустријата и академските истражувања.

Обединувајќи ги сите овие теми, на овогодинешната конференција имаме чест да слушнеме четири особено интересни поканети предавања од нашите пријатели и врвни научници: проф. Markos Papageorgiou, од Техничкиот универзитет од Крит, Грција, проф. Oscar Mayora од Институтот FBK од Италија, проф. Fisnik Dalipi од Линаеус универзитетот во Шведска и проф. Томислав Станковски, од Медицинскиот факултет при УКИМ од Скопје. Сите тие значајно ја збогатуваат нашата програма и нè приближуваат до светските трендови во истражувањата.

Оваа година го прославуваме и 70-тиот јубилеј на проф. Миле Станковски, еден од најистакнатите членови и претседатели на Здружението ЕТАИ, преку посебна сесија во негова чест посветена на неговата работа и заедничкото растење со ЕТАИ.

Конференцијата ЕТАИ традиционално е поддржана од повеќе организации и ентузијасти. Најпрво, како нераскинлив дел од ЕТАИ, сакам да му се заблагодарам на Факултетот за електротехника и информациски технологии при УКИМ и на Деканот проф. Владимир Атанасовски како постојан поддржувач на Здружението и конференциите низ годините. Како и секоја година, конференцијата ќе биде поддржана и од неколку здруженија од македонскиот оддел на меѓународната организација ИЕЕЕ со кои заеднички се организираат неколку сесии. Тука е и Инженерската институција на Македонија од која е дел Здружението ЕТАИ и која секогаш несебично ги поддржува своите членови.

Секако би сакала особено да ги истакнам и заблагодарам на нашите спонзори кои овозможија и оваа година успешно да ја организираме конференцијата: Македонски телеком АД, како главен спонзор на овогодинешната конференција и долгогодишен поддржувач на настаните на Здружението ЕТАИ. Понатаму комапниите кои долги години соработуваат со членовите на ЕТАИ: Искра системи од Скопје, Магна од Штип, WIK Македонија од Прилеп, Контрон од Скопје и секако исто така долгогодишниот поддржувач на конференциите ЕТАИ – компанијата Неотел.

На крајот, сакам да се заблагодарам на сите автори, рецензенти и организатори и волонтери кои придонесоа за создавање на овој зборник. Вашата посветеност и напорна работа се основа на успехот на оваа конференција и на нашиот заеднички напор да го поместиме границите на знаењето и технологијата.

Проф. Марија Календар

Претседател на здружението

ЕТАИ

ЗДРУЖЕНИЕ ЗА ЕЛЕКТРОНИКА ТЕЛЕКОМУНИКАЦИИ АВТОМАТИКА И ИНФОРМАТИКА НА РЕПУБЛИКА МАКЕДОНИЈА

SOCIETY FOR ELECTRONIC TELECOMUNICATIONS AUTOMATICS AND INFORMATICS OF THE REPUBLIC OF MACEDONIA

Preface

Dear readers, participants, and researchers,

It is with great honor and pleasure that I present to you the Proceedings of the 16th Conference on Electronics, Telecommunications, Informatics, and Automation − ETAI 2024. This volume represents not just a collection of scientific papers and presentations but also a significant testament to our commitment to innovation and progress in these dynamic and crucial areas of technology. The ETAI Society, through its annual activities and regular conferences, continues to be a leading platform that brings together the latest research and most significant achievements in the particularly relevant technological fields it covers.

Since the first edition in 1981, the conferences organized by the ETAI Society have aimed to promote the development of science and technology, facilitate knowledge exchange, and foster collaboration among researchers, practitioners, and the industry. For this reason, ETAI conferences have become especially important events, opening the door to numerous innovations and significant achievements every two years, attracting the best minds and experts from around the world.

As always, this year's ETAI 2024 Conference covers several topics that are particularly current and important: the application of machine learning and artificial intelligence in all areas surrounding us, digital transformation and ICT systems, communications, advancements in electronics, materials and design technologies, precise measurements and modern trends in metrology, cybersecurity and its new challenges. All these technologies impact every aspect of our lives − from how we communicate and manage data to our daily activities and industrial processes. As technology advances, our research must keep pace with these changes and address new challenges.

The Proceedings for ETAI 2024 include a wide range of topics covering significant aspects of all these technologies:

Advanced Electronic Systems and Components: These papers focus on new technologies, innovations in the design and manufacturing of electronic components, and their application in various fields.

New Trends in Communication Networks and ICT Systems: Presenting the latest research in communication networks, exploring the challenges of new times and smart networks, as well as innovations in modern ICT systems for data management through current "smart contracts" based on Blockchain technologies.

Cybersecurity and new Security Challenges: This is one of the most current topics, where the constant involvement of people and the increasing number of devices in the globally connected world brings particularly significant challenges. Therefore, in addition to the papers, ETAI 2024 features a dedicated panel discussion − "Emerging Trends and Challenges in Cyber Security" with significant panelists from all critical stakeholders in the country.

Artificial Intelligence and Machine Learning: The papers in this category examine how artificial intelligence and machine learning are applied to solve complex everyday problems and enable process optimization. A particular focus is placed on papers where ML and AI technologies provide improvements in human daily life and health.

System Management, Automation, and Robotics: These papers focus on advancements and new methods in system management, automation, and robotics technologies, and their application in various industries.

Informatics, Big Data Analysis, and Cloud Systems: Research in this area explores new methodologies and technologies for processing and analyzing large amounts of data, while the new capabilities of cloud systems significantly simplify and accelerate the process of designing, developing, and deploying new applications, providing modularity, scalability, and manageability for entire deployed systems.

Sustainability and Energy Efficiency: Finally, the overall technological development significantly impacts everything around us. How can we make our technologies more sustainable while simultaneously reducing their impact on the environment? This topic is explored through innovations and practical solutions.

Each of these areas brings unique challenges and opportunities. As you will see in the papers, the research and solutions presented show how the latest theoretical and practical approaches are being applied to meet the needs of modern technology and industry. They not only highlight the progress in our fields, but also emphasize the importance of continued collaboration and innovation between industry and academic research.

By bringing together all these topics, this year's conference has the honor of featuring four particularly interesting invited lectures from our esteemed colleagues and leading scientists: Prof. Markos Papageorgiou, Prof. Oscar Mayora, Prof. Fisnik Dalipi, and Prof. Tomislav Stankovski. They significantly enrich our program and bring us closer to global research trends.

This year, we also celebrate the 70th anniversary of Prof. Mile Stankovski, one of the most prominent members and presidents of the ETAI Society, with a special session dedicated to his work and his joint growth together with ETAI.

The ETAI conference is traditionally supported by various organizations and enthusiasts. First, as an inseparable part of ETAI, I want to thank the Faculty of Electrical Engineering and Information Technology at UKIM and its Dean Prof. Vladimir Atanasovski for being a constant supporter of the Association and its conferences over the years. Like every time, the conference will also be supported by several chapters from the Macedonian section of the international organization IEEE, with which we jointly organize several sessions. The Engineering Institution of Macedonia, of which the ETAI Society is a part, also selflessly supports its members.

I would especially like to thank our sponsors who have enabled us to successfully organize this year’s conference: Macedonian Telekom AD, as the main sponsor of this year's conference and a long-time supporter of ETAI events. Additionally, the companies that have collaborated with ETAI members for many years: Iskra Systems from Skopje, Magna from Štip, WIK Macedonia from Prilep, Kontron from Skopje, and of course, the long-time supporter of the ETAI conferences − Neotel.

Finally, I would like to thank all the authors, reviewers, organizers and volunteers who contributed to the creation of this volume. Your dedication and hard work are the foundation of the success of this conference and our collective effort to push the boundaries of knowledge and technology.

Prof. Marija Kalendar
President of the ETAI Society

Пленарни предавања
Invited Plenary Lectures

Highlights of Lane-Free Automated Vehicle Traffic with Nudging

Prof. Markos Papageorgiou, PhD
Technical University of Crete, Dynamic Systems and Simulation Laboratory
Chania, Crete, Greece

Biography—Markos Papageorgiou received the Diplom-Ingenieur and Doktor-Ingenieur (honors) degrees in Electrical Engineering from the Technical University of Munich, Germany, in 1976 and 1981, respectively. He was a Free Associate with Dorsch Consult, Munich (1982-1988), and with Institute National de Recherche sur les Transports et leur Sécurité (INRETS), Paris, France (1986-1997). From 1988 to 1994 he was a (tenured) Professor of Automation at the Technical University of Munich. Since 1994 he has been a Professor (since 2021 Professor Emeritus) at the Technical University of Crete, Chania, Greece. Since 2021 he has been a Professor at Ningbo University, China. He was a Visiting Professor at the Politecnico di Milano, Italy (1982), at the Ecole Nationale des Ponts et Chaussées, Paris (1985-1987), at MIT, Boston (1997, 2000); at University of Rome La Sapienza, Italy (2018); Distinguished Visiting Professor at Tsinghua University, China (2018-2021); and a Visiting Scholar at the University of California, Berkeley (1993, 1997, 2001, 2011) and other universities.

Dr. Papageorgiou is author or editor of 7 books and of some 600 technical papers. His research interests include automatic control and optimisation theory and applications to traffic and transportation systems, water systems and further areas. He was the Editor-in-Chief of Transportation Research – Part C (2005-2012). He also served as an Associate Editor of IEEE Control Systems Society – Conference Editorial Board, of IEEE Transactions on Intelligent Transportation Systems and other journals. He is a Life Fellow of IEEE and a Fellow of IFAC. He received a DAAD scholarship (1971-1976), the 1983 Eugen-Hartmann award from the Union of German Engineers (VDI), and a Fulbright Lecturing/Research Award (1997). He was a recipient of the IEEE Intelligent Transportation Systems Society Outstanding Research Award (2007) and Outstanding Application Award (2018); and recipient of the IEEE Control Systems Society Transition to Practice Award (2010). He is the recipient of the 2020 IEEE Transportation Technologies Award. He was presented the titles of Honorary Visiting Professor by the University of Belgrade, Serbia (2010); TUM Ambassador by the Technical University of Munich (2021); and Doctor honoris causa by the Aristotle University of Thessaloniki (2023). The Dynamic Systems and Simulation Laboratory he was heading, received the IEEE Intelligent Transportation Systems Society Institutional Lead Award (2011). He was awarded two ERC Advanced Investigator Grants (2013-2018 and 2019-2025).

Abstract—A novel paradigm (named Traffic Fluid: TrafficFluid) for vehicular traffic in the era of connected and automated vehicles (CAVs) was recently proposed, which is based on two combined principles. The first principle is lane-free traffic, which renders the driving task for CAVs smoother and safer, as risky lane-changing manoeuvres become obsolete; increases the capacity of the roadway due to increased road occupancy; and mitigates congestion-triggering vehicle manoeuvres. Also, lane-free CAV traffic implies that incremental road widening (narrowing) leads to corresponding incremental increase (decrease) of capacity, andthis opens the way for real-time internal boundary control on highways and arterials to flexibly share the total (both directions) road width and capacity among the two traffic directions in dependence of the bi-directional traffic conditions, so as to maximize the total system efficiency. The second principle is vehicle nudging, whereby vehicles may be influencing other vehicles not only behind, but also on the sides or in front of them; this allows for traffic flow to be freed from the anisotropy restriction, which stems from the fact that human driving is influenced only by downstream vehicles. Nudging leads to improved traffic flow capacity and stability.

After presenting the TrafficFluid motivation and general features, some highlights of related work will be outlined, such as: Nonlinear feedback control of CAVs in lane-free traffic with nudging; Optimal path planning for individual vehicles and vehicle groups; Forming of 1-D snake-like interruptible vehicle platoons and flexible 2-D vehicle flocks in lane-free traffic; Emerging macroscopic traffic flow modelling; Internal boundary control; Driving on large-scale lane-free roundabouts (Place Charles de Gaulle in Paris); Signal-free and lane-free urban intersection crossing.

See www.trafficfluid.tuc.gr

Plenary talk chair: prof. Georgi Dimirovski

Securing Academic Records: Where Blockchain Meets AI

Prof. Fisnik Dalipi, PhD
Linnaeus University, Department of Informatics
Kalmar, Sweden

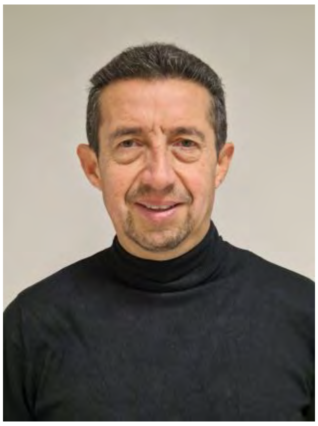
Biography— Fisnik Dalipi is currently working as an Associate Professor with the Department of Informatics, Linnaeus University (LNU) in Sweden. Besides, he also holds the title associate professor in information systems from the University of South-Eastern Norway, where he was previously working. He has authored/coauthored more than 60 papers in international conferences, journals, and as book chapters. His research interests include technology-enhanced learning, security and privacy, human–computer interaction, and applied artificial intelligence. Dr. Dalipi has been supervising students at different academic levels and has been involved in the development and curriculum preparation at all academic levels. He is actively serving as a program committee member, and reviewer for many international conferences, workshops, and journals published by Elsevier, IEEE, and Springer. Throughout his research and academic career, he has participated and coordinated academic and research projects funded by Swedish Knowledge Foundation, Swedish Innovation Agency (Vinnova), The Swedish Foundation for International Cooperation in Research and Higher Education (STINT), Norwegian Research Council, the Regional Research Council of Norway and EU Horizon.

Abstract—In this keynote address, we explore the transformative potential of blockchain and artificial intelligence in the realm of academic credentialing. Traditional methods of diploma verification are fraught with inefficiencies and vulnerabilities to fraud. Our research presents innovative solutions to these challenges through the integration of blockchain technology and AI. We will focus into the conceptual models and review blockchain-based systems, highlighting the DIAR system as a case study. Furthermore, we will discuss the synergistic effects of combining blockchain with AI to enhance the security and efficiency of academic credentialing processes. We envision a future where academic credentials are not only secure but also seamlessly verifiable, paving the way for a more trustworthy and efficient educational ecosystem.

Plenary talk chair: prof. Aleksandar Risteski

Unlocking the Potential of Digital Therapeutics: Exploring Technologies and Intervention Opportunities

Prof. Oscar Mayora, PhD
Fondazione Bruno Kessler, Digital Health Laboratory
Trento, Trentino, Italy



Biography— Prof. Oscar Mayora is senior researcher at FBK and the head of the Digital Health Lab Unit at FBK Center for Health and Wellbeing. He is scientific coordinator for the Joint Research Unit between the Trentino Local Health Trust, the Province of Trento and FBK as part of Trentino Salute 4.0 Initiative. Prof. Mayora is an adjunct professor in the Faculty of Cognitive Sciences at University of Trento (Italy), the School of Medicine at University of Verona (Italy) and FH-Burgenland (Austria). He has published over 200 papers in International Conferences and Journals, participated as Guest Editor of special issues in the topic of Pervasive Healthcare of Journals such as IEEE Intelligent Systems, EURASIP Signal Processing, Springer MONET, IMIA Journal on Methods of Information in Medicine among others. Dr. Mayora is founder of the EAI International Pervasive Health Conference. He has coordinated research projects at National and International level attracting over 12ME of funding in the past 8 years in the topic of pervasive healthcare and assistive technologies (EC FP6, FP7, H2020, HE and ICT Labs among others). He serves as reviewer and evaluator for different national and international agencies such as the European Commission, La Caixa Fellowship Program (Spain), CONACYT (Mexico), and other institutions in Italy and Switzerland.

Abstract—AI-digital therapeutics solution introduces the use of software as both: 1) as an active ingredient used as a digital intervention to improve the patients condition, and 2) as the excipient through which the intervention is conveyed to the patient. This talk will discuss the main aspects related to the design, implementation and testing of digital therapeutics-supported interventions to support patients in dealing with their treatments with the use of clinically validated digital health solutions. Two specific examples will be presented using AI-Supported interventions for mental health and VR-Solutions in the context of palliative care.

Plenary talk chair: prof. Hristijan Gjoreski

Theory and Inference of Coupling Functions: Neural Delta-alpha Coupling in Resting State, Anaesthesia and Sleep

Tomislav Stankovski, PhD
Ss Cyril and Methodius University in Skopje, Faculty of Medicine
Skopje, North Macedonia
Lancaster University, Department of Physics
Lancaster, United Kingdom

Biography–Tomislav Stankovski, PhD, Spec. Med. Nuc. Phys., is an Associate Professor of Medical Physics at the Faculty of Medicine, Ss Cyril and Methodious University in Skopje. He is the Head of Department of Medical Physics at the Faculty of Medicine.

His research is predominantly focused on Nonlinear Biomedical Physics, with research interests including: Coupling Functions, Nonlinear Dynamics, Synchronization, Time-series Analysis, Dynamical Bayesian Inference, Time-varying Dynamics, Non-autonomous Systems, Cardiovascular System, Cardio-respiratory Interactions, Neuroscience, and Systems Neuroscience. He teaches the courses of Biophysics, Radiation Physics, and Digital medical images at the Faculty of Medicine and Faculty of Pharmacy.

He authored number of manuscripts in prestigious scientific journal (both in physical and medical journals), books, chapters, has led and participated in international scientific projects, has organized scientific international conferences and workshops, has been part of scientific committees of international conferences, editor of special issues in scientific journals, editor of scientific journals, reviewer in number of scientific journals, etc.

Abstract–Interacting dynamical systems abound in nature and often the interest is not only to understand if, but also how they interact i.e. to reveal the functions and mechanisms that define and connect them. Coupling functions contain detailed information about the functional mechanisms underlying the interactions and prescribe the physical rule specifying how an interaction occurs. We used a method based on dynamical Bayesian inference in order to reconstruct the neural cross-frequency coupling functions from the phase dynamics of the brainwave oscillations. We focused on the delta-to-alpha coupling function in three cases: (i) resting state, (ii) general anaesthesia induced by propofol and sevoflurane anaesthetics and (iii) natural sleep state. In this way, we studied the delta-to-alpha coupling function form and the quantitative alterations between the different neural states.

Plenary talk chair: prof. Gorjan Nadzinski

Овогодинешното шеснаесетто издание на ЕТАИ е посветено и на 70-годишниот јубилеј на проф. Миле Станковски, кој е еден од основачите на друштвото ЕТАИ, долгогодишен член на управниот одбор, поранешен генерален секретар и претседател, и главен организатор на повеќето претходни конференции.

Преку посебна сесија посветена на него и закажана за сабота 21.9. од 16:00 – 17:00, ЕТАИ ќе му оддаде чест и ќе му се заблагодари на проф. Станковски за неговиот неизмерен придонес кон друштвото и конференцијата во текот на целиот негов работен век.

This year's edition of ETAI is also dedicated to the 70-year jubilee of prof. Mile Stankovski, who is one of the founders of the ETAI Society, a member of the ETAI board for many years, former general secretary and president of the Society, and chief organizer of many of the previous conferences.

By organizing a special session dedicated to him on Saturday 21.9 at 16:00 − 17:00, ETAI will honor and thank prof. Stankovski for his immense contribution towards the ETAI Society and the ETAI conference during his entire professional life.

Short Biography of Prof. Mile Stankovski. PhD

He is a retired full professor at Ss. Cyril and Methodius University, Faculty of Electrical Engineering and Information Technology, Skopje.

He graduated in 1978 at the Ss. Cyril and Methodius University, Faculty of Electrical Engineering and Information Technology in Skopje. His graduation was in the area of Automatics, on the Technical Cybernetics group.

After the graduation, he was employed in the Company for steel pipes productions AD "11 Oktomvri" in Kumanovo, R. Macedonia. He was mainly working in the maintenance, automation and electronics section. For his eighteen-year industrial experience, he changed several positions, from engineer in the maintenance department, to the main engineer for technical and technological activities in the company.

Besides his usual working activities at the Company AD "11 Oktomvri", he managed to go enrol and complete masters studies at the Faculty of Electrical Engineering in Skopje in 1987.

The research work for his PhD was done in Skopje, Kumanovo, and Wolverhampton, UK. In 1997, he successfully finished the PhD dissertation: "Non-conventional Control of Industrial Energy Processes in Large Heating Furnaces" at the Faculty of Electrical Engineering in Skopje. His diploma work, master thesis, and PhD dissertation were all completed under the supervision of prof. Georgi Dimirovski.

From October 1997, he was employed at the Faculty of Electrical Engineering and Information Technologies in Skopje, on the position Teaching Assistant at the Institute of Automation and System Engineering. One year later, he was promoted to Head of Laboratory at the same Institute.

In May 2000 he was promoted to Assistant Professor, in 2005 he was promoted to Associate Professor, while in 2010 he became full professor at the Faculty of Electrical Engineering and Information Technologies. From 2008 to 2016 he held the position of Dean at the same faculty.

During his relatively long academic and industrial career, he has been engaged in more than 120 scientific articles, published and presented on international and domestic conferences and journals. He is a co-author of chapters in four monographies and two books published internationally. He has also written and published two books: "Computer Process Control" and "Microelectronic and Nanoelectronics Applications".

Six doctoral students and more than 20 master students have finished their studies under his mentorship, and he is currently the advisor of two doctoral students.

He has also been employed in number of applicative and scientific projects, as well as being an expert for evaluation of the projects in EU program Horizon 2020.

In the past he has been President of ETAI (Society of Electronics, Telecommunications, Automatics and Informatics), Vice President of the Macedonian Engineering Association (IMI), Chairman of the Council of KOAI (Macedonian Chamber of Authorized Architects and Engineers), and Vice President of IFAC TC-9.3 on Developing Countries (IFAC- International Association of Automatic Control).

In 1981, he was a member of the initiative board for the establishment of the ETAI society. He was a member of the management board of the Society from the beginning. He was the General Secretary of the Society, and on several occasions was also the Chairman of the Society. He actively participated in the organization of all ETAI conferences and was the main organizer in most of them.

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ETAI Sessions

Metrology and Electronics ME

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Determination of the Maximum Clock Frequency of 8-bit Serial Converters for Maximum Length Sequence to Natural Binary Code

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***Abstract*—This paper is dedicated to determining the maximum clock frequency of both types of serial converters (Fibonacci and Galois) for converting a maximum-length sequence into natural binary code, as one of the most important factors influencing the maximum operating speed of pseudorandom absolute position encoders. The maximum clock frequency is determined based on a detailed analysis of propagation delays within the serial code converter. The paper discusses 8-bit serial converters, but the principle and the presented analysis can be applied to other resolution values as well. Based on the theoretical analysis performed, specific numerical values for propagation delays and maximum clock frequency are calculated for the case where the serial code converter is implemented using the 74LVC family of logic circuits. The accuracy of the theoretical analysis was validated through the simulation of both types of serial converters (Fibonacci and Galois) using NI Multisim software.**

Keywords—maximum length sequence; absolute position encoders; serial converter of pseudorandom code; maximum clock frequency

I. INTRODUCTION

A maximum length sequence (M-sequence) of resolution n is a bit sequence of length $2^n - 1$ generated by an n-bit linear feedback shift register (LFSR) [1]-[5]. Each group of n consecutive bits forms a unique code word, yielding $2^n - 1$ different n-bit code words. Consecutive code words differ by only one bit, meaning the last $n-1$ bits of one code word overlap with the first $n-1$ bits of the next. The all-zeros code word is excluded because it would cause the LFSR to get stuck in that state. Thus, there are $2^n - 1$ code words instead of 2^n. Any of these $2^n - 1$ code words can be the initial state, known as the reference code word. After $2^n - 1$ clock cycles, the LFSR cycles through all possible states, generating the complete M-sequence, and returns to the initial state. If the sequence continues, it repeats the same series of code words. Not all LFSRs can generate an M-sequence; only those with the correct feedback configuration of XOR gates, whose number and arrangement are defined by the coefficients of a primitive generator polynomial, can do so. Furthermore, for any LFSR configuration that generates an M-sequence, there is an inverse configuration that will produce the same sequence in reverse order, starting from the same initial state. There are two primary types of M-sequence generators: the Fibonacci generator and the Galois generator. In the Fibonacci generator, the XOR logic gates in the feedback loop are connected in series. In contrast, the Galois generator has the XOR logic gates connected in parallel. The Galois generator is faster than the Fibonacci generator because it avoids the cumulative propagation delays associated with the series-connected XOR logic gates in the feedback loop.

M-sequences find numerous applications across various fields, including telecommunications [5], [6], cryptography [7], testing of VLSI circuit [8] and gas sensors [9], frequency response measurement [4], and wireless localization [10]. Among these, one of the most significant applications of M-sequences is in the implementation of absolute position encoders [11]-[14]. These sensors measure the linear or angular position of a moving system relative to a reference position [15]-[18]. Absolute position encoders are widely used in various applications, including printers, copiers, scanners, servo motors, robots, telescopes, production lines, automated welding, barcode readers, elevators, radars, wind turbines, door control devices, and a range of machines such as labeling, drilling, mixing, bottling, winding, and CNC machines.

The basic principle of operation for absolute position encoders is based on the idea that the entire range of the position being measured is divided into a specific number of sectors, with each sector encoded by a unique code word. For angular position measurements, a code disk rotates along with the moving system, and the bits of each sector's code word are represented on the disk by transparent and opaque (or reflective and non-reflective) fields. An optical system of LED diodes and phototransistors reads these bits from the code disk. By interpreting the read code word, the sector in which the moving system is located can be identified, though there is an inherent position uncertainty within each sector proportional to its width. Increasing the resolution of absolute encoders increases

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the number of sectors, thus reducing their width and consequently minimizing the position measurement error.

Traditional absolute position encoders use Gray code or natural binary code, based on transversal writing of code words on the code disk. This method requires a separate code track and a separate optical reading system for each bit of the code word, leading to an increase in the number of code tracks and reading heads as the resolution n increases, which in turn increases complexity and cost. In contrast, absolute position encoders using M-sequences utilize longitudinal writing of code words on the code disk, requiring only one code track regardless of the resolution n. This approach prevents the increase in the number of code tracks, thus avoiding the corresponding increase in complexity and cost, representing the main advantage of M-sequence-based absolute position encoders over classical encoders. Additionally, M-sequence absolute position encoders offer other benefits: they enable error detection methods, significantly enhancing reliability; and for rotary encoders, they allow direct adjustment of the zero position after mounting the code disk on the shaft [11].

The primary drawback of M-sequence-based code words is that they are not weighted, making them incompatible with conventional digital electronics. Consequently, these code words must be converted into natural binary code. To achieve this, code converters are employed, with the serial code converter being widely used [19]-[20]. This converter utilizes a shift register and is favored for its straightforward implementation. Additionally, it enables direct zero position adjustment with minimal modifications to hardware or software.

There are two primary types of serial converters for translating M-sequences to natural binary code: the Fibonacci converter and the Galois converter [19]. The Fibonacci converter is based on the Fibonacci generator of the inverse M-sequence, while the Galois converter relies on the Galois generator of the inverse M-sequence. Both converters operate on the same principle. Code conversion starts by loading the bits of the read code word into the shift register. The register then transitions to a new state with each clock cycle until it reaches the reference state, which corresponds to the zero position. By counting the clock pulses required for the shift register to reach this reference state, the natural binary code word representing the current position is obtained. However, the Galois serial converter requires an additional component known as *the initial logic* for correct functionality, with its design detailed in [19].

Since the duration of serial conversion equals the number of clock pulses needed for the shift register within the converter to reach the reference code word starting from the read code word, it is clear that the duration of the clock pulses (and therefore the clock frequency) of the code converter is a crucial factor affecting the conversion duration. The maximum clock pulse frequency depends on the propagation delays within the converter. Namely, the duration of the clock pulses must be longer than the longest propagation delay for the converter to operate correctly. From all this, it is clear that determining the maximum clock pulse frequency is very important, as it determines the operating speed of the entire position encoder.

This paper presents a detailed analysis of propagation delays in both types of serial converters (Fibonacci and Galois) for converting M-sequence to natural binary code, for resolution $n = 8$. The primary contribution of this research is the determination of the maximum clock frequency for these converters. An important conclusion of the paper is that the clock frequencies of both types of serial code converters, Fibonacci and Galois, are identical, for the 8-bit resolution. This finding may be surprising, as the Galois M-sequence generator is faster than the Fibonacci generator. However, the study reveals that the dominant delays arise from other elements common for both converter types, such as the logic circuits for reference state detection and for writing bits into the shift register's flip-flops. As a result, the inherent speed advantage of the Galois generator is not realized. Specific values of propagation delays are calculated for the case where the code converter is implemented using the widely used 74LVC family of logic circuits and it is shown that the maximum clock frequency in this case is 29.85 MHz. To validate the theoretical results, a simulation of both types of serial code converters was conducted using the NI Multisim software package. The simulation confirmed that the behavior of the code converter circuit aligns with theoretical expectations. Specifically, the simulation determined a maximum clock frequency of 28.98 MHz, which closely matches the theoretically determined value.

II. DESCRIPTION OF THE STRUCTURE AND OPERATING PRINCIPLE OF AN 8-BIT SERIAL M-SEQUENCE TO NATURAL BINARY CODE CONVERTERS

The code disk of an 8-bit absolute position encoder contains a 255-bit M-sequence, generated using a direct M-sequence generator. This sequence includes 255 code words, each representing a distinct sector of angular position. The code word $Y_8^0 Y_7^0 ... Y_1^0$ that encodes the reference (zero) position is known as the reference code word. The code disk is mounted on a rotating system and rotates along with it. It has already been stated that the code word from the M-sequence cannot be directly fed into the rest of the digital electronics; it must first be converted into a natural binary code word. There are two types of serial converters for translating M-sequences to natural binary code: the Fibonacci and the Galois converters.

In Fig. 1, a block diagram of the 8-bit Fibonacci code word converter from an M-sequence to the natural binary code is shown. The main part of this converter is the 8-bit Fibonacci generator of the inverse M-sequence, which consists of an 8-bit shift register with a feedback loop that generates the M-sequence in reverse order compared to the M-sequence written on the code disk. The shift register consists of eight D flip-flops: FF_1, …, FF_8. For flip-flops FF_2, …, FF_8, the input D bit is equal to the output Q bit of the previous flip-flop (i.e., $D(FF_i) = Q(FF_{i-1})$, $i = 2, ..., 8$). The input bit of the first flip-flop FF_1 is obtained as a linear combination of the output bits of flip-flops, implemented through the feedback loop with XOR logic gates. The structure of the feedback loop (i.e., the number and arrangement of XOR logic gates) is crucial for implementing the generator of inverse M-sequence. This structure is determined by the generator polynomial, which for resolution n takes the form $P_n(X) = c_n X^n + c_{n-1} X^{n-1} + ... + c_1 X + 1$, where c_n $(i = 1,...,n)$ are the binary coefficients, and + denotes addition modulo 2. The coefficients of the generator polynomial that have a value of 1 define the structure of the feedback branch, in a way that if the coefficient c_{n-i} $(i = 1,...,n-1)$ is equal to 1 than the output bit from the flip-flop FF_i is involved in the modulo 2 sum the input bit of FF_1. Specifically, with a resolution $n = 8$, the generator polynomial is $P_8(X) = X^8 + X^6 + X^5 + X^2 + 1$, indicating that the coefficients c_8, c_6, c_5 and c_2 are equal to 1. Consequently, the input bit for FF_1 is derived by adding modulo 2 the output bits from flip-flops FF_8, FF_6, FF_3 and FF_2 necessitating three serially connected XOR logic gates.

In Fig. 2, we see a block diagram of the 8-bit Galois code converter, whose main component is the Galois generator of the inverse sequence. This generator consists of 8 flip-flops and a feedback branch with XOR logic gates connected in parallel. The XOR gates are placed at the inputs of the flip-flops FF_{i+1} corresponding to the coefficients c_i equal to 1, $i = 1, …, n-1$. Specifically, for the resolution $n = 8$, the XOR gates are located at the inputs of the flip-flops FF_3, FF_6 and FF_7.

Thanks to the parallel connection of the XOR gates, their propagation delays do not accumulate. It is important to mention that the Galois code converter requires an additional component, known as the initial logic, for proper functioning. The read code word $Y_8 Y_7 ... Y_1$ from the code disk is not directly entered into the Galois converter. Instead, it first passes through the initial logic, obtaining the modified code word $G_8 G_7 ... G_1$ that is written into the flip-flops of the Galois converter. Additionally, the reference code word for the Galois converter $G_8^0 G_7^0 ... G_1^0$ is derived by modifying the reference code word for the Fibonacci converter $Y_8^0 Y_7^0 ... Y_1^0$ according to the initial logic. Using the results from [19], which provide the design rules for the initial logic, the bits of the code word $G_8 G_7 ... G_1$ are determined as $G_{8-i} = Y_{8-i} + \sum_{j=1}^{i} c_{7-i+j} Y_{9-j}$, $(i = 1, …, 7)$, $G_8 = Y_8$, and the bits of the reference code word for the Galois converter $G_8^0 G_7^0 ... G_1^0$ are determined as $G_{8-I}^0 = Y_{8-I}^0 + \sum_{j=1}^{i} c_{7-i+j} Y_{9-j}^0$, $(i = 1, …, 7)$, $G_8^0 = Y_8^0$.

Both types of serial code converters, Fibonacci and Galois, operate on the same principle. First, the read code word $Y_8 Y_7 ... Y_1$ is written into the shift register of the Fibonacci converter, while the modified read code word $G_8 G_7 ... G_1$ is written into the shift register of the Galois converter. The shift register then transitions to a new state in each clock cycle, moving towards the reference state. When the inverse shift register reaches the reference state ($Y_8^0 Y_7^0 ... Y_1^0$ for the Fibonacci converter and $G_8^0 G_7^0 ... G_1^0$ for the Galois converter), the conversion is completed, and the number of clock cycles required to reach the reference state represents the position of the angular sector we are currently in.

Both types of the serial code converters contain some common important additional elements necessary for correct operation. First, there is a logic needed to detect whether the shift register has reached the reference state or not, which consists of several NOT gates at the outputs of flip-flops where the bit of the reference code word has a value of 0, as well as a $NAND_1$ logic gate.

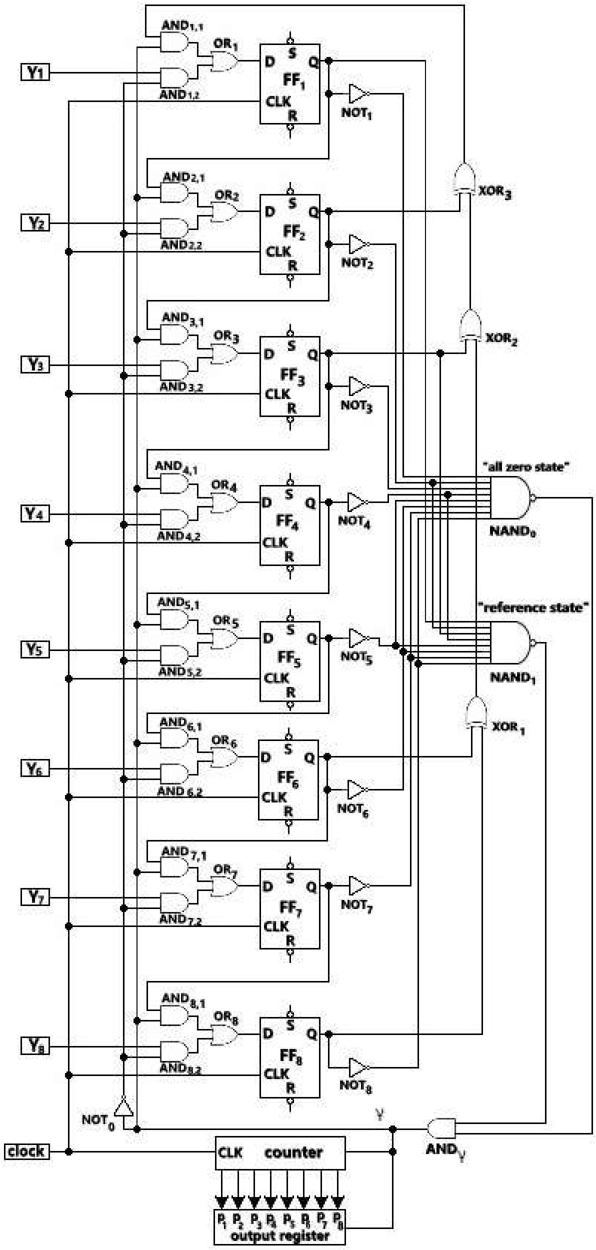

Fig. 1. The Fibonacci serial code converter

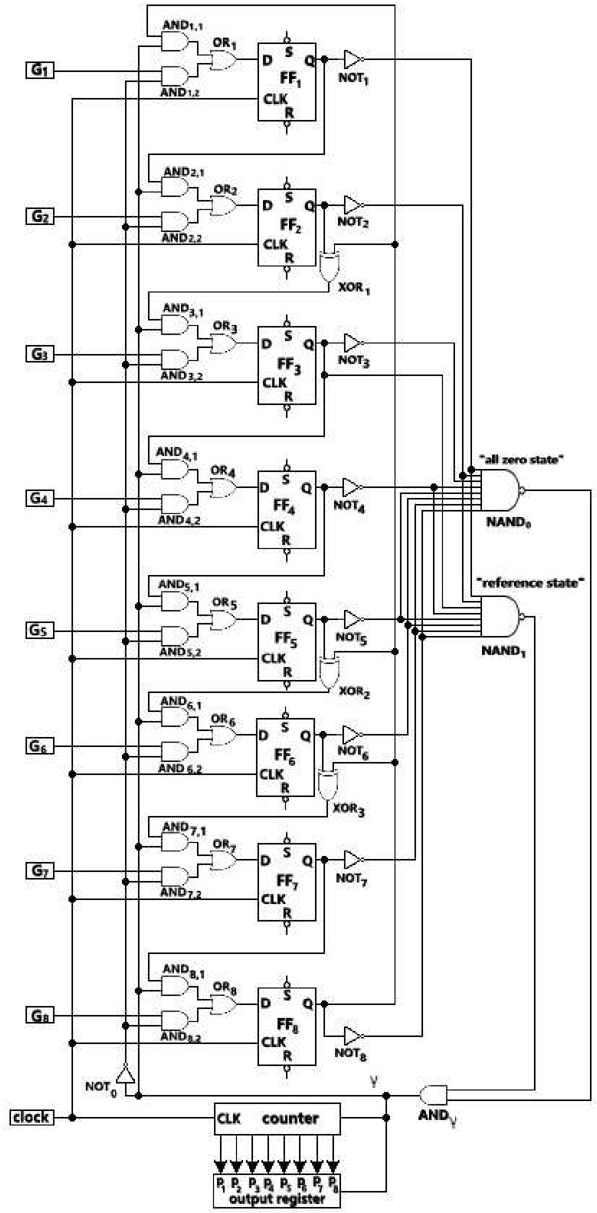

Fig. 2. The Galois serial code converter

In Fig. 1, the logic for detecting the reference state $Y_8^0 Y_7^0 ... Y_1^0$ = 10100000 is shown, while in Fig. 2, the logic for detecting the corresponding modified reference state $G_8^0 G_7^0 ... G_1^0$ = 00100000 is displayed. Additionally, there is a $NAND_0$ circuit that routes the inverted outputs of all flip-flops, enabling the shift register to exit the forbidden all-zero state that it may enter immediately after power-up. Also, there is a counter that counts the clock cycles needed for the shift register, starting from the read code word, to reach the reference state. When the shift register reaches the reference state, the counter's content is written into the output register and represents the 8-bit natural binary code word corresponding to the current position. Simultaneously, the counter resets to zero and is ready for converting a new code word. Additionally, at the input of each flip-flop, there are three logic gates (two AND gates and one OR gate) that control which bits will be written into the flip-flops in a given clock cycle. If the current conversion is not yet completed (i.e., if the shift register has not yet reached the reference state), the bits are written into the flip-flops through the upper AND gates ($AND_{i,1}$, i = 1, …, 8) generated within the shift register. If the current conversion is completed (i.e., the shift register has reached the reference state), the bits of the new read code word are written into the flip-flops through the lower AND gates ($AND_{i,2}$, i = 1, …, 8) and a new conversion begins.

The fundamental principle of operation for serial converters that transform pseudorandom code into natural binary code is illustrated by the algorithm presented in Fig. 3.

III. Analysis of Propagation Delays and Determination of Maximum Clock Frequency

If the read code word is p positions away from the reference code word, the code conversion takes (p + 1) clock cycles because we need p clock cycles to move from the read code word to the reference code word and one more clock cycle to detect that we have reached the reference code word. Since the counter counts from 0, it will reach the value p in (p+1) clock cycles, representing the angular position. The duration of the conversion of the read code word is given by:

$$\delta = (p+1) \cdot T^{clock} = (p+1) / f^{clock} \quad , \tag{1}$$

where T^{clock} and f^{clock} are the period and frequency of the clock pulses, respectively. Based on (1), it is evident that

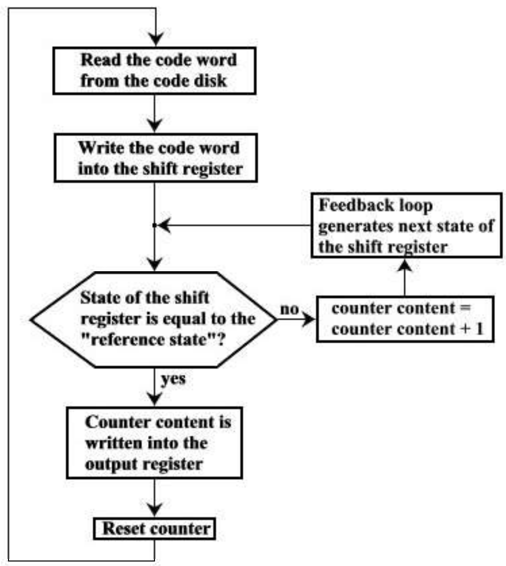

Fig. 3. The algorithm describes functional principle of the serial code converters

f^{clock} impacts the overall duration of code word conversion, thereby influencing the operating speed of the entire absolute position encoder. Consequently, determining the maximum allowable clock pulse frequency $f_{\max}^{clock}$ is a significant research task.

For the serial code converter to operate correctly, the following condition must be met:

$$T_{\min}^{clock} \geq \tau_{\max} , \tag{2}$$

where $\tau_{\max}$ is the maximum propagation delay in the converter circuit.

The following provides a detailed analysis of propagation delay for all data paths in the both types of serial code converter circuits. The propagation delays of the logic gates NOT, AND, OR, and NAND are denoted by τ_{NOT}, τ_{AND}, τ_{OR} and τ_{NAND} respectively, and τ_{FF} represents the propagation delay of a D flip-flop, where $\tau_{FF} = \tau_{CLK\to Q} + \tau_{setup}$. Here, $\tau_{CLK\to Q}$ is the time from the rising edge of the clock that triggers the flip-flop to the moment the value is set on the Q output of the flip-flop, and τ_{setup} is the time required for the data bit value on the D input of the flip-flop to be stable before the flip-flop is triggered. The start of the clock is considered to be the rising edge of the clock that triggers the flip-flop, and all propagation delays in the serial converter circuit are calculated relative to this moment. In Fig. 1 and Fig. 2, all points in the circuit to which data must arrive within one clock cycle are numbered from 1 to 35.

The values of the propagation delays for all points in the circuit of the Fibonacci code converter from Fig. 1 are given by the following expressions: $\tau_1 = \tau_{FF} + 3\tau_{XOR}$, $\tau_2 = \tau_{FF} + \tau_{NOT} + \tau_{NAND} + \tau_{AND}$, $\tau_3 = \tau_{FF} + 2\tau_{NOT} + \tau_{NAND} + \tau_{AND}$, $\tau_4 = \max\{\tau_1, \tau_2\} + \tau_{AND}$, $\tau_5 = \tau_9 = \tau_{13} = \tau_{17} = \tau_{21} = \tau_{25} = \tau_{29} = \tau_{33} = \tau_3 + \tau_{AND}$, $\tau_6 = \max\{\tau_4, \tau_5\} + \tau_{OR}$, $\tau_7 = \tau_{11} = \tau_{15} = \tau_{19} = \tau_{23} = \tau_{27} = \tau_{31} = \tau_{FF}$, $\tau_8 = \tau_{12} = \tau_{16} = \tau_{20} = \tau_{24} = \tau_{28} = \tau_{32} = \max\{\tau_7, \tau_2\} + \tau_{AND} = \tau_2 + \tau_{AND}$, $\tau_{10} = \tau_{14} = \tau_{18} = \tau_{22} = \tau_{26} = \tau_{30} = \tau_{34} = \max\{\tau_8, \tau_9\} + \tau_{OR} = \tau_9 + \tau_{OR}$.

The values of the propagation delays for all points in the circuit of the Galois code converter from Fig. 2 are defined in the following way: $\tau_1 = \tau_7 = \tau_{15} = \tau_{19} = \tau_{31} = \tau_{FF}$, $\tau_2 = \tau_{FF} + \tau_{NOT} + \tau_{NAND} + \tau_{AND}$, $\tau_3 = \tau_{FF} + 2\tau_{NOT} + \tau_{NAND} + \tau_{AND}$, $\tau_4 = \tau_8 = \tau_{16} = \tau_{20} = \tau_{32} = \max\{\tau_1, \tau_2\} + \tau_{AND} = \tau_2 + \tau_{AND}$, $\tau_5 = \tau_9 = \tau_{13} = \tau_{17} = \tau_{21} = \tau_{25} = \tau_{29} = \tau_{33} = \tau_3 + \tau_{AND}$, $\tau_6 = \tau_{10} = \tau_{18} = \tau_{22} = \tau_{34} = \max\{\tau_4, \tau_5\} + \tau_{OR} = \max\{\tau_2, \tau_3\} + \tau_{AND} + \tau_{OR} = \tau_3 + \tau_{AND} + \tau_{OR}$, $\tau_{11} = \tau_{23} = \tau_{27} = \tau_{FF} + \tau_{XOR}$, $\tau_{12} = \tau_{24} = \tau_{28} = \max\{\tau_2, \tau_{11}\} + \tau_{AND}$, $\tau_{14} = \tau_{26} = \tau_{30} = \max\{\tau_{12}, \tau_5\} + \tau_{OR} = \tau_9 + \tau_{OR}$.

For both types of serial converters, Fibonacci and Galois, the propagation delay required to reset the counter when the shift register reaches the reference state, i.e., when the output bit of the NAND gate γ becomes 0, is given by $\tau_{35} = \tau_{CLK\to Q} + \tau_{NOT} + \tau_{NAND} + \tau_{AND} + \tau_{counter}^{reset}$, where $\tau_{counter}^{reset}$ represents the delay of the counter from the moment the bit γ becomes 0 to the moment the counter resets.

The maximum propagation delay in the serial code converter circuit, for both Fibonacci and Galois converters, is $\tau_{\max} = \max\{\tau_i, i = 1, \ldots, 35\}$.

To obtain numerical values, we will consider the specific implementation of the serial code converter using logic gates from the 74LVC family. In this case, the propagation delay values of the logic gates are: τ_{NOT} = 4 ns, τ_{AND} = 4.1 ns, τ_{OR} = 3.8 ns, τ_{XOR} = 5 ns, τ_{NAND} = 6.3 ns, $\tau_{CLK\to Q}$ = 5.2 ns, τ_{setup} = 2 ns, τ_{FF} = 7.2 ns, and $\tau_{counter}^{reset}$ = 6.4 ns.

Propagation delays for the Fibonacci converter implemented with the logic gates from the 74LVC family are: τ_1 = 22.2 ns, τ_2 = 21.6 ns, τ_3 = 25.6 ns, τ_4 = 26.3 ns, $\tau_5 = \tau_9 = \tau_{13} = \tau_{17} = \tau_{21} = \tau_{25} = \tau_{29}$ = 29.7 ns, τ_6 = 33.5 ns, $\tau_7 = \tau_{11} = \tau_{15} = \tau_{19} = \tau_{23} = \tau_{27} = \tau_{31}$ = 7.2 ns, $\tau_8 = \tau_{12} = \tau_{16} = \tau_{20} = \tau_{24} = \tau_{28} = \tau_{32}$ = 25.7 ns, $\tau_{10} = \tau_{14} = \tau_{18} = \tau_{22} = \tau_{26} = \tau_{30} = \tau_{34}$ = 33.5 ns and τ_{35} = 26 ns.

Propagation delays for the Galois converter implemented with the logic gates from the 74LVC family are: $\tau_1 = \tau_7 = \tau_{15} = \tau_{19} = \tau_{31}$ = 7.2 ns, τ_2 = 21.6 ns, τ_3 = 25.6 ns, $\tau_4 = \tau_8 = \tau_{16} = \tau_{20} = \tau_{32}$ = 25.7 ns, $\tau_5 = \tau_9 = \tau_{13} = \tau_{17} = \tau_{21} = \tau_{25} = \tau_{29} = \tau_{33}$ = 29.7 ns, $\tau_6 = \tau_{10} = \tau_{18} = \tau_{22} = \tau_{34}$ = 33.5 ns, $\tau_{11} = \tau_{23} = \tau_{27}$ = 12.2 ns, $\tau_{12} = \tau_{24} = \tau_{28}$ = 25.7 ns, $\tau_{14} = \tau_{26} = \tau_{30}$ = 33.5 ns and τ_{35} = 26 ns.

Considering the previous values of the propagation delays, it is clear that the both Fibonacci and Galois converters have the same value of the maximum propagation delay $\tau_{\max}$ = 33.5 ns, and therefore the same value of the maximum clock frequency $f_{\max}^{clock} = 1/\tau_{\max}$, as presented in Table 1.

To validate the theoretical analysis, simulations of both types of serial code converters (Fibonacci and Galois) were performed using NI Multisim software. The maximum clock frequency values $f_{\max}^{clock}$ obtained from these simulations are also presented in Table 1. Although there is a slight mismatch

TABLE I. THEORETICAL AND SIMULATION RESULTS

	Theoretical results		**Simulation results**
	$\tau_{\max}$	$f_{\max}^{clock}$	$f_{\max}^{clock}$
Fibonacci code converter	33.5	29.85	28.98
Galois code converter	33.5	29.85	28.98

between the theoretical and simulation results (likely due to the tolerances in propagation delay values relative to their nominal values) the simulation results are closely aligned with the theoretical predictions. This consistency confirms the validity of the theoretical analysis. Furthermore, the simulations verify the theoretical finding that the maximum clock frequency $f_{\max}^{clock}$ is identical for both the Fibonacci and Galois code converters.

IV. Conclusion

The paper addresses the problem of determining the maximum clock frequency of both types (Fibonacci and Galois) of 8-bit serial code converters for M-sequence code words into natural binary code, as one of the main factors influencing the maximum angular speed at which the 8-bit absolute angular position encoder based on the M-sequence can operate. The paper first explains in detail the structure and operating principle of both types of the serial code converters, and then derives an expression for the maximum clock frequency based on a detailed analysis of propagation delays along all paths within the serial converter circuits. Numerical values for the propagation delays and maximum clock frequency were calculated for the case where the serial code converter is implemented using logic circuits from the 74LVC family, resulting in a maximum clock frequency value of 29.85 MHz for both types of serial converters. It was shown that although the Galois generator of an inverse M-sequence is faster than the Fibonacci generator, the Galois code converter is not faster than the Fibonacci code converter, due to the dominant effect of propagation delays of some other elements common for both converter types, such as the logic circuits for reference state detection and for writing bits into the shift register's flip-flops. Additionally, a simulation of the Fibonacci and Galois serial code converters was conducted using NI Multisim software, yielding a maximum clock frequency of 28.98 MHz for both converters. The close agreement between the theoretical and simulated maximum clock frequency values validates the theoretical analysis, despite the slight discrepancy observed. This discrepancy can be attributed to the tolerance of propagation delays inherent in the logic circuits used.

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Performance Evaluation of the 24-bit Floating Point Format in Different Variance Ranges for Digital Representation of Measurement Data

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***Abstract*—The goal of the paper is to achieve fast, efficient, and accurate performance evaluation of the 24-bit floating point (FP24) format, aiming to decrease complexity of AI (artificial intelligence) algorithms by representing their parameters and data by the FP24 format instead of the standardly used FP32 (32-bit floating point) format, supporting in this way implementation of AI algorithms on resource-constrained sensor nodes and edge measuring devices. By leveraging the established analogy between floating point formats and piecewise uniform quantizers, the performance of the FP24 format can be determined using the Signal-to-Quantization Noise Ratio (SQNR) of the corresponding piecewise uniform quantizer. However, calculating this involves summing 254 terms, resulting in high computational complexity. Given that in most applications, the data variance range is much narrower than the dynamic range of the FP24 format, this paper introduces an approach that divides the dynamic variance range of the FP24 format into subranges and computes the SQNR within these subranges. This method significantly reduces the number of segments in the piecewise uniform quantizer impacting performance, thereby decreasing the number of terms in the SQNR sum. This approach simplifies the computation of FP24 format performance without sacrificing accuracy.**

Keywords*—*floating point format; Gaussian source; piecewise uniform quantizer; SQNR; artificial intelligence-based measurement systems

I. INTRODUCTION

Deep neural networks (DNNs) represent a very powerful tool for processing measurement data. By default [1], the weights of DNNs, as well as the input measurement data, are represented by the FP32 digital format defined by the IEEE-754 standard [2], since it provides very high-quality digital representation over a very wide dynamic range of variance [3]. However, there is a growing need to move away from the traditional approach of executing DNN algorithms on powerful servers and clouds [4], and instead bring them as close as possible to the source of measurement data and execute them locally on sensor nodes and edge measurement devices [5-11]. This shift aims to increase response speed, as well as the security and integrity of the measurement data, representing very topical research direction. Nevertheless, due to the limited processing and memory capacities of sensor nodes and edge measurement devices, as well as the very limited available energy in battery-powered systems, the high complexity of the FP32 format can pose a significant problem [12, 13]. Therefore, there is an increasing need to use FP (floating point) formats with a smaller number of bits, such as 24-bit FP24 [14], 16-bit bfloat16 [15, 16], or 8-bit FP8 [17], to reduce implementation complexity. However, reducing the number of bits also decreases the performance of the FP format. Hence, it is essential to develop methods to evaluate the performance of different floating point formats to determine their suitability for various applications.

In [16, 18, 19], a significant contribution was made in evaluating the performance of FP format by establishing an analogy between the FP format and a piecewise uniform quantizer (referred to as *the floating point quantizer* FPQ). This analogy enabled the performance of the FP format to be expressed through an objective measure, such as the Signal-to-Quantization-Noise Ratio (SQNR) of the FPQ. However, the expression for the SQNR of FPQ derived according to [18, 19] is highly complex, as it involves summing a large number of terms, each corresponding to one segment of the FPQ. For instance, in FP formats like FP32, FP24, and bfloat16, which use 8 bits to encode the exponent, the sum within the SQNR expression includes 254 terms. Additionally, since the SQNR calculation must be repeated for different variances of the measured data, the complexity of the SQNR expression becomes even more pronounced. Thus, there is a clear need to simplify this SQNR expression to develop a fast and efficient method for assessing the performance of FP formats, which is the primary goal of this paper.

The paper explores the FP24 format as a simpler alternative to the FP32 format, making it a viable candidate for systems with limited resources. It is important to emphasize that [18, 19] has demonstrated that the performance of FP formats is influenced by the probability density function (PDF) of the measurement data. This paper focuses on the Gaussian PDF since it can be used for statistical modeling of a number of stochastic measurement signals [20, 21].

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The paper starts from the empirically confirmed fact that, for the vast majority of applications, the range of the variance of measurement data is significantly narrower than the dynamic range of the variance of the FP24 format, which has a width of 1500 dB. The main idea of the paper is to divide the dynamic range of the variance of the FP24 format into 10 subranges of variance, each 150 dB wide, which is sufficiently broad for the vast majority of applications. The paper then demonstrates that within a single subrange of variance, a small number of segments of the FPQ have a probability substantially different from 0 and therefore an impact on the SQNR, while the vast majority of segments have a negligible probability and therefore a negligible impact on the SQNR. This leads to the main contribution of the paper, which is the derivation of expressions for the SQNR in different subranges of variance, containing at most 31 terms in the sum, which is significantly less compared to the initial expression for SQNR that contains a sum of 254 terms. In this way, the expression for SQNR is significantly simplified, and thus the complexity of calculating the performance of the FP24 format is greatly reduced. Furthermore, it is shown that this method does not reduce the accuracy of SQNR calculations. This approach can be extended to other FP formats as well. Providing an efficient method for performance evaluation of floating point formats, the paper contributes to the implementation of AI-based sensor nodes and edge measurement devices by enabling the use of less complex FP formats compared to the standard FP32.

The paper is structured as follows. Section 2 describes the FP24 format, draws an analogy with the piecewise uniform FPQ, and derives expressions for SQNR. Section 3, the core of the paper, focuses on defining simplified expressions for SQNR across various subranges of variance. Finally, Chapter 4 concludes the paper.

II. Description of the FP24 Format and Analogy With a Piecewise Uniform Quantizer

A real number x is represented in the FP24 format as:

$$x = se_1 ... e_8 m_1 ... m_{15} \ , \tag{1}$$

where one bit is used for encoding the sign of x, 8 bits for encoding the exponent, and 15 bits for encoding the mantissa. The number x, represented in the form (1), is calculated as:

$$x = (-1)^s 2^{E^*} \left(1 + \frac{M}{2^{15}}\right) \ , \tag{2}$$

where $E = (e_1 ... e_8)_2 = \sum_{i=1}^{8} e_i 2^{8-i}$ is the exponent, $E^* = E - bias$ is the biased exponent, and $M = (m_1 ... m_{15})_2 = \sum_{i=1}^{15} m_i 2^{15-i}$ is the mantissa. The exponent E can take values from 0 to 255, but the two extreme values (0 and 255) are reserved, so only the values of E from 1 to 254 are used for encoding numbers. Therefore, the biased exponent E^* can take values from $E^*_{\min}$ = -126 to $E^*_{\max}$ = 127. The mantissa M ranges from 0 to $2^{15} - 1$. The FP24 format is symmetric around 0 because for every positive FP number, there is its negative counterpart. The maximum positive FP24 number, obtained for the maximum values of E^* and M, according to (2), is $x_{\max} = 2^{128}$. Positive FP numbers can be divided into 254 groups so that each corresponds to one value of E^*, with each group containing 2^{15} numbers (one for each value of M). A group of numbers with the same value of E^* are placed within the range $S_{E^*} = [2^{E^*}, 2^{E^*+1})$. The numbers within one group are equidistant, with a step size of:

$$\Delta_{E^*} = 2^{E^*}\left(1 + (M+1)/2^{15}\right) - 2^{E^*}\left(1 + M/2^{15}\right) = 2^{E^*-15} \, . \tag{3}$$

The same structure of 254 groups with 2^{15} equidistant numbers also exists for negative numbers due to symmetry. It is clear that the structure of the FP24 format corresponds to the structure of a symmetric piecewise uniform quantizer [16, 18, 19] with a support region $[-x_{\max}, x_{\max}]$. This quantizer has 254 segments S_{E^*} on both the positive and negative sides, each corresponding to one value of E^*, ($-126 \le E^* \le 127$), with uniform quantization of 2^{15} levels performing within each segment with a quantization step size of Δ_{E^*}. We will refer to this piecewise uniform quantizer as *the floating point quantizer* (FPQ). This analogy between the FP24 format and the FPQ is very useful because it allows us to calculate the performance of the FP24 format through an objective measure such as the SQNR of FPQ.

The SQNR of FPQ, and therefore the performance of FP24, depends on the probability density function (PDF) of the input measurement data. In this paper, the Gaussian PDF, often used for statistical modeling of measurement data, is considered, defined with [20]:

$$p(x,\sigma) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{x^2}{2\sigma^2}\right) \ , \tag{4}$$

where σ^2 is the variance of the input measurement data.

The distortion D, which represents the mean squared quantization error for FPQ, is defined as:

$$D(\sigma) = 2 \sum_{E^*=-126}^{127} \frac{\Delta_{E^*}^2}{12} P_{E^*} \ . \tag{5}$$

Multiplying by 2 in expression (5) accounts for the distortion in the negative part of the real axis. Each term in the sum represents the distortion within one segment S_{E^*}, for $-126 \le E^* \le 127$. $P_{E^*} = 2\int_{2^{E^*}}^{2^{E^*+1}} p(x,\sigma)dx$ represents the probability of segment S_{E^*}. For $p(x,\sigma)$ defined by (4), we obtain the following expressions for P_{E^*}:

$$P_{E^*} = \frac{1}{2}\left(\operatorname{erf}\left(\frac{2^{E^*+1/2}}{\sigma}\right) - \operatorname{erf}\left(\frac{2^{E^*-1/2}}{\sigma}\right)\right). \quad (6)$$

If it is necessary to consider the variance over a very wide range, as is the case with the FP24 format, it is common to express the variance in the logarithmic domain as $\alpha\,[\mathrm{dB}] = 10\log_{10}(\sigma^2/\sigma_{ref}^2)$, where σ_{ref}^2 is a reference variance. Without loss of generality, we can assume that σ_{ref}^2 = 1, so we get $\alpha\,[\mathrm{dB}] = 10\log_{10}\sigma^2$, from which it follows:

$$\sigma = 10^{\alpha/20}. \quad (7)$$

SQNR is defined as:

$$\mathrm{SQNR}(\sigma)\,[\mathrm{dB}] = 10\log_{10}\frac{\sigma^2}{D(\sigma)}. \quad (8)$$

Taking into account (2), (5), (6), (7) and (8), we obtain the final expression for the SQNR of FPQ:

$$\mathrm{SQNR}(\alpha) = -10\log_{10}\left(\sum_{E^*=-126}^{127}\frac{2^{2E^*-32}}{3\cdot 10^{10}}\left(\operatorname{erf}\left(\frac{2^{E^*+\frac{1}{2}}}{10^{\frac{\alpha}{20}}}\right) - \operatorname{erf}\left(\frac{2^{E^*-\frac{1}{2}}}{10^{\frac{\alpha}{20}}}\right)\right)\right). \quad (9)$$

III. Performance Evaluation of the FP24 Format in Different Variance Subranges

The problem with the expression (9) for SQNR is its computational intensity, as it involves a sum of 254 terms. Additionally, expression (9) calculates the SQNR value for only a specific variance, necessitating repeated calculations for all variances of interest. Given the wide dynamic range of variance for FP24, this makes performance calculations even more complex. Therefore, simplifying expression (9) for SQNR of FPQ is essential to enable faster, more efficient, and less computationally demanding performance calculations for the FP24 format, which is the goal of this paper.

The dynamic range of variance α for the FP24 format, within which it enables high-quality digital data representation, is extremely wide, Δ_α = [-750 dB, 750 dB]. However, for most practical applications, a much narrower range of variance is of interest. Hence, we decided to divide the entire dynamic range of variance Δ_α for the FP24 format into 10 narrower subranges of width 150 dB:

$$\delta_\alpha^i = [-750+150(i-1), -600+150(i-1))\ [\mathrm{dB}],\ i = 1,\dots,10, \quad (10)$$

considering that a variance range of 150 dB is sufficient for most applications. Thus, for the majority of applications, it is adequate to consider only one of the subranges δ_α^i instead of the entire range Δ_α.

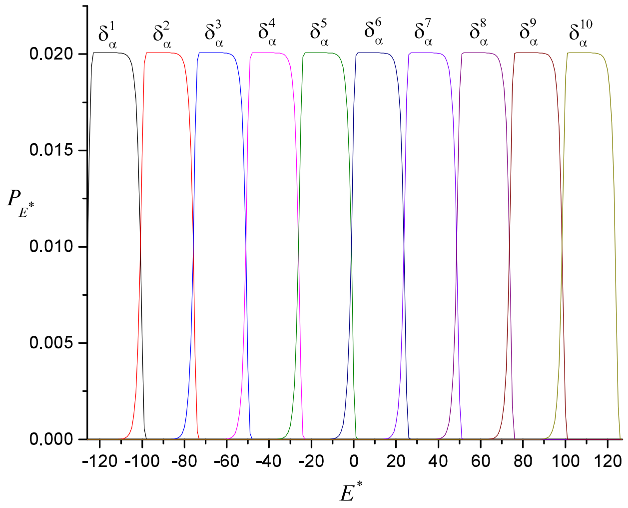

Fig. 1. Probabilities of FPQ segments for different variance subranges

TABLE I. The Range of Indexes [$\theta_{\min}^i$, $\theta_{\max}^i$] of FPQ Segments S_{E^*} That Affect SQNR, For Different Variance Subranges δ_α^i

i	δ_α^i	$\theta_{\min}^i$	$\theta_{\max}^i$
1	[-750 dB, -600 dB)	-126	-100
2	[-600 dB, -450 dB)	-104	-75
3	[-450 dB, -300 dB)	-79	50
4	[-300 dB, -150 dB)	-54	-25
5	[-150 dB, 0 dB)	-29	0
6	[0 dB, 150 dB)	-4	25
7	[150 dB, 300 dB)	20	50
8	[300 dB, 450 dB)	46	75
9	[450 dB, 600 dB)	71	100
10	[600 dB, 750 dB]	96	125

TABLE II. Exact and Approximate Values of SQNR for Different Values of Variance α

α [dB]	-500	-250	0	250	500
SQNR(α) [dB]	103.758	103.782	103.754	103.785	103.751
SQNR^i(α) [dB]	103.758	103.782	103.754	103.785	103.751

Fig. 1 shows the probability of the segments S_{E^*}, ($-126 \le E^* \le 127$) of the FPQ if the variance α belongs to different subranges δ_α^i. We see that for each subrange δ_α^i, only a small number of segments S_{E^*} have a probability substantially different from zero, while most of the other segments have negligible probabilities very close to zero, making their impact on SQNR negligible. This leads to an important conclusion: if we calculate SQNR by focusing on a specific variance subrange δ_α^i, the sum in the SQNR expression can contain significantly fewer terms compared to the 254 terms in expression (9). We will define the following approximate expressions for calculating SQNR in different variance subranges δ_α^i:

$$\mathrm{SQNR}^i(\alpha \mid \alpha \in \delta_\alpha^i) = \\ -10\log_{10}\left(\sum_{E^*=\theta_{\min}^i}^{\theta_{\max}^i} \frac{2^{2E^*-32}}{3\cdot 10^{\frac{\alpha}{10}}}\left(\operatorname{erf}\left(\frac{2^{E^*+\frac{1}{2}}}{10^{\frac{\alpha}{20}}}\right)-\operatorname{erf}\left(\frac{2^{E^*-\frac{1}{2}}}{10^{\frac{\alpha}{20}}}\right)\right)\right), \quad (11)$$

where $[\theta_{\min}^i, \theta_{\max}^i]$ denotes the range of indexes E^* of segments S_{E^*} with probabilities substantially different from zero when $\alpha \in \delta_\alpha^i$. The values for $\theta_{\min}^i$ and $\theta_{\max}^i$ for different subranges δ_α^i of variance α are given in Table I.

We observe that for each subrange of variance, only a subset of FPQ segments has an impact on SQNR. Therefore, the sum within the approximate expression (11) encompasses at most 31 terms, significantly fewer than the 254 terms found in expression (9). This achieves the goal of simplifying the SQNR expression, thereby making the calculation of FP24 format performance faster, more efficient, and less computationally demanding. Importantly, this simplification does not reduce the accuracy of the performance calculations, as demonstrated in Table II, where identical values for SQNR and SQNR^i are obtained for different values of α.

IV. CONCLUSION

The paper presents a method for simplifying SQNR calculation of FPQ, resulting in a fast and efficient way to calculate the performance of the FP24 format. The proposed method focuses on narrow subranges of 150 dB width, which is sufficient for most applications, rather than considering the entire 1500 dB dynamic range of the FP24 format. This approach significantly reduces the number of segments of the FPQ that impact the SQNR, thereby reducing the number of terms in the sum of the SQNR expression from 254 to at most 31 terms. It is shown that this method does not maintenances the accuracy of the SQNR calculation. The presented method can also be applied to other FP formats, and different divisions of the dynamic range of variance into subranges can be used, which may be the subject of further research. The results of this paper can be particularly significant in the implementation of DNNs on sensor nodes and edge measurement devices, enabling the use of FP formats with lower complexity compared to the standardly used FP32 format.

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DC-DC Converters in GaN Technology – measurements and SPICE simulations

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***Abstract*— GaN technology has transformed power electronics by providing exceptional efficiency, high electron mobility, and outstanding thermal conductivity. This paper presents an in-depth analysis of DC-DC converters utilizing Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs) through measurements and SPICE simulations. A detailed SPICE model of GaN-HEMT, which incorporates a detailed subcircuit schematic, is presented and validated through experiments with Infineon's evaluation board, demonstrating good compatibility and accuracy in predicting switching waveforms and efficiency metrics in simulations. The experimental measurements and simulations are performed for buck and boost converter configurations, with the results showing remarkably high efficiency and overall performance. The paper establishes a good foundation for further advancements in GaN HEMT modeling, aiming to enhance simulation accuracy and drive innovations in power electronics.**

Keywords; GaN-HEMT; DC-DC converters; power efficiency; switching performance, SPICE modeling;

I. Introduction

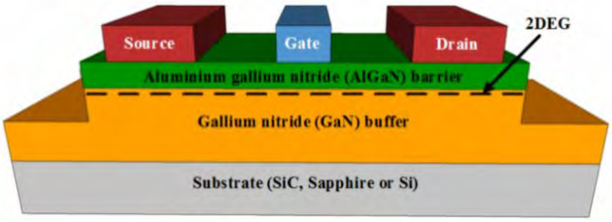
The rapid advancement of power electronics has led to the exploration and adoption of new semiconductor technologies to achieve higher efficiency, smaller size, and better performance. Among these, Gallium Nitride (GaN) technology has emerged as a game-changer, particularly for DC-DC converters [1], [2]. GaN offers several advantages over traditional silicon (Si), including higher electron mobility, higher breakdown voltage, and superior thermal conductivity [3]. These properties enable GaN transistors to show remarkable improvements in the performances of switching power supplies and other power electronics devices that operate at high voltages and frequencies. Due to the lower values of the internal capacitances as well as the lower on-resistance, the devices have significantly smaller power losses. As a result, DC-DC converters utilizing GaN technology can operate at higher switching frequencies with reduced losses, making them ideal for a wide range of applications from consumer electronics to renewable energy systems.

Accurate modeling of GaN transistors is crucial for the design and simulation of high-performance DC-DC converters. They enable designers to predict and evaluate key parameters such as power dissipation, switching times and overall efficiency. This is especially important in high-frequency applications where the dynamic performance of the GaN transistor has a significant impact on the performance of the converter. Various models have been developed to capture the unique characteristics of GaN transistors. The generic models include the SPICE built-in models for MOSFETs and MESFETs [4]. These models provide the foundation for simulating basic transistor behavior. However, GaN High Electron Mobility Transistors (HEMTs) exhibit complex behaviors that require more sophisticated modeling approaches. In addition to the simple SPICE built-in models, several other models have been proposed and developed by academia to capture the unique properties of GaN HEMTs. These include the Vitanov model, MVSG-RF and the ASM-HEMT model among others [5], [6], [7]. These models include modeling of various physical phenomena such as trapping effects, self-heating, and frequency dependence, which are critical for accurate simulation and prediction of GaN HEMT performance [8]. The addition of these phenomena sometimes leads to a higher computational complexity, which can be a big disadvantage. On the other hand, manufacturer models capture device-specific parameters and the device behavior that might not be fully reflected in the literature-based models, which in turn affects simulation accuracy for the particular device. These models are provided by the device manufacturers and are usually presented as detailed subcircuit netlists. They capture effects such as nonlinear capacitances, thermal characteristics and parasitic elements that might not be fully represented in generic or academia-based models. By using these manufacturer models, designers can ensure higher simulation accuracy, which is crucial for optimizing turn-on and turn-off times and enhancing the overall efficiency of DC-DC converters and other power electronic applications.

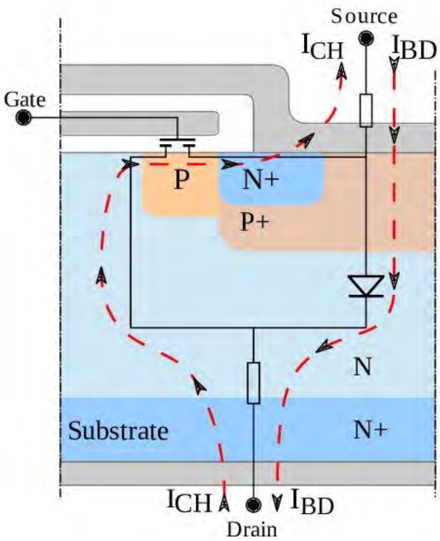
In this paper, we present an accurate GaN HEMT SPICE model developed through a detailed subcircuit schematic. The subcircuit schematic incorporates several key elements that represent the physical behavior of the GaN transistor, including parasitic inductances, capacitances, and nonlinear resistances. The model has been used in simulation of basic DC-DC converter configurations. The obtained results for switching waveforms and power efficiency are compared with the experimental measurements in order to validate the presented model, as well to analyze the performances of GaN-based DC-DC converters.

II. SPICE Subcircuit Model for GaN HEMT

A GaN-HEMT is a field-effect transistor (FET) that utilizes a heterojunction between materials with different bandgap widths, which creates a distinctive two-dimensional electron gas (2DEG) conduction channel, as shown in Fig. 1 a). This 2DEG channel is the main difference between the structures of GaN-HEMTs and Si power MOSFETs (Fig. 1 b)). Also, GaN-HEMTs do not incorporate a built-in (body) diode, which accelerates their operational speed and simplifies driver circuit complexity.



a)



b)

Fig. 1. Cross section of: a) GaN-HEMT b) Si power MOSFET

Fig. 2 represents the electrical model of the GaN-transistor, which is a typical SPICE model for GaN HEMT used by most of the manufactures [9]. The structure of this model is very similar to the traditional MOSFET, with the absence of the intrinsic body diode being the key difference. The main feature of this model is the bidirectional current source, which represents the 2DEG conduction channel. For a positive V_{DS}, when V_{GS} is less than the threshold voltage the HEMT is in the off state. If V_{GS} exceeds the threshold voltage value, the 2DEG starts conducting current. When V_{DS} is negative, in a traditional MOSFET, the parasitic body diode begins to conduct. But in the case of GaN HEMT, since there is no intrinsic body diode the HEMT turns back on and behaves like a diode with a forward voltage that depends on gate voltage and thus the dependence of the reverse conduction on the gate-drain voltage as shown in Fig. 2. The on-resistance ($R_{DS,on}$) is separated as $0.8R_{DS,on}$ and $0.2R_{DS,on}$ to represent the physical position of the gate, with the distance between gate and source being four times smaller than the distance between gate and drain.

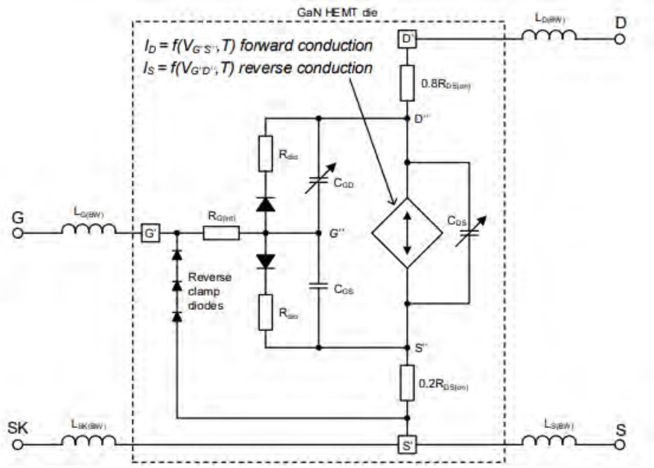


Fig. 2. GaN-transistor electrical model, picture taken from [9]

The subcircuit model used in this paper is extracted from Infineon's CoolGaN tech0 general subcircuit netlist of the 600 V GaN transistor family [9], represented in Fig. 3. The subcircuit is based on the electrical model shown in Fig. 2, and consists of two level three MOSFETs, which emulate the forward and reverse conduction, two level one MOSFETs and voltage dependent voltage sources that help in the charging/discharging of the parasitic capacitor (gate-drain and gate-source) as well as internal resistors and diodes. The gate-source parasitic capacitance is independent of the gate-source and drain-source voltages, so no additional voltage dependent voltage source is used. The model uses the general subcircuit for the 600V GaN family and by adjusting the fitting parameters used to calculate the parasitic capacitances and internal resistors, we can match the switching behavior of the modelled HEMT. It uses two fitting parameters. The first one is the internal gate resistance, and its value is directly taken from the device datasheet. This parameter affects the charging and discharging rate of the gate capacitance as well as the gate ringing and stability. The other parameter, which is crucial for the modeling of the dynamic behavior, can be obtained using the on-resistance as initial value (with it being split as $0.8R_{DS,on}$ and $0.2R_{DS,on}$ on the drain and source side respectively) and then adjusting the parameter in order to match the switching times and waveforms given in the datasheet. In addition to these fitting parameters external resistors and inductors are used to improve the dynamic behavior by adding the voltage spikes and ringing that naturally occur during the switching transients in experimental measurements

In order to validate the selected model, a simple test is made. Using the buck configuration with an input voltage of 24 V, switching frequency of 50 kHz and duty cycle of 50% the switching waveforms of the upper switch are analyzed. Both the simulation and measurement produced the same output voltage of 12 V, while the voltage of the upper switch (drain-source) voltage is 24 V. Fig. 4, shows the drain-source and gate-source voltages of the IGI60F1414A1L and Fig. 5 the same voltages of the used model in the simulations. From the figures, one can observe that the switching waveforms form measurements and simulations are matching.

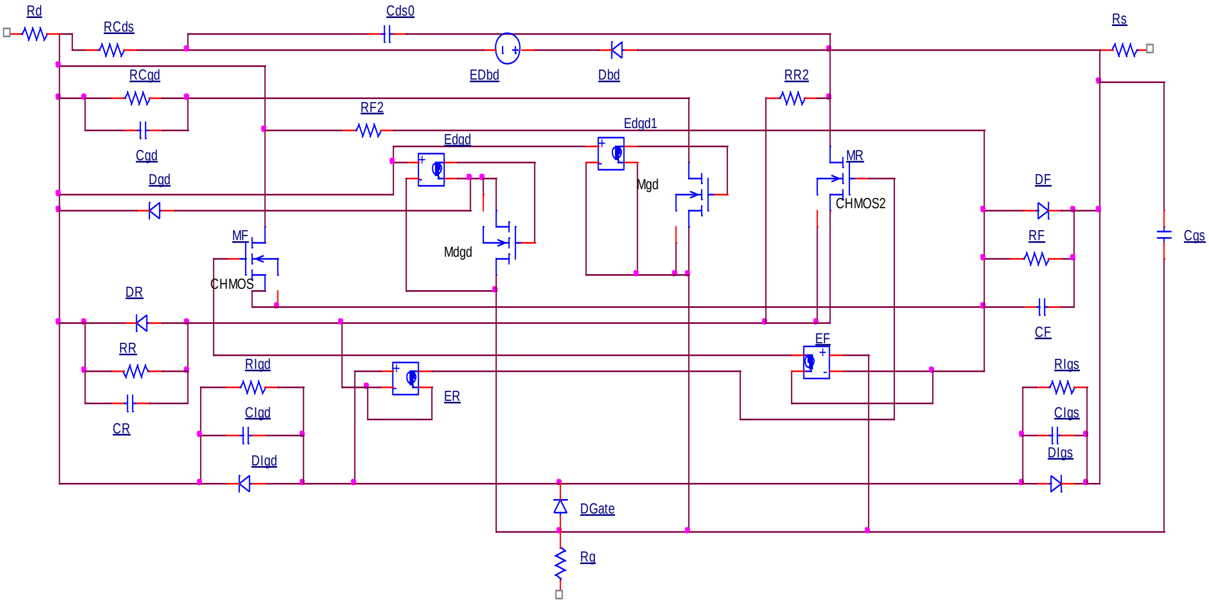


Fig. 3. Schematics of the GaN-transistor electrical model from Fig.2 based on the CoolGaN_tech0 subcircuit.

The chipset with its integrated gate driver produces clean and precise switching, resulting in smoother switching waveforms. For the simulations, a simple PWM source is used as a driver, resulting in less smooth waveforms. Nevertheless, both switching waveforms correspond and show matching switching performances, which validates the use of this model in the later simulations. It should be noted that this general subcircuit is validated for Infineon's 600 V GaN transistor family. Using this model for other manufacturer GaN-HEMTs, such as GaN-Systems, some discrepancies in the switching characteristics during turn-off were observed, while the turn-on characteristics were close to those in the datasheet. Additional adjustments to the fitting parameters as well as the external inductors and resistors are necessary in order to achieve the accurate results

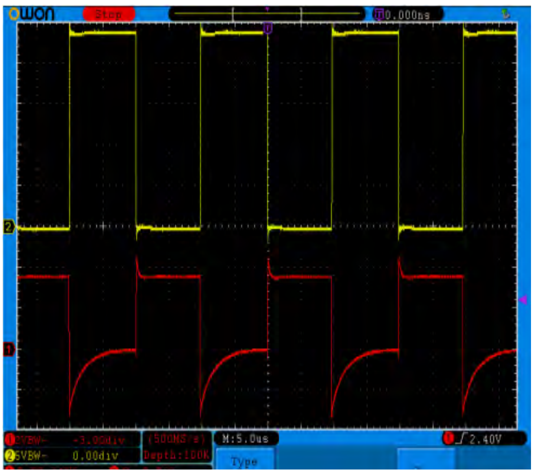


Fig. 4. Drain-source (top) and gate-source (bottom) switching voltage waveforms of the IGI60F1414A1L chipset (measurements)

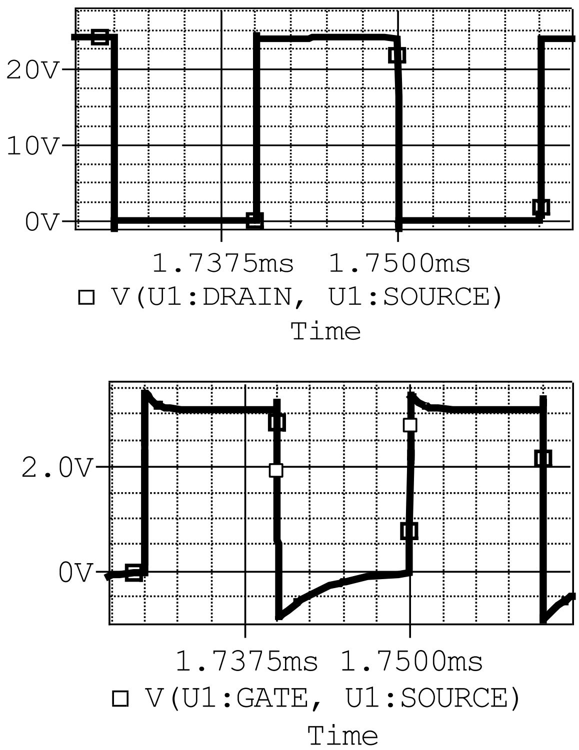


Fig. 5. Drain-source (top) and gate-source (bottom) switching voltage waveforms of the IGI60F1414A1L chipset (simulations)

III. SPICE Simulations and Measurements of DC-DC Converters Simulations and Measurements

The evaluation board EVAL_HB_GANIPS_G1 [10], made by Infineon Technologies, is used for the experimental measurements. The board (Fig. 6) features Infineon's 600 V IGI60F1414A1L chipset, which consists of a half bridge configuration of two 140mΩ / 600V CoolGaN transistors. Additionally, the board has an integrated gate driver circuit with a single PWM input intended for connection to a 50 Ω pulse or signal generator. Using an external inductor, the hardware can be configured in one of multiple configurations such as: buck converter, boost converter, inverter, double pulse test and others.

Fig. 6. EVAL_HB_GANIPS_G1 evaluation board, taken from [10]

In this paper an external 1.1mH inductor is used in both the buck and boost configuration of the evaluation board. Both configurations were analyzed in terms of efficiency for the continuous conduction mode of the converters (CCM), where the current flowing through the inductor always has a positive value. The efficiency is obtained by measuring both the input and output voltages and currents using equation (1):

$$\eta = \frac{P_{OUT}}{P_{IN}} = \frac{V_{OUT} \cdot I_{OUT}}{V_{IN} \cdot I_{IN}} \quad (1)$$

A. Buck Converter

The experimental measurements and simulation of the buck converter can be separated in low and medium voltages measurements. First, we will look at the low voltage measurements, for which two sets of measurements were conducted. The switching frequency for both sets is 80 kHz. In the first set, the efficiency of the buck converter is analyzed in terms of a fixed duty cycle (D = 50%), while the input voltage is changed from 20 V to 60 V. The experimental measurements and the corresponding simulation results are shown in Fig. 7.

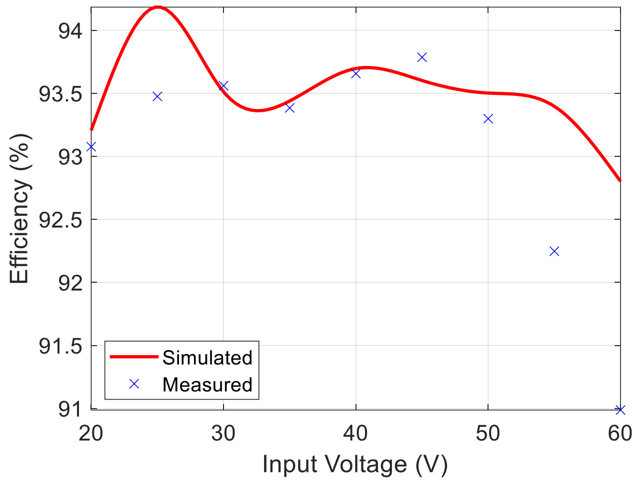


Fig. 7. Efficiency vs. input voltage of a buck converter for a switching frequency of 80kHz

In the second set of measurements, the efficiency of the buck converter with a fixed input voltage of 40 V and variable duty cycle (20% - 70%) is analyzed and the results are presented in Fig. 8. Both, Fig. 7 and Fig. 8 show that the simulation results are in the good agreement with the measurements. One can also observe a very high efficiency for the buck converter under different operating conditions. In the first case (see Fig. 7), the efficiency generally decreases as the input voltage is increased since the power losses are proportional with the input voltage. On the other hand, the increase in duty cycle for a fixed input voltage leads to an increase in the overall efficiency of the converter (Fig. 8).

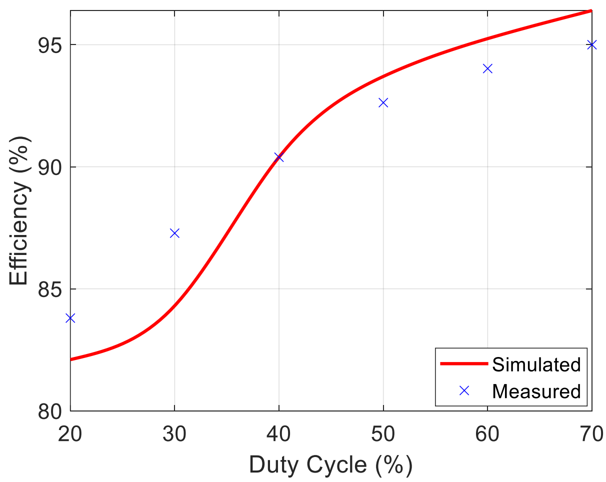


Fig. 8. Efficiency vs. Duty Cycle – buck converter

The buck converter is again analyzed in terms of its efficiency for higher input voltages (100 V – 300 V) for three different switching frequencies (50 kHz, 100 kHz and 150 kHz). The output voltage in the measurements is fixed to 49.3 V, while the output current can be either 1 A, 1.5 A and 2 A which is obtained by changing the resistance used as load. The results are shown in Figs. 9-11.

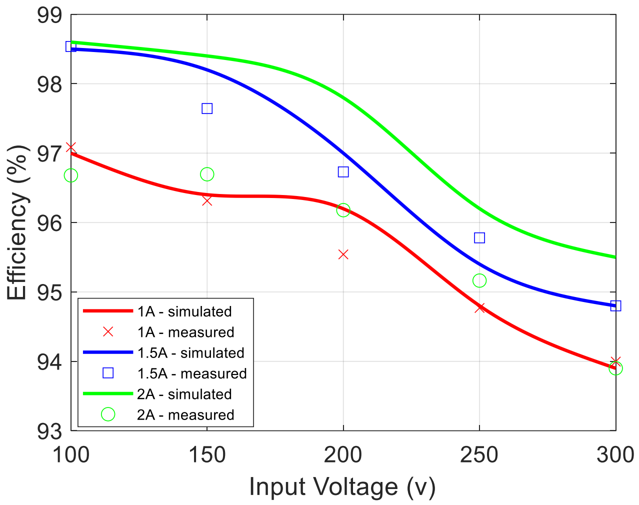


Fig. 9. Efficiency vs, input voltage for a switching frequency of 50 kHz

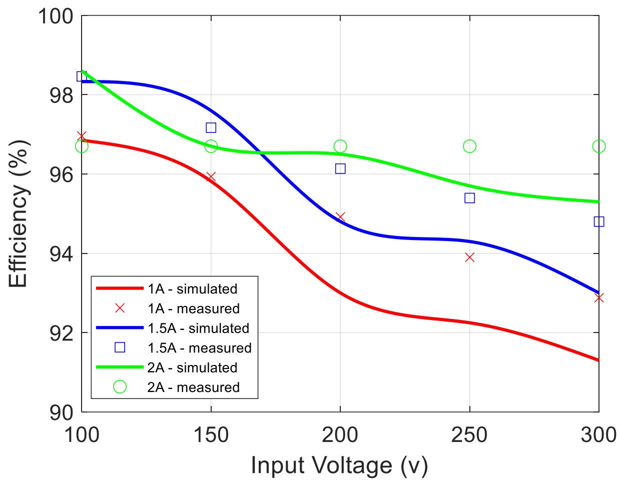


Fig. 10. Efficiency vs, input voltage for a switching frequency of 100 kHz

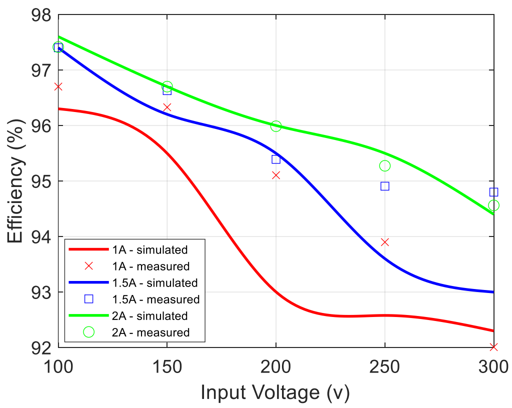


Fig. 11. Efficiency vs, input voltage for a switching frequency of 150 kHz

The difference in the results of the simulations and measurements is due to the occurrence of periodic oscillations of the output voltage shown in Fig. 12, as well as the imperfection of the measuring instruments. These oscillations in the output voltages occur during the “dead time”, i.e. the period of change of state of the two switches (the upper switch from off to on and vice versa for the lower switch) in both measurements (at low and medium voltages). In these switch transitions, the inductor current circulates in the loop formed by the parasitic components of the switches and the output inductor and stores some energy in them. After the "dead time" has elapsed, the upper switch switches on and the energy stored in the parasitic components causes the voltage to ring. Moreover, the imperfections inherent in measuring instruments contribute to discrepancies between simulated and measured values. Understanding and mitigating these factors are crucial for improving the accuracy of simulation models and validating their performance against real-world measurements. By improving simulation parameters to account for these oscillations researchers can enhance the predictive capability of simulation models and ensure they accurately reflect the dynamic behavior of GaN-based DC-DC converters.

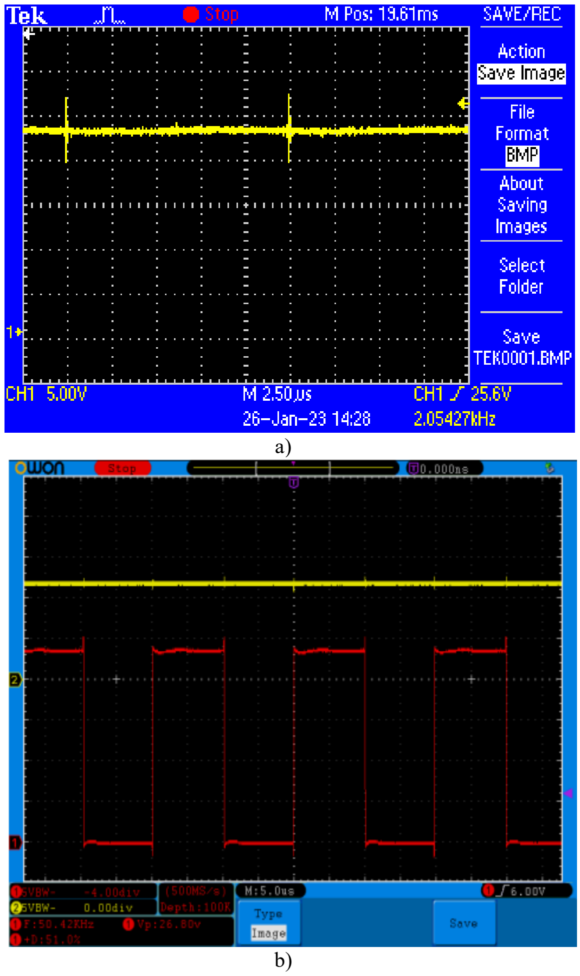


Fig. 12. Periodic oscillations in the measured output voltage: a) 20 V-60 V b) 100 V-300 V (top - output voltage, bottom - switching pin voltage)

Additionally, the use of an ideal driver circuit in simulations contributes to small deviations in the obtained results, as ideal drivers do not account for real-world characteristics such as timing, handling of parasitic elements, overvoltage and ringing. However, the results of the experimental measurements and simulations are in good agreement, especially at the 50 and 100 kHz switching frequencies. They show high values for the overall efficiency of the buck converter.

B. Boost Converter

The efficiency of the boost converter is analyzed for two different duty cycles and input voltage values, for a switching frequency of 80 kHz. The results are shown in Table I. for the measurements and simulations respectively.

TABLE I. EFFICIENCY RESULTS FOR BOOST CONVERTER EXPERIMENTAL MEASUREMENTS AND SIMULATIONS

D [%]	V_{IN} [V]	V_{out} [V]		P_{IN} [W]		P_{OUT} [W]		η [%]	
		Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
40	20	33.33	32.93	11.12	11	10.71	10.62	96.3	96.3
	30	50	50	24.9	24.68	24.1	23.885	96.7	96.7
50	20	40	40	15.6	15.68	15.15	15.239	97.12	97.1
	30	60	59.91	34.8	35.224	33.94	34.264	97.54	97.3

As can be seen from the table, the boost converter achieves a high efficiency value, especially at a duty cycle of 50 %. The obtained results correspond to the results obtained in [11], where a boost converter operating at a switching frequency of 80 kHz achieves the highest efficiency at a duty cycle of about 65 %. By increasing the switching frequency, the efficiency of the boost converter is higher at a higher duty cycle.

IV. CONCLUSION

GaN technology has revolutionized power electronics, particularly in DC-DC converters, by offering superior efficiency and performance attributes such as high electron mobility and thermal conductivity. The experimental and simulation results show that GaN based DC-DC converters have high efficiency especially for applications that operate at low and medium voltages and high switching frequencies. In order to improve the efficiency, it is necessary to select GaN-HEMTs with lower characteristic capacitances and lower on-resistance. The lower capacitances lead to lower switching power losses, while the lower on-resistance will lead to lower conduction losses, thus lowering the power losses in the switch and increase the overall efficiency of the converter.

Accurate modeling of GaN transistors is essential for optimizing converter designs, predicting power dissipation, and enhancing overall efficiency. The GaN HEMT SPICE model utilized in this paper, validated through experiments with the evaluation board, demonstrates good compatibility and accuracy in simulations. Despite the occasional discrepancies due to periodic oscillations at different switching frequencies, overall simulation results closely match experimental measurements, affirming the validity of the model for converter simulations. The GaN HEMT SPICE model presented in this paper serves as a solid foundation for future improvements and developments in GaN-HEMT modeling, offering a reliable basis for refining simulations and expanding the capabilities of next-generation GaN transistor technologies.

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Dixon Outlier Detection Approach Implemented in Sensor-to-Microcontroller Interface

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Abstract— **Outliers are data points significantly deviating from other observations, often arising from measurement noise or sensor interference, which can impact data accuracy. This paper explores the Dixon Q-test, a statistical method for detecting a single outlier in small, univariate datasets, particularly suited for embedded systems with limited computational resources, such as microcontroller-based sensor interfaces. The simplicity and efficiency of the Dixon Q-test make it ideal for real-time applications, ensuring reliable measurements by filtering out extreme values. The paper discusses the implementation of the Dixon Q-test in microcontroller firmware, highlighting its use in direct sensor-to-microcontroller interfaces for resistive sensors and presents experimental analysis demonstrating its effectiveness in noise-affected environments.**

Keywords — outlier, Dixon Q-test, sensor interface, microcontroller

I. INTRODUCTION

Outliers are data points in a dataset that are significantly different in magnitude from the majority of the values in the set. They often arise when a measurement system is subject to considerable noise or other types of signal interference, such as in the interfacing of sensors to microcontrollers. Outliers can significantly impact central tendency measures, like the mean or average, thereby reducing the overall accuracy of the measurement system.

Outliers can be classified into two types: univariate and multivariate. Univariate outliers appear in the distribution of values within a single feature space, whereas multivariate outliers are detected in an n-dimensional space.

There are numerous approaches for outlier detection. Some of the most common methods include Z-score or extreme value analysis [1], probabilistic and statistical modelling [2], linear regression models [3], proximity-based models, information theory models [4], and high-dimensional outlier detection methods [5]. However, when implementing outlier detection on a microcontroller, the computational complexity must be carefully considered. One of the simpler methods suitable for microcontroller implementation are the Grubbs statistical test [6], [7], and Dixon Q-test, which is specifically designed to identify a single outlier in a small, univariate dataset.

The Dixon Q-test is particularly well-suited for implementation in embedded systems with limited computational resources. Its simplicity and low computational overhead make it an ideal choice for real-time outlier detection in applications such as sensor data analysis. In microcontroller-based systems, the Dixon Q-test can be easily integrated into firmware to monitor and filter out extreme data points that may result from sensor noise, ensuring more accurate and reliable measurements.

This paper outlines the principles of the Dixon Q-test and its implementation in embedded systems featuring microcontrollers with sensor interfaces via analog-to-digital or time-to-digital conversion. It includes an introduction to the Dixon Q-test, its microcontroller implementation aspects, and experimental analysis of outlier detection using a direct sensor-to-microcontroller interface for resistive sensors.

II. OUTLIER DETECTION BY THE DIXON Q-TEST

The Dixon Q-test is a statistical method used to detect outliers in small, univariate datasets. Named after W.J. Dixon, this test is particularly effective for identifying a single outlier when the sample size is relatively small, typically between 3 and 30 observations. Unlike some other outlier detection methods that require assumptions about the distribution of the dataset, the Dixon Q-test does not assume a normal distribution, making it versatile for various practical applications.

The Dixon Q-test operates by evaluating the ratio of the gap between a suspect outlier and its nearest neighbour to the overall range of the dataset. The test focuses on identifying the most extreme data point, either the maximum or minimum value in the dataset, as a potential outlier. The test is especially useful when the outlier is at the boundary of the dataset, such as the smallest or largest value.

While the Dixon Q-test does not require the dataset to follow a specific distribution, it is generally applied to datasets that are expected to be approximately normal but where this assumption may not be strictly valid. The test assumes that there is at most one outlier in the dataset and is primarily designed for small sample sizes, where more sophisticated methods may not be applicable due to computational or practical constraints.

To perform the Dixon Q-test, the dataset $(X_1 \dots X_i)$ is first sorted in ascending order $(X_1 \leq X_2 \leq \cdots X_i)$. The test statistic Q is then calculated using the formula:

$$Q = \frac{|X_i - X_{i\pm1}|}{X_{max} - X_{min}}, \tag{1}$$

where X_i is the suspect outlier (either the smallest or largest value in the dataset), X_{i+1} is the nearest neighbour to X_i, X_{max} is the maximum value in the dataset, and X_{min} is the minimum value in the dataset. This ratio provides a measure of how extreme the suspect outlier is compared to the rest of the dataset. The larger the value of Q, the more likely it is that the suspect value is an outlier.

The critical value for the Dixon Q-test, denoted as Q_{crit}, depends on the sample size and the chosen significance level (e.g., 0.05 for a 95% confidence level). These critical values are typically obtained from statistical tables specifically designed for the Dixon Q-test [8]. If the calculated test statistic Q exceeds the critical value Q_{crit}, the suspect data point is classified as an outlier.

Once an outlier is identified using the Dixon Q-test, it is typically removed from the dataset, and the test may be rerun to check for additional outliers. However, it is important to note that the Dixon Q-test is designed to detect one outlier at a time, and its accuracy diminishes if applied repeatedly to the same dataset. For this reason, it is advisable to use the Dixon Q-test as an initial step in outlier detection, followed by more robust methods if multiple outliers are suspected.

III. DIRECT SENSOR-TO-MICROCONTROLLER INTERFACE

Direct sensor-microcontroller interface is an alternative approach for conditioning of modulating resistive, capacitive and inductive sensors without the use of an Analog to Digital (AD) converter. The microcontroller uses the built in timer to measure the charging or discharging time of RC circuit formed by the sensor and reference resistor/capacitor. In this way, the microcontroller and the sensor form a relaxation oscillator causing the modulating sensor to act like a quasi-digital sensor. This sensor interface approach can be effectively used to demonstrate the microcontroller implementation of the Grubbs outlier detection method.

Two measurement methods are proposed: a method based on charging [9] or discharging time [10] of the *RC* circuit. The two methods differentiate by the crossing of the upper or the lower threshold voltage (V_{th} or V_{tl}) of the Schmitt Trigger port to create an interrupt. The method based on discharging time gives better measurement results [11] because the lower threshold voltage V_{tl} has better rejection of the power supply interference and because usually the microcontroller ports can sink more current than they can source. The most basic direct sensor-microcontroller interface can be realized by using two microcontroller pins, one output and one input pin (Fig.1). The measurement contains two phases: charging phase and discharging phase. The wave shape of the capacitor voltage in the two phases is shown in Fig.2.

At the beginning the pin P_i is set as output with logical state "1" and the pin P_0 is set as input (high impedance state). The capacitor charges through R_p to V_{dd} in a period t_1-t_2. In the next step the pin P_0 is set as output with logical state "0", the timer starts and the pin P_i is set to high impedance state. This time the capacitor discharges through R_x until the voltage reaches the lower threshold voltage V_{tl}. Crossing of the threshold voltage V_{tl} initiates interrupt that stops the timer.

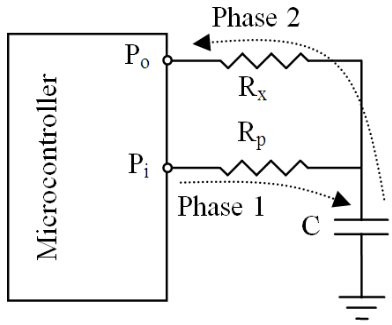

Fig. 1. Direct sensor–microcontroller interface based on measurement of discharging time

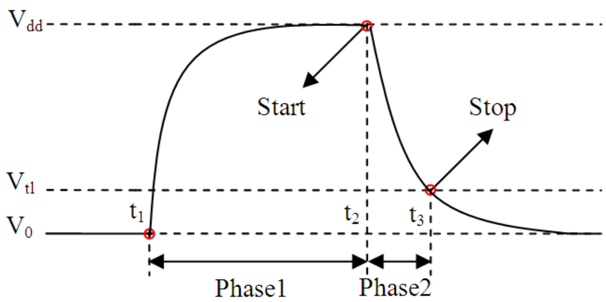

Fig. 2. Wave shape of the capacitor voltage in the two measurement phases

The time needed for the capacitor to discharge from V_{dd} to V_0 is expressed with the equation:

$$t_x = (t_3 - t_2) = \tau \ln\left(\frac{V_0 - V_{dd}}{V_0 - V_{tl}}\right), \tag{6}$$

where $\tau = R_x C$ is the discharging time constant. Having in mind that V_0, V_{dd}, V_{tl} and C are constant, from (6) can be seen that the time interval t_x is proportional to the measuring resistance R_x. This time interval (t_x) is measured with the built in timer in the microcontroller. The result of the time to digital conversion can be expressed as:

$$N = kR_x, \tag{7}$$

where k is constant dependent on V_0, V_{dd}, V_{tl}, C and the time base of the timer. In practice, the input/output resistances and leakage currents of the microcontroller ports cause gain, offset and nonlinearity errors [12]. Additionally the constant (k) in the equation (7) is not very stabile. Therefore, usually direct sensor to microcontroller interface is realized by using some calibration technique [13], [14] that cancels the contribution of V_0, V_{dd}, V_{tl} and C.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experiments are realized by using microcontroller PIC16F877A with clock frequency of 16MHz, effective instruction cycle speed 4MHz and period 0.25µs. The falling edge of the input signal was registered with the RB0/INT Schmitt trigger pin. This pin initiates interrupt that stops the 16-bit timer - Timer1. The results of the measurements are sent to personal computer through the serial RS232 port. The MAX232 (TTL/RS232) level translator was supplied from separate power supply to prevent transients (about 170kHz) from interfering with the power supply rails of the microcontroller. Standard noise-reduction techniques were used to reduce the noise effects affecting the voltage comparison between V_c and V_{tl}:

- Decupling capacitor of 100 nF was placed as close as possible to the microcontroller pins as recommended from the manufacturer
- The board ground plane was carefully designed for low electromagnetic interference
- Only the microcontroller was supplied from the power supply to eliminate other interference effects
- The microcontroller didn't execute any other task while waiting for the interrupt
- The program algorithm was not changed while performing the experiments

However, to perform a controllable noise injection, a white Gaussian noise was superimposed on the power supply through an arbitrary function generator. The noise was injected to increase the probability of outliers in the experimental measurements of the time interval.

The measurement of the time interval t_x was performed by using the electrical circuit shown in Fig.1 having the resistance $R_x = 680\ \Omega$ and capacitance $C = 47\ \mu F$. The measurement was preformed 100 times. The histogram of the measurements is shown in Fig.3, where it can be seen that the shape of the histogram is roughly Gaussian. This proves that the voltage comparison of the low threshold voltage of the Schmitt trigger port is affected by noise from the power supply.

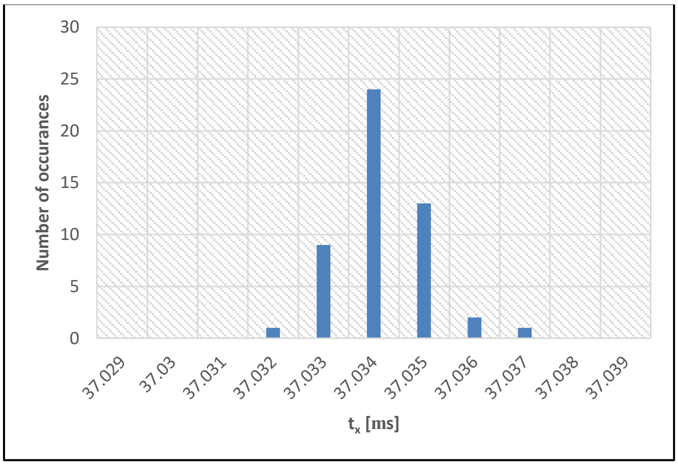

Fig. 3. Histogram for the measurement of discharging time t_x

To perform the Dixon Q-test for outlier detection, we divided the group of 50 measurements into 10 subgroups, denoted with Roman numerals in Table I. For each subgroup, we calculated the average, maximum, and minimum statistics. The critical Q test value for a confidence level of 95% and a sample size of 5, was found to be Q_{crit}=0.71.

By examining the critical value (Q_{crit}) from the test, we identified two outliers in groups I, ans IV. Removing these outliers from the dataset resulted in an approximately 0.3 µs change in the mean discharging time, which is comparable to the microcontroller's time-base resolution. Therefore, we conclude that the implementation of the Dixon outlier detection method significantly enhanced the accuracy of the measured discharging time interval to within the microcontroller's time-base resolution.

TABLE I. APPLICATION OF DIXON Q-TEST OUTLIER DETECTION METHOD TO DATASET OF 50 MEASUREMENTS

	Subgroups									
	I	***II***	***III***	***IV***	***V***	***VI***	***VII***	***VIII***	***IX***	***X***
X_1 [ms]	37.03250	37.03200	37.03325	37.03300	37.03325	37.03225	37.03325	37.03275	37.03225	37.03125
X_2 [ms]	37.03350	37.03225	37.03350	37.03325	37.03375	37.03325	37.03350	37.03350	37.03250	37.03200
X_3 [ms]	37.03350	37.03300	37.03450	37.03350	37.03400	37.03375	37.03375	37.03400	37.03350	37.03225
X_4 [ms]	37.03375	37.03325	37.03475	37.03350	37.03475	37.03425	37.03375	37.03450	37.03450	37.03325
X_5 [ms]	37.03375	37.03400	37.03500	37.03475	37.03650	37.03450	37.03375	37.03475	37.03475	37.03550
$\bar{X}$ [ms]	37.03340	37.03290	37.03420	37.03360	37.03445	37.03360	37.03360	37.03390	37.03350	37.03285
X_{min} [ms]	37.03250	37.03200	37.03325	37.03300	37.03325	37.03225	37.03325	37.03275	37.03225	37.03125
X_{max} [ms]	37.03375	37.03400	37.03500	37.03475	37.03650	37.03450	37.03375	37.03475	37.03475	37.03550
Q_{max}	0.80000	0.12500	0.14286	0.14286	0.15385	0.44444	0.50000	0.37500	0.10000	0.17647
Q_{min}	0.00000	0.37500	0.14286	0.71429	0.53846	0.11111	0.00000	0.12500	0.10000	0.52941
Q_{crit}	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
$\bar{X}_{corr}$ [ms]	37.03363	37.03290	37.03420	37.03331	37.03445	37.03360	37.03360	37.03390	37.03350	37.03285
$\Delta\bar{X}$ [µs]	0.22500	/	/	-0.28750	/	/	/	/	/	/

CONCLUSION

This paper demonstrates the efficacy of the Dixon Q-test for detecting outliers in small, univariate datasets, particularly within the context of embedded systems such as microcontroller-based sensor interfaces. The simplicity and computational efficiency of the Dixon Q-test make it highly suitable for real-time applications in environments with limited resources, such as microcontrollers. Experimental results showed that the Dixon Q-test effectively identified outliers caused by noise in direct sensor-to-microcontroller interfaces, thereby enhancing the accuracy of measurements.

By implementing the Dixon Q-test in microcontroller firmware, we successfully filtered out noise-induced extreme values in the measured data, which improved the reliability of the time interval measurements. This method proved to be an invaluable tool for noise-affected environments, demonstrating its practical benefits in ensuring that the microcontroller's output remains within its time-base resolution limits. We anticipate that this improvement will be even more pronounced for longer discharging time intervals and for higher RMS values of superimposed Gaussian noise.

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Ultra-low power wrapper of the Ethos-U55 AI accelerator in the PSOC^{TM} Edge E84 MCU

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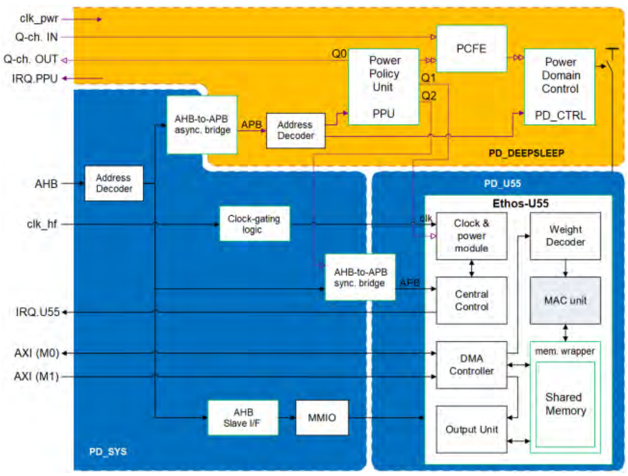
Keywords—ultra-low power; artificial intelligence; accelerator;

I. Single Page Extended Abstract

The Infineon's PSOC^{TM} Edge E84 is a high-performance, low-power, secured Microcontroller Unit (MCU) with hardware-assisted machine learning (ML) acceleration for next generation applications. It is based on high-performance Cortex-M55, including Helium DSP support paired with Ethos-U55, as well as a low-power Cortex-M33 paired with Infineon's ultra-low power NNLite hardware accelerator for neural networks in Machine Learning and Artificial Intelligence (AI) applications. It also features an always-on, acoustic activity detection capability that enables Human-Machine Interface (HMI) operation with low active and standby power consumption for longer life of battery-powered products. The PSOC supports advanced graphics, voice, audio and standard communication peripherals for a variety of consumer and industrial applications including HMI, smart home, wearables, robotics and other Internet of Things (IoT) products.

The U55 neural network accelerator acts like a coprocessor of the M55 processor core. It is embedded in the Ultra-Low Power (ULP) architecture of the Infineon's PSOC development platform. The Figure shows the U55 ULP wrapper. The U55 operates with two Advanced eXtensible Interfaces (AXI) M0 and M1 which are used to fetch the command stream, weights and biases usually from a non-volatile memory and to read/write inputs and outputs from/to the RAM. M0 is a read/write master I/F, while M1 is a read-only master I/F. The U55 raises interrupts for signaling completion, errors and performance.



The ULP wrapper has a single Advanced High-performance Bus (AHB) for the Memory-Mapped I/O (MMIO) configuration. Since the U55 has an Advanced Peripheral Bus (APB) for configuration, an AHB-to-APB synchronous bridge is used, with both sides of the bridge operating at the same *clk_hf* frequency (max. 400 MHz). Similarly, an AHB-to-APB asynchronous bridge is used for the Power Policy Unit (PPU) and the Power Domain Control (PD CTRL). However, here the AHB side of the bridge operates at *clk_hf* frequency, while the APB side operates at *clk_pwr* frequency (max. 48 MHz). The PPU sends requests to the system over the standard AMBA Q-channel Low Power Interface (LPI) and raises interrupts for completion of power state transitions. On the other side, the Power Control Front-End (PCFE) takes the power down requests from the system over the input Q-channel LPI.

In order to provide the end-user, the possibility to optimally tune the system power consumption, the ULP wrapper enables the following capabilities. 1) Power Gating: the *PD_U55* power domain encapsulating the U55 allows zero leakage 'idle' operations; 2) Programmable Power Transitions: the PPU enables autonomous and manual power transitions; 3) Power Sequencing: a transition to power-ON will only be initiated when all prerequisite logic is powered; 4) Access Control Gate: Controlled access to the *PD_U55* power domain during power-OFF, being able to respond with an error response or a waited transfer initiating power-ON sequence. In power-ON state, all logic and RAMs are powered and functional, while in power-OFF state, all logic and RAMs are powered off and all states are lost. The PPU interacts via three Q-channels: Q0 requests quiescence of dependents, Q1 requests quiescence of the U55 and Q2 requests quiescence of the U55 APB access.

The *PD_U55* power domain is a logical child of the *PD_SYS* domain in which the M55 core resides. Thus, the *PD_SYS* has to be powered before *PD_U55*. The *PD_SYS* domain is controlled by the system Power Dependency Control Matrix (PDCM) (not shown in the Figure). On the other hand, the *PD_DEEPSLEEP* domain is a low frequency, always powered-on domain containing the power control logic. Additional power saving functionality is the smart clock gating logic which enables the clock for the U55 only when needed.

Finally, all reference documentation regarding the M55, U55, AMBA, AXI, AHB, APB, LPI, PPU, etc., can be found at https://developer.arm.com/documentation, while PSOC documentation can be found at www.infineon.com.

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Comparison of the properties and efficiency of photovoltaic cells

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***Abstract*—This research paper compares the effectiveness and parameters of different types of heterojunction photovoltaic cells. As photovoltaic cells are formed of two main layers: the base and the emitter, which come together to form a junction, there are several possibilities in which these layers can be arranged. The paper aims to analyze the cell parameters of each photovoltaic cell, discuss the phenomena affecting the parameters of the cell, and compare the theoretical expectations and physical measurements. For this study cells containing a GaAs base and InGaP emitter are used. By changing the layout of the base and emitter and the p or n type doping of each layer, multiple types of cells are created whose parameters and effectiveness vary. The cells are measured on their parameters such as fill factor, short-circuit current density, open circuit voltage, and external quantum efficiency. Lastly, the results are compared and analyzed to summarize their potential application. Summarily, the advantage in terms of short-circuit current and open-circuit voltage of the front-heterojunction (FHJ) cells are confirmed.**

Key words: photovoltaic cells, efficiency, heterojunction, photovoltaic cell parameters, renewable energy

I. Introduction

As photovoltaic cells become increasingly relied upon for producing power in the new wave of green and sustainable energy production, research into the optimal design of the photovoltaic cells upon which these photovoltaic panels are based on is intrinsically needed. For use in this paper InGaP/GaAs photovoltaic cells are used. InGaP/GaAs tandem photovoltaic cells are considered to have the potential for achieving a conversion efficiency of more than 30% [2]. Furthermore, In 2017, a team of researchers at NREL reported record efficiencies of 32.68% for dual junction InGaP/GaAs photovoltaic cells, making the research of these cells highly enticing. [3]

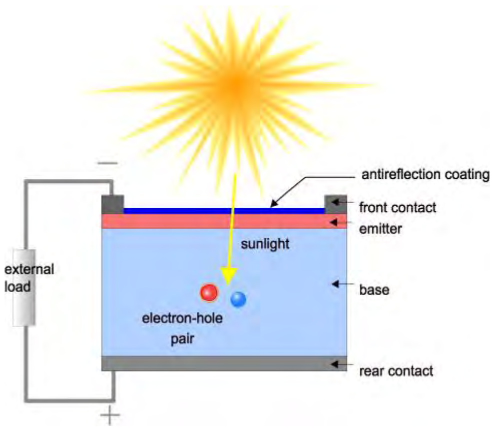


Figure 1: Basic diagram of a FHJ photovoltaic cell [1]

In this paper several structures of InGaP/GaAs photovoltaic cells are measured based on several parameters and the results are discussed leading to possible improvements into their design. The goal of the paper is to evaluate the most efficient layout of the photovoltaic cell, as well as deduce the factors influencing them.

In Section 3 an overview of the properties and parameters upon which photovoltaic cells are compared is given. Section 4 then lays out the conditions the measurement is conducted under as well as the structure of the photovoltaic cells. Afterwards, in Section 5, an overview and discussion of the measured results is given. Lastly, the findings and their relevance as well as possible future applications are summarized in Section 6.

II. State of the Art

Single p–n junction crystalline silicon devices are now approaching the theoretical limiting power efficiency of 33.16%.[4] On the other hand, theoretically, with an infinite number of layers, the corresponding limit is 86%, making multi-junction photovoltaic cells a high priority for research.[5] Multi-junction photovoltaic cells operate by utilizing several p-n junctions, who respond on different wavelengths to produce a current. Subsequently, the quantum efficiency for different wavelengths drastically increases. As of 2024 the best lab examples of traditional crystalline silicon (c-Si) photovoltaic cells had efficiencies up to 27.1% [6], while lab examples of multi-junction cells have demonstrated performance over 46% [7]. Subsequently, research multi-junction photovoltaic is being heavily undertaken, although the applications of single junction photovoltaic cells remains high, owing to the lower manufacturing costs.

III. AN OVERVIEW OF PHOTOVOLTAIC CELLS

As seen on figure 1, the most basic structure of the cell contains the contacts and two layers, the emitter and the base. The emitter is extremely thin, usually around 50-100 nm, while the base can be measured in micrometers. The function of these components will be looked at later in the study. Based on the arrangement, photovoltaic cells can be differentiated as FHJ-Front heterojunction if the light enters the emitter first, otherwise it's a RHJ-Rear heterojunction.

A. *Light generated current*

The generation of current in a photovoltaic cell, known as the "light-generated current", involves two key processes. The first process is the absorption of incident photons to create electron-hole pairs or generation. Electron-hole pairs will be generated in the photovoltaic cell provided that the incident photon has an energy greater than that of the band gap.[8] However, the minority carrier is meta-stable and will only exist, on average, for a length of time equal to the minority carrier lifetime before it recombines.

A second process, the collection (separation) of these carriers by the *p-n* junction, prevents this recombination by using a *p-n* junction to spatially separate the electron and the hole.. If the light-generated minority carrier reaches the *p-n* junction, it is swept across the junction by the electric field at the junction, where it is now a majority carrier, with lower chances of recombination. As such, the collection of the holes is the key aspect in enabling the light-generated current to flow.[9]

Ideally we want the p-n junction to be as close to the surface as possible in order to maximize the collection rate. However, this presents a different problem. A shorter distance also means that wavelengths with lower absorption coefficients will not be fully absorbed.

Thus, a compromise is needed. The junction needs to be close enough to maximize collection, yet far away enough to enable the absorption of lower energy wavelengths. The function of the emitter is ideally to maximize collection due to the high amount of absorbed photons, while the thickness of the base maximizes generation for the lower energy wavelengths. Logically, we can expect that FHJ would yield much higher light-generated current than the RHJ, as most generation occurs on the front contact rather than the rear, which would be unable to utilize the advantage of the emitter.

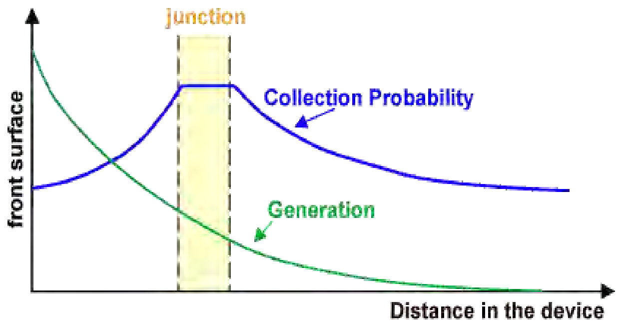


Figure 2: collection probability and generation rate in FHJ [1]

B. *Photovoltaic cell parameters*

Without illumination, the photovoltaic cell behaves according to the diode law, showing an exponential increase in the current with the increase of the applied voltage. However once illuminated, a certain light current flows in the opposite direction. By convention, the referent direction for the IV curve is as a generator. This light current shifts the IV curve along the y-axis and gives us the two main parameters of the photovoltaic cell. Firstly, when a short circuit is applied to the photovoltaic cell, only the light current flows through the short circuit. This is the short-circuit current I_{sc}, oftentimes expressed as short circuit current density, which represents the light-generated current. On the other hand, at a certain voltage, no current flows through the contacts. This is known as the open-circuit voltage V_{oc}.

The power of the cell is a product of the voltage and current. As such, the power rises until a certain point where it reaches the maximum value, after which it drastically declines. The value for which the power has a maximum value is denoted as P_{max}, while the current and voltage for which this value is achieved are denoted as I_{max} and V_{max} respectively.

$$P_{max} = I_{max} V_{max} \tag{1}$$

C. *Fill Factor*

The short-circuit current and the open-circuit voltage are the maximum current and voltage respectively from a photovoltaic cell. However, at both of these operating points,

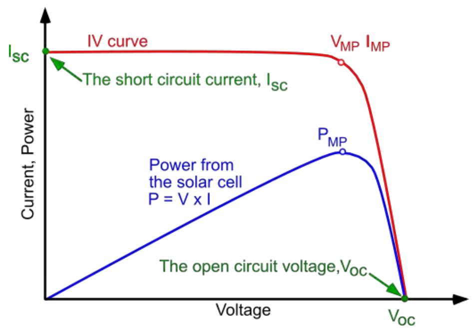


Figure 3: IV curve along with the Pmax [1]

the power from the photovoltaic cell is zero. The fill factor FF is a parameter that determines the maximum power from the photovoltaic cell. It is the maximum power divided by the short circuit current times the open circuit voltage.[10] Visually the FF is a measure of the "squareness" of the graph and is also the area of the largest rectangle which will fit in the IV curve.

$$FF = \frac{P_{max}}{I_{sc} V_{oc}} \tag{2}$$

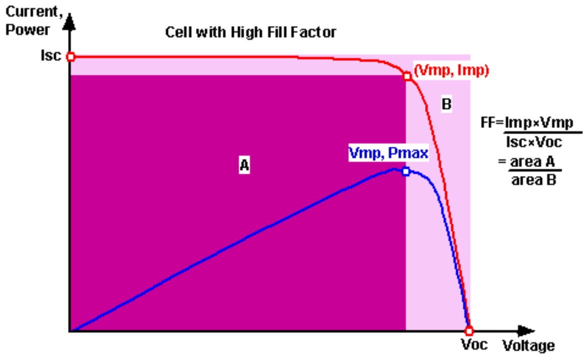


Figure 4: Visual representation of Fill factor on an IV curve [10]

D. *Efficiency*

Efficiency is the most commonly used parameter to compare the performance of one photovoltaic cell to another. Efficiency is defined as the ratio of energy output from the photovoltaic cell to input energy from the sun. The efficiency of a photovoltaic cell is determined as the fraction of incident power that is converted to electricity and is defined as:

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{oc} I_{sc} FF}{P_{in}} \quad (4)$$

E. *External Quantum Efficiency*

The quantum efficiency is the ratio of the number of carriers collected by the photovoltaic cell to the number of photons of a given energy incident on the photovoltaic cell. If all photons of a certain wavelength are absorbed and the resulting minority carriers are collected, then the quantum efficiency at that particular wavelength is 100%. The quantum efficiency for photons with energy below the band gap is zero. [11]

In this study, external quantum efficiency is measured which also takes into account reflection and outside losses. These losses are most apparent among lower wavelengths. The EQE is measured at 0V voltage to determine the EQE at the short-circuit current.

F. *The effect of parasitic resistances*

Resistive effects in photovoltaic cells reduce the efficiency of the photovoltaic cell by dissipating power in the resistances. The most common parasitic resistances are series resistance and shunt resistance. In most cases and for typical values of shunt and series resistance, the key impact of parasitic resistance is to reduce the fill factor.[12]

Series resistance in a photovoltaic cell has three causes: firstly, the movement of current through the emitter and base of the photovoltaic cell; secondly, the contact resistance between the metal contact and the silicon; and finally the resistance of the top and rear metal contacts. The main impact of series resistance is to reduce the fill factor, although excessively high values may also reduce the short-circuit current. Near the open-circuit voltage, the IV curve is strongly affected by the series resistance.

On the other hand, the shunt resistance is mostly a result of manufacturing defects. Low shunt resistance causes power losses in photovoltaic cells by providing an alternate current path for the light-generated current. Such a diversion reduces the amount of current flowing through the photovoltaic cell junction and reduces the voltage from the photovoltaic cell. The effect of a shunt resistance is particularly severe at low light levels, since there will be less light-generated current. The loss of this current to the shunt therefore has a larger impact at lower voltages. [13]

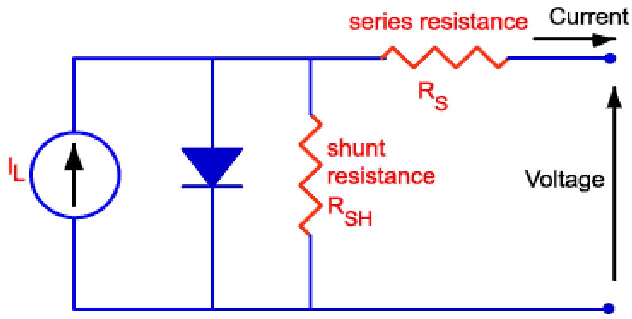


Figure 5: Equivalent scheme of resistance in real photovoltaic cell

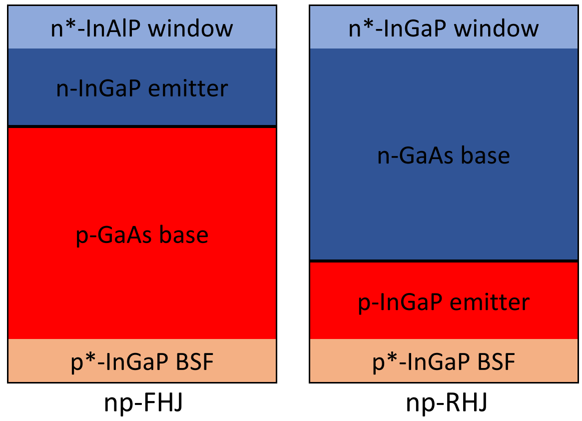
IV. STRUCTURE AND MEASURMENT PARAMETERS

A. *Measurment properties*

The measurement was conducted under AM 1.5 spectrum, which is the approximate spectrum of the sunlight on the earth's surface. The temperature is adjusted at 298 K, while the input power is 1kW/m^2. The surface area of each cell is 0.25 cm2 while instead of current *I* in mA, current density *J* in mA/cm2 is measured in order to help standardize the data.

B. *Cell structure*

The cells used in this study consist of a GaAs base (thick 2.9 µm) and InGaP emitter (thickness 100nm). Furthermore, apart from the base two layers, an additional thin window layer and base substrate BSF layer made of InGaP and InAlP are used. The goal of these layers is to create an energy well in order to limit the flow of carriers in an unwanted direction. Both of these layers are thin (~50nm) and are heavily doped. This bandgap difference is small enough not to significantly affect the light generated current, while also preventing losses and improving the collection rate.



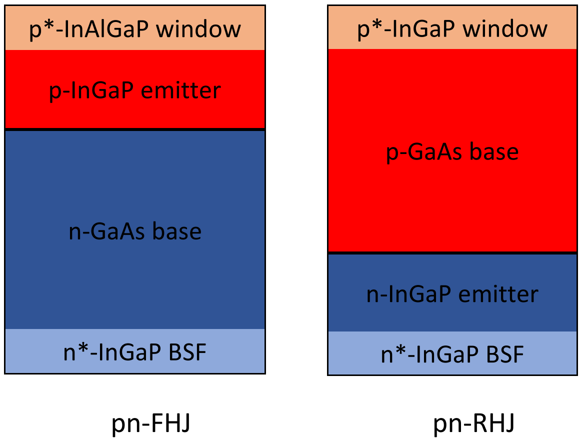


Figure 6: Layout of the measured photovoltaic cells

There are four cells used in the measurements classified by two parameters, the position of the emitter and base relative to the entry point (i.e. the heterojunction) and the n and p layers relative to the incident light. Due to the theoretical data we can expect a better performance from the FHJ cells as they are able to have the best collection on the surface of the emitter, as opposed to the RHJ cells, where the generation in the emitter would be negligible to justify the improved collection rate.

V. RESULTS OF MEASURMENT

A. *Table of results*

Table 1: comparison of the stats of cells

Cell type	J_{sc}(mA/cm2)	V_{oc}(V)	P_{max} (mW/cm2)	FF (%)	η (%)
np-FHJ	21.7688	1.0108	17.6137	80.05	17.614
np-RHJ	19.3208	1.0278	16.3876	82.53	16.388
pn-FHJ	21.0861	1.05	16.1813	73.09	16.181
pn-RHJ	19.5744	0.9521	13.6273	73.12	13.627

B. *Visualisation of IV curves*

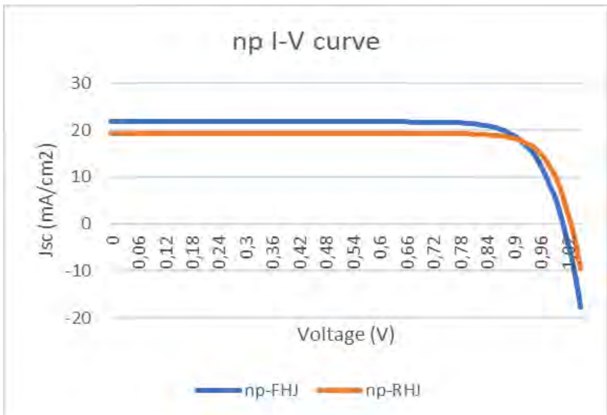


Figure 7: I-V curve comparison of the np photovoltaic cells

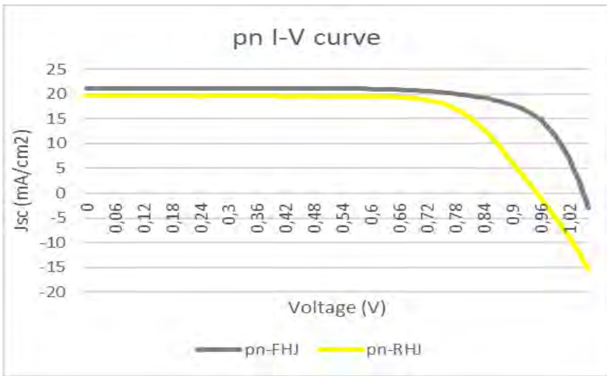


Figure 8: I-V curve comparison of the pn photovoltaic cells

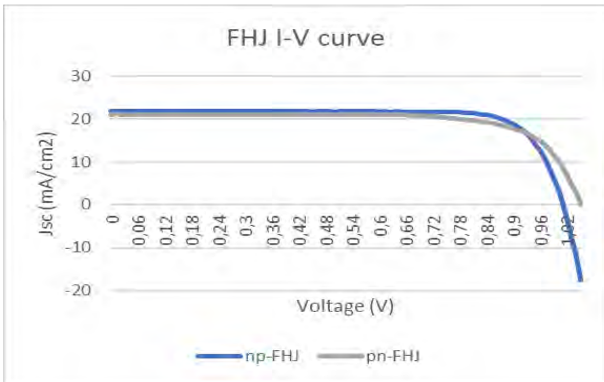


Figure 9: I-V curve comparison of the FHJ photovoltaic cells

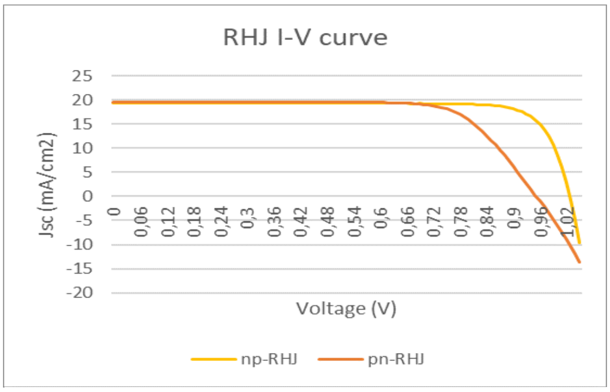


Figure 10: I-V curve comparison of the RHJ photovoltaic cells

C. *Disscussion of the I-V results*

From the results presented in Table 1, Fig. 7 and Fig. 8, it can be clearly inferred that the FHJ cells have a much higher short circuit current, owing to the optimal setup of the emitter which permits the highest possible collection of carriers generated on the surface. It can be noted from the table that the np-FHJ has the highest short circuit current and displays the overall best performance.

This can be attributed to the difference in mobilities of electrons and holes. The mobility of electrons in GaAs is 8500 cm^2 V^{-1}s^{-1} while the mobility of holes is 400 cm^2 V^{-1}s^{-1}, nearly

20 times less.[14] Thus, cells where the base minority carrier is electrons, or cells that have a p-base, would have a higher collection rate, as the distance needed to be covered in the base is much larger than the emitter. This also explains why the pn-RHJ cell also has a higher short-circuit current than np-RHJ, as seen on Fig,9, seeing how both possess a p-doped base.

It should be noted that although the pn-FHJ has a lower efficiency than the np-RHJ cell, this can be attributed to the low fill factor on the pn-FHJ cell. The fill-factor is lowered from faulty manufacturing that leads to shunt and series resistance, which is also reflected in the imperfect I-V curve. Furthermore, as both the short circuit current and the open circuit voltage are higher in the pn-FHJ cell, under better manufacturing we can expect a much better performance compared to the np-RHJ cell, largely owing to the efficiency of the Front-heterojunction.

Summarily, we can evaluate that the RHJ cells are far less effective, owing not only to their lower short circuit currents, but also to the lower open circuit voltage. Both of these values significantly limit the potential for energy generation.

D. *Visual representation of EQE*

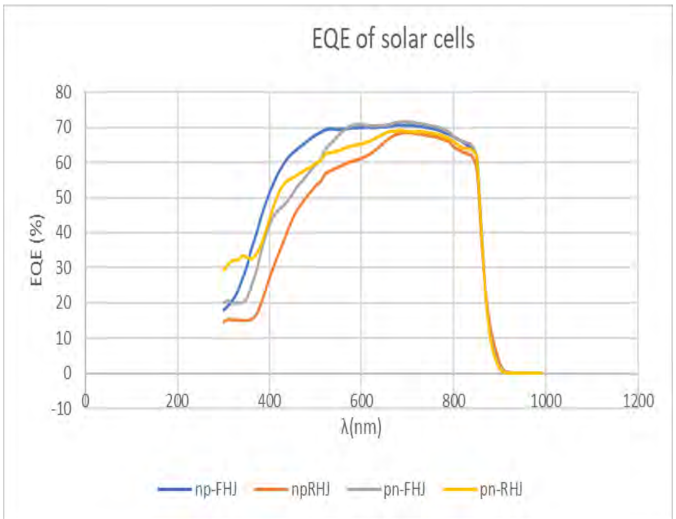


Figure 11: External quantum efficiency across all wavelengths of the AM 1.5 spectrum

E. *Discussion of EQE results*

As can be inferred from Fig.10, the EQE results confirm the conclusions from Fig.6-9. The np FHJ has the best external quantum efficiency, especially for wavelengths in the range of 500-950nm, owing to the advantages of the front hetero junction as well as the optimal np layout due to the reasons mentioned earlier. Similarly, the pn-FHJ follows, while the RHJ cells show significantly worse performance. On the other hand the pn-RHJ shows much better performance than the np-RHJ, owing to the previously mentioned better collection and higher mobility of electrons. This is even more apparent for the lower wavelengths which would be able to be collected much more easily from the emitter due to the higher mobility of electrons. The lowest wavelengths in the range of approximately 350-400nm are largely inconsistent with the rest of the measurement, mostly owing to the different window layers present among all of the cells. These differences are sadly necessary in order to be able to properly design each cell, as the window layer depends mostly on the adjacent material's bandgap energy. A large fall-off of EQE can be noticed at around 900nm, corresponding to the bandgap of the base.

VI. CONCLUSION

In summary, the paper confirms the theoretical expectations and the efficiency of the Frontheterojunction compared to its alternative. It further discusses the advantages of the p-doped GaAs base owing to the higher mobility of electrons compared to the holes, leading to better collection of the carriers across the pn-junction. It can be noted from Fig.10 that the np-FHJ maintains the maximum EQE of 70% throughout a much wider spectrum, explaining the high short-circuit current and cementing its effectiveness as a single junction cell. On the other hand, the pn-FHJ displays slightly better performance for wavelengths higher than 600nm, hinting at its potential applications in multi-junction photovoltaic cells, where these advantages could be properly utilized. There is room for further research in this field, specifically concerning the improvement in manufacturing of the cells for optimizing the fill-factor, especially among the pn-FHJ cell, as well as its applications in multi-junction photovoltaic cells. In addition, additional research could be conducted into the performance of different materials as the basis of photovoltaic cells. In spite of this, the study presents findings from which a general trend can be inferred concerning the application of materials in photovoltaic cell production.

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PointFEIT – Point Feature Extraction with Image PreTraining for 3D Semantic Segmentation

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***Abstract*—Semantic segmentation of point clouds is a very important technique in the field of robotics and autonomous systems. In this paper we propose an approach for 3D semantic segmentation with simultaneous use of several types of knowledge transfer. We examine how knowledge transfer can be used for improvement of 3D neural networks using 2D images, and the different approaches when tackling this issue. Then, we propose a novel method of combining two transfer knowledge techniques: the first being weight inflation, and the second knowledge distillation using combined learning with 3D point clouds and 2D images. The basic idea is to transfer previously acquired knowledge from training on 2D images, a much easier problem, to the 3D world and helps with prediction in tasks involving point clouds. Finally, we present our findings from a series of experiments on the SemanticKITTI dataset and provide detailed analysis of the results, which show the potential of knowledge transfer in the improvement of smaller models and training of larger ones.**

Keywords*—*semantic segmentation of point cloud, knowledge transfer, 3D deep learning

I. Introduction

Autonomous systems have gained incredible significance in people's daily lives with the rapid advancement of science and technology. A necessary component of the development of these systems is the way in which they perceive the world around them, as a mean of interaction with their environment. Using semantic segmentation has become the central focus of this movement, especially and vitally in the fields of robotics and autonomous vehicles.

Point clouds have emerged as the main data structure for storing spatial information in 3D. Essentially, they are composed of a collection of unordered points, where each point consists of x, y, z coordinates, intensity information and other potentially useful attributes. Most of the point clouds are gathered using a laser sensor, such as LiDAR, which uses laser beams in order to generate depth information, but there are also efforts that use regular cameras combined with different processing techniques.

Semantic segmentation in 2D images has been studied for a long time, but the real revolution in this field started about ten years ago with the use of deep learning techniques and convolutional neural networks [1]. Since then, we can observe the development of better models for detection as well as for segmentation of objects in 2D images [2], and we can consider the problems of processing images in two dimensions as mainly solved. But, in order to discuss true autonomous systems we must develop methods for interacting with visual data in three dimensions, with point clouds, a problem that is much more difficult than processing 2D images, because of the increased dimensionality of 3D data and computational intensity required for training the models.

Various methods have been proposed for solving the problem of semantic segmentation of point clouds [3]. The earliest attempts are methods that project the 3D point cloud onto a 2D plane and do the segmentation using 2D neural networks [4]. But these haven't proven satisfactory and the need for end-to-end 3D networks is clear. The current situation regarding point cloud detection and segmentation is one of models with growing complexity but minimal improvements in the results, so alternative approaches are of interest. One such approach would be to transfer some of the knowledge we have from 2D image processing, where we already have more than satisfying performances.

In this paper we use the current high-performance networks for 2D image processing tasks in the 3D world. Our approach is a combination of two ideas based on modern works in this field: the first idea is to train point cloud segmentation models using 2D priors, where during training we assist the 3D segmentation model with features found in 2D images of the same environment [5]; the second idea is a more efficient and faster achievement of the desired accuracy by using pretrained 2D models, i.e. transferring the parameters from an already trained 2D model to a 3D model and thereby transferring existing knowledge that should result in a good starting point for training with 3D data [6]. The main contribution of the paper is the proposed method that combines two types of knowledge transfer with the goal of improving the performance on 3D semantic segmentation tasks. We thoroughly evaluate the proposed method on a publicly available benchmark dataset, and discuss the findings and the results.

The paper is structured as follows: in Section II examines the related work on the subject of point cloud processing techniques and 3D semantic segmentation; Section III presents our method and details of its inner workings; the experimental results and discussions are presented in Section IV; and the conclusion in Section V.

II. Related Work

Point Cloud Processing

During the development of point cloud processing techniques, several categories of methods have come to prominence. Projection-based methods start by first projecting the point cloud onto a 2D image plane [7], and perform processing using 2D techniques, namely 2D convolutions [1] in order to extract features. Some prominent efforts of this type include multi-view representations [8] and spherical representations [4]. Traditionally these methods have exhibited problems of information loss. Point-based methods directly operate on the point cloud data, usually using a pointwise multilayer perceptron (MLP). The most famous effort here is PointNet [3], and its successor PointNet++ [9], which group points and aggregate local features, but also suffer from data loss because of sampling problems. Voxel-based methods offer efficient ways of point cloud processing, rasterizing the point cloud into regular grids (voxels), to which 3D convolutions can be applied. Of special importance here are sparse convolutions [10], which only perform computations on non-empty voxels, further improving efficiency. Prominent networks in this domain are Cylinder3D [11] and AF^2-S3Net [12].

Multi-Sensor Approaches

While LiDAR sensors offer precise and detailed depth information, they inherently lack robust texture information and provide only sparse output. On the other hand, camera images provide fine texture and color information, but don't offer any depth sensing. From here it seems logical to try and fuse the two kinds of sensors in order to get better quality spatial data and consequently better results during semantic segmentation. Approaches that are focused on sensor fusion use a mapping between the points from the point cloud and the pixels of the image in order to get the joint features and the result of semantic segmentation [13-16]. Most of these use the 2D and 3D data both during training and inference, but one novel approach [5], uses the two modalities only during training, performing distillation from 2D to 3D, and during inference uses only the 3D part of the network, which amounts to only about half of the parameters of the full model.

Cross-Modal Knowledge Transfer

Cross-modal knowledge transfer is already a proven technique for using data from multiple modalities, where by fine tuning a pretrained model on a specific task yields better results than training from scratch. Extensive efforts have been put into using knowledge transfer for 3D tasks where data availability isn't plentiful [18,19] with promising results, such as a method for using pretrained 2D image models for 3D point cloud tasks by weight inflation with a simple pretraining-finetuning scheme [6].

Another avenue of doing cross-modal knowledge transfer is by performing distillation from a teacher network to a student [17]. A milestone effort in this direction is the method proposed by [5], where 2D knowledge is transferred through multi-scale fusion, by training a joint 2D-3D network, but performing inference using only the 3D network.

Outdoor Semantic Segmentation Datasets

A general notion in deep learning is that the quality of our model is mostly dependent on the quality of our data. There were very few datasets for outdoor semantic segmentation with satisfactory size and quality until the appearance of the SemanticKITTI dataset [20]. It is one of the largest outdoor-scene datasets for point cloud segmentation to date, and is an extension of the KITTI Vision Odometry Benchmark [21]. It provides dense annotations for each scan of 11 sequences that are gathered from diverse urban environments. There are also another 10 sequences that are used as a test set for online benchmarking of models. The neat part about this dataset is that besides annotated point clouds it also includes 2D RGB images from the same scenes, which is useful for methods that utilize training with multiple sensors.

III. Method

In this section we propose a novel method for point cloud feature extraction with image pretraining (PointFEIT) and decompose how it implements two efforts for transferring knowledge from 2D deep learning models trained on images to 3D models used for semantic segmentation of point clouds. In continuation, we explain the model architecture, the implementation of each knowledge transfer method within it, the training process, and the experiments with their results.

Architecture overview

The architecture used in the model (Fig. 1) is inspired from the one used in [5], but the 3D network has been changed and with it the feature fusion part where the 3D feature maps are merged with the 2D feature maps. Namely, the architecture of the 3D network is similar to that of [22], where it is envisioned as ResNet18 [23] with only minor changes made to work with 3D data and is implemented with sparse convolutions to work more effectively with sparse data, which is a frequent occurrence in point clouds. It should be noted that we only use the encoder, which is less than half the size of the original model that has a U-Net architecture with a decoder. The basis of the 3D network is exactly this encoder, because this is the easiest way to transfer the parameters from ResNet18, and at the same time it is the simplest and smallest network from the ResNet family contributing to lower computational costs.

The 3D network from [5] uses a constant number of filters in the convolutions, that is, 64 and 256 in the small and large versions, respectively. The layers of the 3D network that is implemented by us do not have a constant number of convolutional filters, instead it varies in the same way as the filters in ResNet18. In addition to the convolutions, the parameters of the batch normalization (BN) layers are also copied. The activation functions are Leaky ReLU instead of ReLU, in order to retain more information.

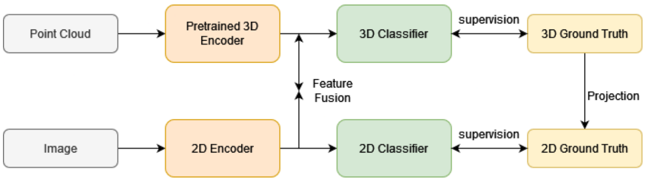

Fig. 1. Architecture of the proposed model.

The 2D part of the network, is close to the original one [5], with a few changes. As a basis ResNet34 is used, and experiments are carried out both with and without the pretrained parameters. The 2D decoder and the classifier were also modified in order to bring the layer outputs to the same filter dimensions as the outputs from the 3D model. The main change here is the number of convolution filters in the last layers of the decoder. We also made minimal changes in the fusion section. These were mainly in the input and output dimensions of the networks for conversion from 3D to 2D features and for prediction from fused features. The reason for that is the difference in the size of the filters used for convolutions in the 2D and 3D networks, and the need for same dimensions in the extracted features.

Weight Inflation

For the weight inflation we mainly followed the recipe set by [6], with the difference that the transfer method was adjusted. The main reason for this is the sparse convolution library that was used, where the convolution parameters are represented differently from those in the library used in [6,22]. Fortunately, our convolutions are presented much more intuitively, and are very similar to those in the PyTorch library and in the original ResNet implementation. Our method included transposing the dimensions of the filter in the form that we need and adding a dimension to the axis along which the expansion needs to be made and projecting the filter along it. The weights were extended along the z-axis because according to [6] there is no difference in performance depending on the projection axis. The extensions along the other axes were also implemented as an option for further experimentation.

2D Priors Assisted Semantic Segmentation

This type of transfer learning involves distillation where the main idea is to assist the training of the 3D network by doing modality fusion with 2D features extracted from images (Fig 2.). Similar to [5], during training both the 2D and 3D inputs are passed through separate 2D and 3D networks where in parallel features of multiple scales are extracted, after which feature fusion is performed with the purpose of getting enhanced 3D features. These enhanced 3D features have the benefit of utilizing the high quality texture and color information from the images while at the same time using the knowledge from the 3D data. With the enhanced 3D features semantic predictions are generated and supervised learning is performed with the 3D labels from the dataset.

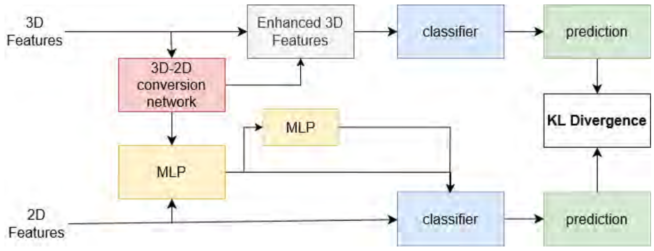

Fig. 2. Pipeline for training with 2D priors.

This type of training assists the 3D network by knowledge distillation. The multi scale 3D features are converted to 2D using a separate network, and fused with the extracted 2D features from the images. Next, the fused features are passed through a 2D classifier from which the 2D segmentation result is obtained. In the 3D network the pure 3D features enhanced with the same 3D-to-2D converted features are passed though the 3D classifier from which the 3D segmentation result is generated. Thus, by using knowledge from the 2D world we can improve the performance of the 3D network. Also important to note is that the 2D and fusion networks are used only during training, and then discarded during inference, halving the size of the network, and letting us use only pure 3D data as input.

IV. EXPERIMENTS

In order to investigate the effectiveness of combining the two methods for transferring knowledge from 2D to 3D models, we performed a series of experiments involving 6 models and a detailed analysis of their performance.

The first model is the plain version of the SPVCNN18 [22] - pure 3D architecture trained from scratch. Then we trained the same model again, but this time using the previously explained weight inflation as a type of knowledge transfer method. The third and fourth models are the small and large versions of the 2D priors method (2DPASS), introduced in [5], with filters of dimension 64 and 256, respectively. The fifth model in the sequence is our mixture of the two knowledge transfer methods, where we also use pretrained parameters in the 2D network. The last model is very similar to the previous one, in that we don't use a pretrained network for the 2D part, but a ResNet34 encoder with a decoder adapted for our purpose instead. This is the main model that we compare with the original 2DPASS. Finally, we retrained the better model of the last two, using the validation split of SemanticKITTI in addition to the standard training split. The purpose of this is that this model was submitted for online evaluation on the site of KITTI to see its performance on test data and how it is going to rank with the best models out there, and most the methods on that ranking list, including [5], in general are trained with the validation split.

General Training Parameters

All the models were trained for 16 epochs. During training we perform learning rate scheduling. Namely, Cosine Annealing scheduling is used, which progressively decreases the learning rate in a given period depending on the number of

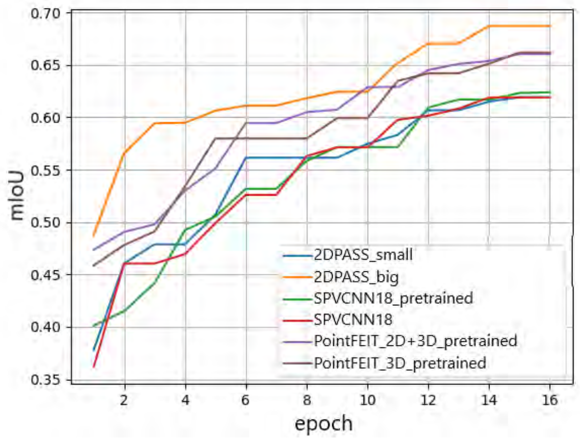

Fig. 3. mIoU on the validation split of SemanticKITTI.

the epoch. We set the initial rate to 0.24 and the minimum rate to 10^{-5}, with the aim of finer tuning in the last epochs.

Several types of loss functions are also used during training. First, the already well-known "cross entropy", a classic performance measurement function for model classification, is used [24]. We also use "Lovász-Softmax", a specific function that is intended for the optimization of the mean intersection over union (mIoU) metric in deep neural networks, [25]. This function has been empirically proven to improve results in semantic segmentation, especially in the segmentation of smaller objects, while in the case of larger objects there are also improvements even though they are smaller [25]. In the networks where we perform distillation, as mentioned above, the "Kullback–Leibler divergence" function is used [26], which measures the statistical distance, i.e. how much one statistical distribution differs from another, reference distribution.

Empirical Evaluation

The validation is done during training and uses sequence 08 as the validation split. The testing is performed using the SemanticKITTI online benchmark, where first we use the model to generate predictions for sequences 11-21 and upload the predictions to the benchmark server in order to obtain the testing results.

We first start by looking at the general performance of the models, i.e. how they perform on the mIoU metric of the validation set of SemanticKITTI. The results are shown in Fig. 3, and the first thing to notice is that we get the worst performance from the small version of 2DPASS. It is important to mention for this model that it has significantly fewer parameters than the other models, but still it performs well in the first epochs, before lagging behind and reaching 0.619 mIoU. Overall this model should perform much better [5], but since it was only trained for 16 epochs and it is quite small, we can conclude that with enough epochs it has the potential to show more impressive results.

Next is the pure version of our 3D model, with no weight expansion and no use of 2D priors. It is slightly better than the last model and it reaches 0.621 mIoU, but considering the number of parameters it does not show satisfactory performance. Similar is the pure 3D model using weight inflation, where although the performance is only marginally better than the version without parameter transfer with 0.623 mIoU, we can observe significantly better results after only one epoch (0.401 vs. 0.361 mIoU). We believe this is due to the transfer of weights from the pretrained ResNet18, which helps initialize the model parameters at the beginning of training.

The fourth model is our combination of knowledge transfer methods, which additionally uses a pretrained network in the encoder of the 2D part (PointFEIT 2D + 3D pretrained). Here the benefit of using the 2D priors method can be best seen, as for the same number of epochs the same 3D network used above achieves significantly better performance with a final result of 0.66 mIoU. In addition, in the result after the first epoch is significantly better than the previous models (0.473 mIoU).

The next model is very similar to the previous one, but it doesn’t use a pretrained network in the 2D part (PointFEIT 3D pretrained). Here we have marginally better results and in the last epoch we reach 0.661 mIoU. By far the best results we see are from the large version of 2DPASS, which exceeds all previous models by a solid margin from the first epoch where it has 0.487 mIoU, until the last one where it reaches 0.687 mIoU. This is somewhat expected given that this model is the most complex: it has a significantly larger number of parameters, about 6 million more than our PointFEIT approach, and the biggest size of hidden layers which all greatly contributes to its performance.

By focusing on the training we can notice that the PointFEIT validation performance is consistently higher than the other 2 versions of SPVCNN18, and from this we can conclude that by using multiple modalities in training, we can significantly improve the performance of a model in predicting a specific modality.

From the results of the trained models we can do an ablation study where we compare the performance gains obtained with each addition of a knowledge transfer method. From what is shown in Table I, it can be observed that by training the pure 3D model we reach a validation accuracy of 62.11 mIoU. By using the weight transfer method we improve this result to 62.34, which is less than expected, but further attempts can be made where the expansion is done along other axes. The 2D priors method makes the biggest difference, and the model here shows a significantly better result with 66.1 mIoU. Finally, we can note that using a pretrained network in the 2D part does not contribute to the performance, and in our case we even get a slightly worse result. All in all, we can come to the conclusion that knowledge transfer methods contribute significantly to the training of point cloud semantic segmentation models.

Finally, we take a look at the model we retrained with the validation set in order to officially see its performance on SemanticKITTI's online testing. The model "PointFEIT 3D pretrained" that we trained is the most successful version of the previous experiments. Retraining on the validation set is almost necessary, because in the standard training data there are not enough examples containing the class "motorcyclist", and using only the training split we get poor segmentation performance on this class.

TABLE I. ABLATION STUDY OF USING THE KNOWLEDGE TRANSFER METHODS

Pure 3D Model	Weight Inflation	2D Priors	Pretrained 2D Network	SemanticKITTI (mIoU)
✓				62.11
✓	✓			62.34
✓	✓	✓		66.1
✓	✓	✓	✓	66.04

It should be noted that there are two different values for mIoU on the test set. The first is obtained by simply predicting the results with one pass of the clouds through the model before passing them to the test server, and its 66.0 mIoU. The second is obtained by using augmentation during testing, i.e. the clouds that are given as input to the model are previously augmented randomly, usually rotated or translated, and then passed as input several times, before taking the average of all predictions, resulting in 68.2 mIoU.

Table II shows the detailed performance by class on the SemanticKITTI online benchmark. From here it can be seen the accuracy with which each class is predicted (that is, segmented) by each model, and thus see where there is the most room for improvement.

V. CONCLUSION

The main goal of this paper was to analyze the effect of knowledge transfer from 2D to 3D neural networks in semantic segmentation tasks, which can significantly improve performance and their training effectiveness. We fully presented the idea behind this technique, which transfers previously acquired knowledge from training on 2D images, a much easier problem, to the 3D world and helps with prediction in tasks involving point clouds. We first reviewed the current situation in the field of point cloud deep learning, specifically the state of the art techniques and availability and quality of datasets. Then we presented findings from recent works and considered how they can help us in the complicated task of 3D semantic segmentation. Specifically, we saw that we can use already pretrained networks by transferring the weights from 2D to 3D by projecting the convolutional filters along any of the three axes, while allowing a good starting point of the model, i.e. a good initialization of the parameters. We also looked at the possibility of using images and point clouds in tandem, making it possible to utilize the benefits of the rich features of 2D images and to transfer knowledge from one modality to another. The main goal of this paper was to see the results of applying a combination of the two approaches mentioned above to a semantic segmentation task. We proposed our approach, PointFEIT, which combined two promising methods, and we conducted a series of experiments where the techniques were implemented in different ways and their impact on performance was considered. Specifically, we progressively added elements to the modified 3D model that aimed to improve semantic segmentation results.

The results show that knowledge transfer has a huge potential both in improving smaller models and in aiding the training of larger ones and highlights possibilities for further work, where we enhance these methods with other modern techniques that emerge daily in this fast-growing field.

TABLE II. PER CLASS RESULTS ON SEMANTICKITTI BENCHMARK

Method	mIoU	Road	Sidewalk	Parking	Other-ground	Building	Car	Truck	Bicycle	Motorcycle	Other-vehicle	Vegetation	Trunk	Terrain	Person	Bicyclist	Motorcyclist	Fence	Pole	Traffic sign
PointNet ++	20.1	72.0	41.8	18.7	5.6	62.3	53.7	0.9	1.9	0.2	0.2	46.5	13.8	30.0	0.9	1.0	0.0	16.9	6.0	8.9
SPV NAS	67.0	90.2	75.4	67.6	21.8	91.6	97.2	56.6	50.6	50.4	58.0	86.1	73.4	71.0	67.4	67.1	50.3	66.9	64.3	67.3
Cylinder3D	68.9	92.2	77.0	65.0	32.3	90.7	97.1	50.8	67.6	63.8	58.5	85.6	72.5	69.8	73.7	69.2	48.0	66.5	62.4	66.2
$(AF)^2$-S3Net	70.8	92.0	76.2	66.8	45.8	92.5	94.3	40.2	63.0	81.4	40.0	78.6	68.0	63.1	76.4	81.7	77.7	69.6	64.0	73.3
2DPASS small	72.9	89.7	74.7	67.4	40.0	93.5	97.0	61.1	63.6	63.4	61.5	86.2	73.9	71.0	77.9	81.3	74.1	72.9	65.0	70.4
Point FEIT	68.2	90.6	76.2	64.7	25.9	91.4	97.1	59.7	59.0	59.0	66.2	86.3	73.1	71.4	75.2	81.1	16.1	67.1	63.8	70.1

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Siamese Neural Network Architectures for Efficient Person Re-identification

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***Abstract*— This paper presents a computationally efficient Siamese Convolutional Neural Network (CNN) for person re-identification (ReID) with a small number of parameters, trained exclusively on synthetic data. The CNN successfully estimates similarity of person images across consecutive frames, and after long-term occlusion. The results indicate that a small CNN with carefully tuned training and data selection strategy provides promising ReID results in challenging conditions. The small drop in performance in the presence of detection errors and cross-domain application on complex real-world video footage predominantly results from severe object detection errors. With the demonstrated accuracy and potential for real-time and cross-domain application, the proposed Siamese CNN provides a solid basis for a fully appearance-based computationally efficient online object tracker.**

Keywords*— *Siamese neural network, person re-identification, object re-identification, CNN, computational efficiency, appearance-based tracking, online tracking

I. Introduction

Object re-identification (ReID) has emerged as a critical challenge in computer vision, particularly in the domains of surveillance, autonomous systems, and multi-object tracking (MOT) [1]. Person ReID has witnessed significant progress in recent years through the use of deep learning. Traditional ReID methods rely heavily on CNNs (Convolutional Neural Networks) and transformer-based architectures to extract and match visual features across different frames or views [2, 3, 4, 5, 6]. However, they often come with significant computational costs, making them impractical for applications where processing speed and resource efficiency are crucial. The variability in real-world scenarios (changes in lighting, occlusions, presence of distractors) further complicates the ReID task, requiring models that generalize well across various conditions. To address privacy concerns associated with real-world data, synthetic data has been increasingly utilized in training deep learning models [7, 8, 9]. Siamese neural networks have gained popularity for their ability to estimate image similarity with a relatively low parameter count, making them well-suited for real-time application. These networks have been particularly effective in appearance-based matching, which is essential for ReID and tracking tasks.

In this work, we evaluated the hypothesis that a small Siamese-based neural network [10] for estimating image similarity, trained on a limited dataset of user-specific data, can provide an optimal solution for real-time object ReID. We compared three Siamese-based CNN architectures for person ReID, analyzed the effects of architecture and loss function choice on the relationship between decision accuracy and confidence, analyzed the effect of detection accuracy on ReID performance, and evaluated the CNN performance on images of synthetic and real video footage.

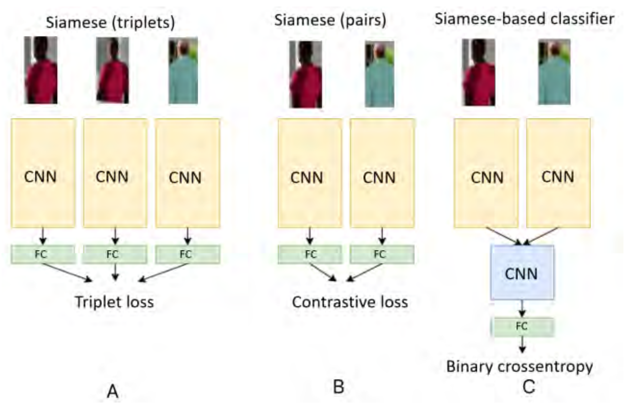

Figure 1 Variants of Siamese-based CNN architectures for person ReID: A – Siamese (triplets), B – Siamese (pairs), C – Siamese-based classifier. The yellow blocks represent a sequential CNN architecture with convolutional and max-pooling layers, and the blue block contains convolutional layers only. Each green block represents a fully connected layer. Blocks with same label and color share an identical architecture across all architectures, and within the same architecture also have shared weights.

The rest of this paper is structured as follows. An overview of the related work is given in Section II. Section III presents the proposed CNN architectures and potential applications, and Section IV the experiment design. The dataset description is given in Section V. Results are presented and discussed in Section VI, and conclusions are presented in Section VII.

II. Related Work

Early ReID algorithms focused on neural networks that explore the relationship between the extracted features [11], as well as combinations of global feature encoding with feature-dropping mechanisms to enhance robustness [12]. Ref. [13] proposes a CNN model that works on multiple scales with adaptive fusion, thus reducing model complexity, while maintaining performance. The significance of loss functions has been explored by introducing triplet loss [14, 15], which has become widely used in ReID and metric learning tasks. Sampling methods have advanced from early random approaches [16] to more refined techniques like semi-hard negative mining [17]. Transformer-based ReID networks (TransReID [18]) are increasingly used to overcome CNN limitations through addressing local neighborhood focus and downsampling-related information loss, while GAN-based methods [19, 20] have been introduced to enhance ReID dataset diversity. Part-based feature learning [12] has improved accuracy by extracting and assembling part-level features. Occluded ReID remains an open challenge, with recent efforts [21] struggling when both query and gallery images contain occlusions.

Siamese neural networks, known for their efficiency in estimating image similarity, are increasingly used for appearance-based matching and joint appearance and motion modeling [22, 23, 24, 25]. They have become popular in MOT for their effectiveness in estimating image similarity and addressing MOT challenges. Notable advancements include SiamRPN++ [26], Siamese Instance Search for Tracking [24], and Distractor-aware Siamese Networks [23]. Recent approaches (SiameseDETR [27]) integrate CNN architectures and view-invariant representations to enhance performance. State-of-the-art algorithms are generally offline trackers using large, complex end-to-end algorithms [28, 29], or multiple object detectors [5, 6, 30, 31, 32] with large, complex deep CNNs or transformers for feature extraction [33, 34, 35]. This makes them impractical for real-time applications.

To address the issues identified in previous works, we propose a Siamese-based CNN architecture for object ReID with minimal parameter count, trained exclusively on synthetic data. Provided sufficient ReID accuracy, the compact Siamese CNN can be incorporated as a core component into an online, efficient, fully appearance-based tracker.

III. Siamese-based CNN Architectures for People ReID

This work focuses on designing a small, efficient CNN architecture for person ReID, that will be able to generalize over different objects and background environments, with a high degree of occlusion from background objects or other people. As part of a tracking algorithm, the proposed CNN will operate on bounding boxes generated by an object detector, and produce image similarity scores for all people in consecutive frames. We design and compare three CNN architectures based on the Siamese neural network architecture: original Siamese architecture trained with image triplets (Fig. 1a, Network A), Siamese architecture trained with pairs (Fig. 1b, Network B), and Siamese-based classifier (Fig. 1c, Network C).

The architecture of the main branch (yellow block marked with CNN in Fig. 1) is presented in Fig. 2. The branch consists of 3 consecutive VGG blocks, each containing two convolutional layers with filters of size 3x3, and one max-pooling layer with non-overlapping window of size 2x2. All convolutional layers are followed by ReLU activations, and operate on zero-padded input feature maps. The block is followed by a fully convolutional layer, that generates a 1-dimensional feature vector of appearance embeddings of size 64.

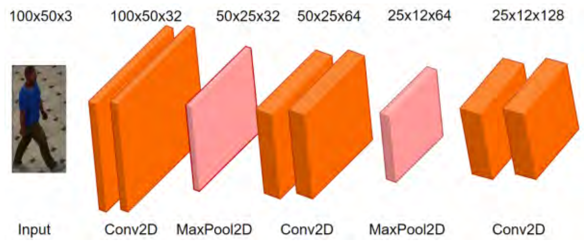

Figure 2 Architecture of the base branch of the Siamese networks (yellow block labeled CNN in Fig. 1). Bottom – layer names, top - sizes of layer output. First two numbers from the output dimensions represent height and width of feature maps generated by the layer, the last number represents the number of feature maps – number of convolution filters in the layer.

The input is RGB color images of size 50x100px. The traditional Siamese architecture networks (Fig. 1, A and B) consist of branches with identical architecture and shared weights. They produce a low-dimensional embedding vector for each input image, such that the Euclidean distance between vectors of similar images is small, and the distance between vectors of different images is large. Thus, the Euclidean distance between the two vectors represents an image similarity coefficient. Network A is trained with three input images (two images of the same person, and one of a different person), with the triplet loss function [14, 15] which aims to ensure that the Euclidean distance between the feature vectors of the images of the same object is smaller than the distance between images of different objects. Networks B and C are trained with pairs of images that can contain the same person, or different people. In Network B, the contrastive loss [36] minimizes the distance between similar pairs, and maximizes the distance between dissimilar pairs. Network C consists of two identical branches with shared weights, a third CNN block that receives the concatenated output of the two branches as input, followed by a fully connected layer. It uses the binary cross-entropy loss function, and outputs the probability that the two input images are of the same object.

To isolate only the influence of the loss function and network connections, for each network we used identical architectures of the base network branches. We analyzed the influence of the loss function on the standard Siamese architecture, and the effect of combining the concepts of Siamese and classifier networks on the accuracy and probability distribution of the output.

The networks were trained on 50,000 image triplets (Network A) or pairs (Networks B and C). Pairs of images of the same person were selected at a distance of 5 to 30 frames, where a distance of 30 frames corresponds to 1 second. Pairs of images of different people were selected from the same frame.

IV. Experiments

The primary focus of this paper is selecting an optimal CNN architecture. Additionally, we analyzed the effect of object detection accuracy on the ReID results, and cross-domain application potential.

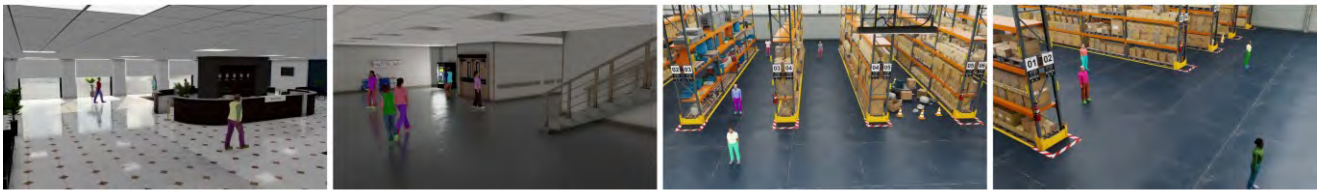

Figure 3 Example scenes from the Multi-Target Multi-Camera People Tracking Dataset.

Figure 4 Ground truth annotation mistake. The object with ID 36 is fully occluded behind the aisle, and the bounding box contains only a part of the aisle (right).

Figure 5 Example indoor scene from the MOT17 dataset of real video footage. Ground truth detections (generated by Faster R-CNN) are marked with green bounding boxes. Labeling errors: significantly wider bounding boxes (blue arrows), duplicate detections (yellow arrow), unlabeled persons (blue circle).

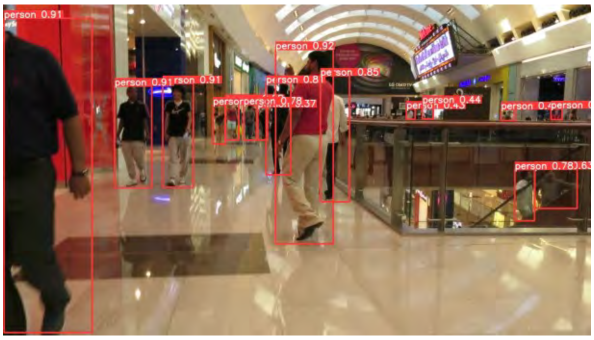

Figure 6 YOLOv5-large object detections for the video frame in Fig. 5. Despite some small, distant objects remaining undetected, YOLOv5-large generally provides more accurate object detections compared to Faster R-CNN which is regarded as ground truth by the MOT Challenge.

A. *Effect of Detection Accuracy on Person ReID Accuracy*

To analyze the effects of the changes in CNN architecture and loss function on the ReID accuracy without the influence of the object detection accuracy, we performed two experiments. First, we analyzed the effects of the proposed architecture changes and loss functions with the ground truth object detections provided in the MTMC-PT dataset [37] described in detail in Section V. Next, we repeated the experiments with detections generated by a pre-trained object detection network (YOLOv5-large [41]) to analyze the effect of detection accuracy on the ReID results.

B. *Cross-domain performance*

Although trained exclusively on synthetic data, to assess the potential for cross-domain application, we tested the proposed CNN architectures on images of people extracted from real video footage. For this purpose, we selected the video sequences of indoor settings from the MOT17 dataset [39], described in more detail in Section V.

C. *Implementation details*

All proposed networks (Section III) were trained for 100 epochs with ADAM (ADAptive Moment estimation) [40] with a learning rate of 10^{-4}, and a mini-batch of 32 samples. All experiments were performed on a machine with the following specifications: AMD Ryzen 7 3700X 8-Core CPU, 32GB RAM, NVIDIA GeForce RTX 2070 SUPER GPU.

V. DATASET

Two datasets are used in this work: MTMC-PT (Multi-Target Multi-Camera People Tracking) [37] used for training and evaluation, and MOT17 [39] used only for evaluation.

A. *MTMC-PT Dataset of Synthetic Data*

The MTMC-PT dataset was released by NVIDIA as a part of Track 1 of the 7th AICityChallenge [37]. It consists of 22 scenes captured by multiple cameras per scene. 21 of the scenes contain synthetic video data generated by the NVIDIA Omniverse Platform, and 1 scene contains real video footage. 10 minutes of Full HD (1080p) video at 30 fps (frames per second) is provided for each camera. Examples of several scenes and views are shown in Fig. 3.

Ground truth annotations are provided for all synthetic scenes, and include bounding boxes for persons with minimum 20% overall visibility, or a visible head. The bounding boxes encase only the visible parts of the person. As a result, the aspect ratios of the bounding boxes vary greatly – from 1:1 to 1:5. Furthermore, each person retains the ID indefinitely – periods of full occlusions are up to 8 minutes. Several types of labeling errors can be noticed, mainly on occluded objects: annotations exist even if the object is fully occluded (Fig. 4), or bounding box inconsistency for heavily occluded persons.

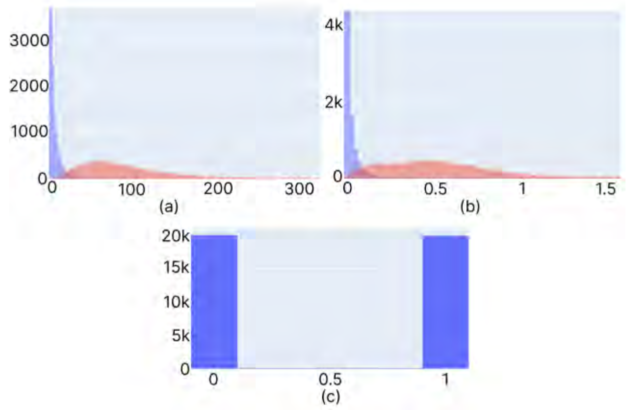

Figure 7 Histograms of the probability distributions of the CNN output for the test samples. a – Siamese (triplets), b – Siamese (pairs), c – Siamese classifier. For a and b, the histogram of distances for the positive image pairs are blue, and for the negative image pairs - red.

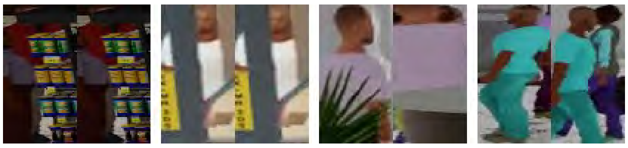

Figure 8 Correctly classified hard samples (low object visibility and presence of multiple objects in the frame). True positives (1 and 2), and true negatives (3 and 4).

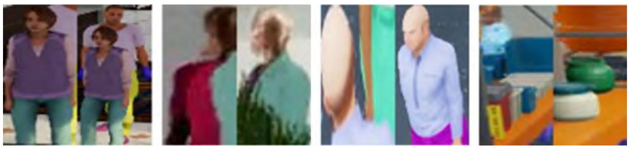

Figure 9 Errors: false positives (a, b), and false negatives (c, d). The errors occur in cases with high degree of overlap (a), high occlusion degree (b, c), and object detection errors (d).

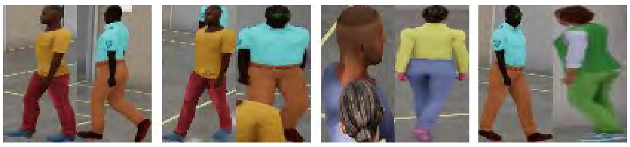

Figure 10 Low-confidence errors from the Siamese (triplets) network. True positives (1, 2), and true negatives (3, 4).

B. *MOT17 Dataset of Real Video Footage*

Since ground truth data are not provided for the real video footage in the MTMC-PT dataset, for the experiments with real data (Section IV.B) we used the MOT17 dataset from the MOT Challenge [39]. For evaluation, we used the 30-second Full HD video with 30 fps, covering an indoor scene (Fig. 5).

The provided ground truth annotations for the MOT dataset are not human-labeled – the detections are generated with Faster R-CNN [32]. As a result, the data contains many labeling errors (Fig. 5), especially pronounced for small, distant objects. The errors create challenging conditions both for the Siamese CNNs, and for calculating a correct detection accuracy of other object detectors.

VI. RESULTS AND DISCUSSION

The results presented in Section VI.A – VI.C are obtained on the 5 different scenes in the validation subset of the MTMC-PT dataset. The test set contains 45,000 image triplets / pairs selected at random from every scene and every view. The performance evaluation is done on people and scene backgrounds not present in the training set. The results in Section VI.D are obtained on the 30-second indoor video in MOT17, on 45,000 image triplets / pairs selected at random.

A. *People ReID*

Table I contains the results of the performance comparison of the three proposed architectures (Section IV.A), evaluated through standard image classification metrics. The class is computed using fixed threshold binarization for the classifier network, and a fixed distance threshold for the Siamese networks, both empirically determined through analysis of the histograms of CNN outputs (Fig. 7).

According to Table I, the Siamese classifier (Network C) offers the strongest performance, followed closely by the Siamese CNN trained on triplets (Network A). The top results of Network C are in part due to the small increase in network parameters. However, analyzing the histograms of the output (Fig. 7) shows that Network C has high confidence both for the correct, and incorrect decisions. Whereas, the incorrect decisions made by the Siamese networks (Networks A and B) are with significantly lower confidence (located in the area of overlap of the two histograms).

Visual analysis of the results shows that the networks are capable of reliably re-identifying objects, even with significant degrees of occlusion (Fig. 8). The errors are mainly a result of detection errors, and extreme degrees of object occlusion (Fig. 9). Examples of low-confidence errors of the Siamese triplet network are shown in Fig. 10.

TABLE I. PERFORMANCE COMPARISON OF THE PROPOSED CNN ARCHITECTURES FOR PERSON REID WITH GROUND TRUTH OBJECT DETECTIONS

	Acc. (%)	**Precision**	**Recall**	**F1**	**Num. params.**
Siamese (triplets)	96.71	0.9781	0.9781	0.9668	**733,856**
Siamese (pairs)	94.46	0.9494	0.9405	0.9449	**733,856**
Siamese classifier	**98.6**	**0.9856**	**0.9866**	**0.9861**	877,217

B. *Effect of Detection Accuracy on ReID Accuracy*

As the top two performers from Table I, we selected the Network A (Siamese triplets) and C (Siamese classifier) for the following experiments. As seen in Table II, when testing with imperfect object detections generated by YOLOv5-large [41] trained on COCO data [42], there is a noticeable drop in performance compared to ideal (ground truth) object detections (Table I). Upon visual inspection, it can be noticed that the ReID errors from both networks are predominantly a result of object detection errors (Fig. 11 b), or multiple persons present in one image (Fig. 11 d). Though the Siamese classifier presents better overall performance, it performs significantly

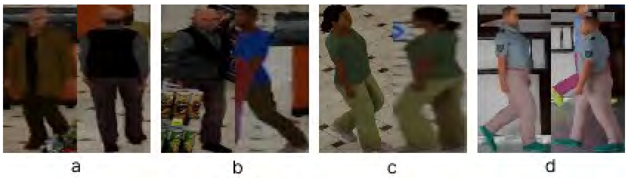

Figure 11 Misidentified samples with YOLO object detections. a, b – false positives generated by the Siamese triplets network; c, d – false negatives generated by the Siamese classifier network.

Figure 12 Misidentified samples on real video footage from the Siamese triplets network. Top – false negatives, bottom – false positives. a, b – with ground truth object detections; c, d – with YOLO object detections. Errors with ground truth object detection (generated with Faster RCNN) are predominantly a result of errors in object detections.

worse in terms of false negative samples. Whereas, false positive errors dominate in the Siamese triplets results.

TABLE II. PERFORMANCE COMPARISON OF SIAMESE ARCHITECTURE VARIANTS WITH OBJECT DETECTIONS GENERATED BY YOLOV5-LARGE

	Acc. (%)	Precision	Recall	F1
Siamese triplets	75.93	61.73	**86.01**	72.06
Siamese classifier	**79.58**	**95.13**	62.39	**75.57**

C. *Cross-domain application on real video footage*

Table III provides a performance comparison of the CNN architectures on real video footage from an indoor scene from the MOT17 dataset. For YOLO object detections, similar to the results with synthetic data (Table II), the classifier provides better overall performance, false positive errors dominate in the Siamese triplets results, and false negative errors dominate in the Siamese classifier results. With ground truth detections, most ReID errors result from detection errors (Fig. 12, a,b). With YOLO detections, although some ReID errors result from detection errors (Fig. 12c), most of the errors result from other causes (Fig. 12d). The ground truth (generated by Faster R-CNN) contains many object detection errors (Fig. 5), which results in a significant performance drop for both networks compared to the YOLO detections.

Using YOLO object detections, both networks show better performance on the real video data compared to the synthetic data, which is due to the real video data containing simpler scenes, fewer high-degree occlusions from background objects, and a significantly larger variety between the appearance of different people. Overall, the ReID CNNs achieved satisfactory results on out-of-domain data with accurate object detections, despite being trained exclusively on synthetic data.

TABLE III. PERFORMANCE COMPARISON OF THE SIAMESE ARCHITECTURE VARIANTS ON REAL VIDEO FOOTAGE

		Acc. (%)	Precision	Recall	F1
Siamese triplets	**GT**	76.72	61.33	88.41	72.28
	YOLO	85.52	78.56	91.41	84.40
Siamese classifier	**GT**	75.93	61.82	86.12	71.94
	YOLO	90.79	95.41	85.72	90.41

As the proposed object ReID network is designed to be the main part of an object tracking algorithm, the networks' task is optimally matching detections from two consecutive frames. For that, strong decision confidence is not crucial – assigning a higher similarity score to the images of the same object compared to any other image, regardless of the value of the similarity score, is enough to ensure correct ReID. In this regard, since for the Siamese CNN trained with triplets, there is a much higher correlation between the correctness and confidence score of a decision compared to the Siamese classifier, it can be hypothesized that the Siamese is a better choice for an appearance-based tracker compared to the classifier, marking an interesting direction for future research.

VII. CONCLUSION

This paper presents and compares variants of Siamese CNN architectures applied to person ReID, trained exclusively on computer-generated data. We demonstrated that Siamese networks with small number of parameters are able to produce excellent ReID results on computer-generated data. Additionally, the networks produce promising results in the presence of object detection errors, and can be applied to real data, with most of the errors being a result of object detection errors. Through using small neural networks trained exclusively on synthetic data, this paper addresses privacy concerns raised by using real video datasets and storing personally identifiable data. Future work will focus on comparing the traditional Siamese architecture and Siamese classifier in terms of tracking accuracy, and compare the performance to computationally demanding trackers with complex architectures in terms of accuracy and required computing power.

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Siamese Networks for Vehicle Re-Identification

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***Abstract*—In this paper we present a compact and computationally efficient Siamese CNN architecture designed for vehicle re-identification (ReID). We compared two architecture variants (traditional Siamese network and Siamese-based classifier) with different loss functions, to analyze their influence on model accuracy. Promising results were achieved under varying conditions – different times of day, lighting, and weather. The model's errors predominantly occurred with either very distant (small) vehicle samples, or vehicles that are visually very similar. Overall, the choice of loss function had minimal impact on performance. Despite the small number of parameters, Siamese networks demonstrated strong capabilities in vehicle ReID. Based on accuracy metrics, this approach is well-suited for use in vehicle tracking systems, particularly for re-identification and speed calculation.**

Keywords—vehicle re-id; CNN; Siamese neural networks; classification; contrastive loss

I. Introduction

Vehicle re-identification is a fundamental technology within intelligent transportation systems, playing a vital role in the development of smart cities. Through automatic detection, localization, and tracking of vehicles across multiple cameras, this technology enables intelligent parking, suspicious vehicle tracking, vehicle event detection, vehicle counting, and many other functions at a significantly reduced labor and costs. Additionally, an important application of vehicle ReID is estimating vehicle speed. The integration of speed calculation with vehicle ReID enhances the accuracy of traffic monitoring systems, providing more reliable data for traffic analysis and infrastructure planning.

Recent advances in deep learning have significantly enhanced the capabilities of vehicle re-identification, leading to significant increase in accuracy over traditional methods based on feature extraction and classification techniques, introducing substantial progress in this field. Using CNNs combined with similarity metrics is highly effective due to their ability to capture and compare complex visual features, crucial for distinguishing between different vehicles in different environments and weather conditions.

In this work, we aim to explore the benefits of using Siamese neural networks for vehicle re-identification. We propose a classifier CNN based on the Siamese network structure, and compare the proposed architecture to a traditional Siamese CNN. Moreover, we explore the potential of the proposed network to be used as the integral part of a vehicle tracking algorithm.

The paper is organized as follows: In Section II we discuss related work on vehicle tracking algorithms, and the use of Siamese CNNs for tracking. Section III presents the proposed Siamese-inspired classifier CNN, and several architecture variations. In Section IV, we give the details on the dataset used for training and evaluation. The results and discussion are provided in Section V, and finally, conclusions and future work are presented in Section VI.

II. Related work

Traditional machine learning methods for vehicle re-identification involve feature extraction techniques like SIFT [1], HOG [2], and LBP [3], which focus on specific image aspects such as local appearance, edges, and texture. Zapletal and Herout [4] combined features from a color histogram and histogram of oriented gradients (HOG) with linear regression to perform vehicle re-identification. Chen et al. [5] proposed a novel grid-based approach to re-identification vehicles grid-by-grid by extracting their HOG features for coarse search, and refined the result by using their histograms of matching pairs (HOMs). In [6], Local Variance Measure (VaR) for vehicle re-identification are implemented using Local Binary Patterns (LBP) and joint descriptors. While effective for certain tasks, these hand-crafted features often suffer from poor generalization across different application scenarios.

Some research papers focus on achieving re-identification using features from local regions [7], [8], [9], [10]. The general idea of such works is to emphasize the local characteristics or details of vehicles. For example, in [7], this is achieved by dividing the feature maps into overlapping windows, and then each of these individual maps is fed into several sequential fully connected layers. The motivation behind this approach stems from cases where two vehicles of the same make look very similar, making it difficult to distinguish between them based solely on their global appearance. The aforementioned methods, while accurate, often involve computationally intensive processes such as key point extraction and region segmentation. These methods can significantly increase computational load and processing time, making them unable to be used in real-time systems where speed is crucial.

Another group of studies incorporates the method of metric learning [11], where during training with pairs of images the aim is to learn the similarity between them so that the distance between identical/similar vehicles is minimized, while the distance between different ones is maximized.

Recently, a large number of re-identification methods have employed Siamese neural networks [12], [13], [14]. In [15], the authors combine a Siamese network with a feature extraction module that emphasizes the parts of the vehicles most likely to differ. Two Siamese networks are used in [12], where one network provides the distance between two images of a vehicle, and the other provides the distance between the license plates of the same vehicles. These pieces of information are combined, and a decision for classification is made using several fully connected layers. Vehicle Re-ID using similarity metrics combined with Convolutional Neural Networks (CNNs) is highly effective due to their ability to capture and compare complex visual features. CNNs excel at automatically learning discriminative features from vehicle images, such as shape, color, and unique identifiers, which are crucial for distinguishing between different vehicles. When paired with similarity metrics, these learned features enable precise comparison between vehicle images, determining whether they represent the same vehicle. In [16], a multi-task learning framework, referred to as ALDR (Attribute Learning and Deep Ranking), is employed to extract robust global features, which are then used to generate an initial ranking list. Subsequently, local similarities between image patches from the initial ranking list and the query image are calculated using a Multi-Channel and Multi-Scale Siamese network (MCMS-Siam).

This work aims to create a computationally efficient vehicle ReID algorithm for accurate speed estimation robust to visual and weather conditions, that will mitigate the aforementioned limitations of previous works.

III. CNN ARCHITECTURE FOR VEHICLE RE-ID

We present a classifier CNN based on the Siamese network structure to generate probability that two images show the same object. We compare the performance and parameters with the original Siamese CNN structure with contrastive loss.

A. *Siamese CNN with contrastive loss*

The first variant of the Siamese network was composed of three convolutional layers, with a subsampling (max pooling) layer after the first two convolution layers. The convolutional layers contain filters with dimensions of 3x3, with the initial layer containing 32 filters, the second layer 48 filters, and the final layer 64 filters. The ReLU activation function was applied across all layers, and the initial values for all filter weights were randomly initialized using a uniform probability distribution. After the final convolutional layer, the output was vectorized, followed by a fully connected layer with 128 output neurons. This approach was designed to produce feature vectors for the input samples, which were then used to calculate the distance or similarity between them. The described architecture is shown on *Figure* 1.

❖ Contrastive Loss

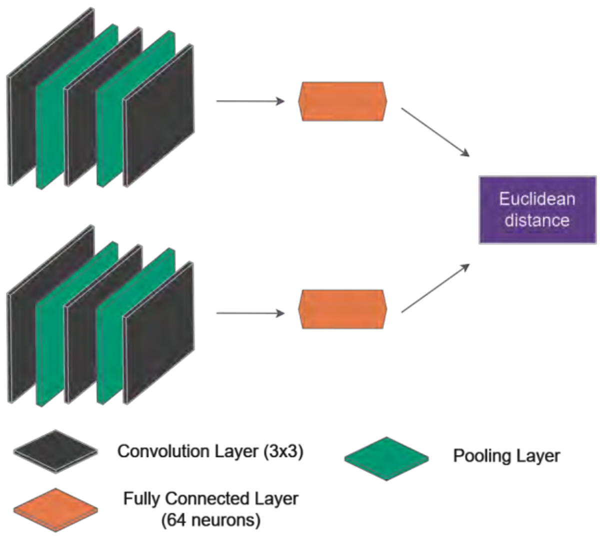


Figure 1 Siamese CNN architecture

Contrastive loss is a distance-based loss function that aims to minimize the distance between the vector embeddings of similar pairs (positive pairs) and maximize the distance between vector embeddings of dissimilar pairs (negative pairs) [16].

$$L = \frac{1}{2}(y \times D^2 + (1 - y) \times \{\max(0, m - D)\}^2)$$

B. *Siamese-based classifier*

In order to make a comparison, the architecture of this classifier is largely similar to the model described in Section III-A, with only minor modifications introduced due to the use of different loss function (*Figure* 2). The model begins with two identical convolutional branches that extract hierarchical features from the input image pairs. Each branch consists of two consecutive blocks of one convolutional layer followed by a max-pooling layer. These feature representations are then

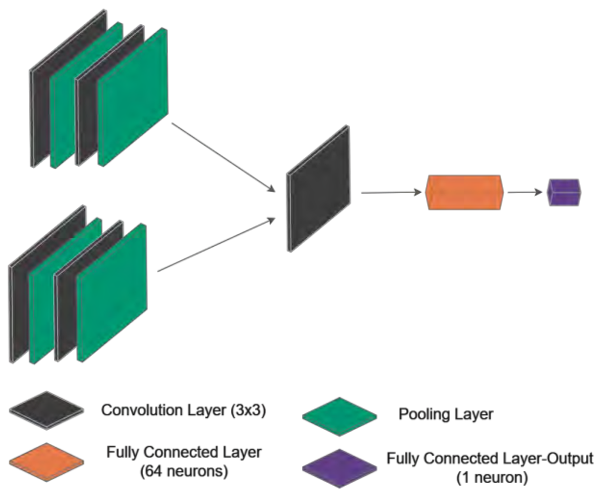


Figure 2 Siamese-based classifier architecture

Figure 4 Pairs from the dataset, positive pair/same vehicle(left); negative pair(right)

concatenated, merging the information from both images. The concatenated features undergo an additional convolutional operation to refine the joint representation, followed by a dense layer with 64 neurons to capture complex patterns. Finally, a single neuron with a sigmoid activation function produces the output that marks the probability that the two input images contain the same vehicle. The model is optimized using binary focal loss, which effectively addresses class imbalance by focusing on hard-to-classify samples, making the architecture well-suited for imbalanced datasets.

Both networks (Section III.A and Section III.B) were trained for 30 epochs, with batch size of 72.

IV. Dataset

To train variations of Siamese neural networks for vehicle re-identification, the majority of the dataset was obtained using a custom pre-trained model specifically designed for vehicle detection. The model was applied to images obtained from video surveillance cameras installed along the highway Miladinovci-Shtip. It was used to generate bounding boxes around the vehicles in these images, which were then modified to form square regions, ensuring consistent aspect ratios. Finally, the squared images were resized to 48x48 pixels to standardize the input for the network. This process resulted in a dataset consisting of images representing four different categories of vehicles: cars, trucks, vans, and buses.the images were extracted from 14 different scenes captured at various times of the day and under different weather conditions. Depending on the architecture of the Siamese network and the loss function employed, the input images form pairs (an anchor and a positive sample from the same class/vehicle as the anchor, and an anchor and a negative sample from a different

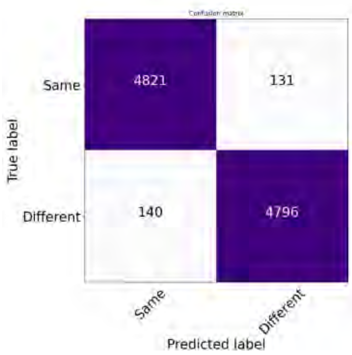


Figure 5 Confusion matrix for Siamese network with contrastive loss

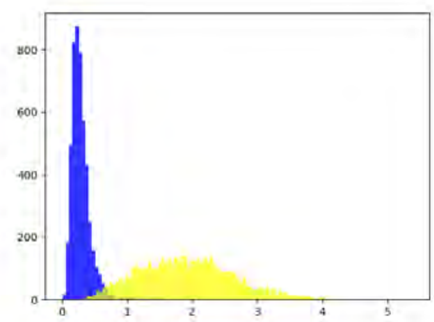


Figure 3 Histograms of distances between input image pairs. Distances between positive pairs in blue, and distances between negative pairs in yellow. Bin width: 0.05

class/vehicle). To achieve this, the images were organized based on their vehicle IDs, with each vehicle assigned a unique identifier.

Both networks (Section III.A and III.B) were trained with approximately 400.000 pairs formed from 27.000 images that correspond to 385 different vehicles. Positive pairs were created by pairing each frame of a vehicle with six adjacent frames (three preceding and three following frames). Negative pairs were randomly selected from the entire dataset, maintaining a 4:1 ratio with positive pairs. Examples of the dataset and the formed image pairs are illustrated in *Figure* 4. For the validation and test sets, vehicles not included in the training set were selected, and pairs were formed from these vehicles, comprising 10% of the number of pairs in the training set.

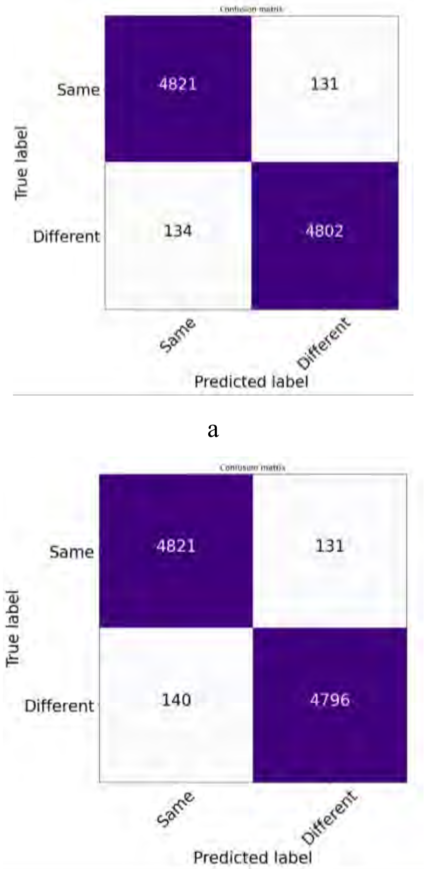
V. Results and Discussion

In this section, a comparison of the Siamese-inspired classifier architecture to a traditional Siamese CNN is provided, highlighting the differences in performance and design. Additionally, we analyze the influence of the chosen loss function on the Siamese-classifier hybrid.

Table 1 shows classification results for the discussed architectures. The performance is compared with standard classification metrics: Accuracy (%), Precision, Recall, and F1-score. The values for True Positives (TP), True Negatives (TN), False Positives (FP), and False Negatives (FN) are determined through the binarization of the network output, which is discussed in detail in the subsequent subsections (5.a and 5.b).

A. Siamese CNN with contrastive loss

For the Siamese network, a similarity coefficient is generated by calculating the Euclidean distance between the vector embeddings generated by the CNN. *Figure* 3 illustrates the histogram of distances between input image pairs. Since the predicted output of the model is a distance rather than probability, smaller distance indicates a higher similarity between the image pairs, and distance smaller than the threshold suggests that both input images contain the same car. Conversely, distance larger than the threshold implies that the



a

b

Figure 7 Confusion matrices. a- Siamese based classifier with binary crossentropy loss; b- Siamese based classifier with focal loss

cars are different. The image shows overlapping of the histograms of positive and negative pairs. Since the histograms of distances between positive and negative pairs overlap, the evaluation strategy involved thresholding image similarity to classify pairs as positive or negative. The threshold was determined by analyzing the histograms of distances generated for positive and negative image pairs of the validation set. A threshold of 0.65 provided the highest accuracy.

The confusion matrix illustrates the model's classification performance (*Figure* 5). As seen, the errors are balanced – the

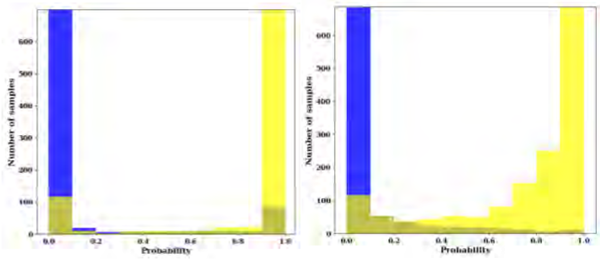


Figure 6 Histograms of probabilities for Siamese-based classifier with binary crossentropy loss (left) and for Siamese-based classifier with focal loss(right).

CNN does not favor a specific class.

B. Siamesed based classifier

The model generates a probability coefficient indicating the probability that two input images depict the same object. To distinguish between images of the same and different vehicles, this probability is subjected to a thresholding process. The threshold is empirically derived from the validation set based on classification accuracy, resulting in a threshold of 0.3 for the Siamese-based classifier with focal loss and 0.35 for the Siamese-based classifier using the binary cross-entropy loss. Image pairs with probabilities exceeding this threshold are classified as representing the same vehicle, while those below the threshold are deemed different vehicles. *Figure* 6 showcases a histogram of these probability distributions for both variants of the proposed classifiers, accompanied by confusion matrices (*Figure* 7) that detail the classification performance under the applied thresholding strategy.

C. Discussion

The results presented in Table 1 are obtained by averaging over two trainings of each model with different initial weights. The presented CNN architectures with small number of parameters deliver satisfactory accuracy with real-time performance. As shown in Table 1, the traditional Siamese CNN and the classifiers achieve comparable results. Also, its worth noting that the classifier using focal loss produces significantly less false positive samples with high confidence score, indicating a reduced tendency toward overconfidence in

Table 1 Classification results

	Acc. (%)	**Precision**	**Recall**	**F1 score**	**Num. of parameters**	**Threshold**
Siamese CNN - contrastive loss	**97.3**	**0.974**	**0.972**	**0.973**	**632,368**	0.65
Classifier - binary crossentropy	96.9	0.973	0.964	0.969	660,081	0.3
Classifier - focal loss	97.1	**0.974**	0.965	0.970	660,081	0.35

the model's misclassifications, as seen from the probability histogram in *Figure* 6.

From the visual inspection of the errors (*Figure*), we see that for all networks, the errors are concentrated in cases where vehicles are at a great distance to the camera, the vehicles are at a significantly different angle to the camera, or different vehicles with very similar features. The model from the traditional Siamese network as depicted on *Figure* -a produces errors for distant objects, and in situations where the angle is significantly different. Similarly, the errors from the model with crossentropy loss are caused by distant vehicles and vfehicles with similar global features, depicted on *Figure* 8-b. As shown on *Figure -c* the errors on the first two pairs of images show false negative samples where the vehicles are far from the camera, and additionally, due to imprecise annotations, a large amount of background is included. The second pair shows the same vehicle from a different angle of view, and the last pair consists of vehicles that have similar visual characteristic including the color, which is considered as FP. The confusion matrices shown on *Figure* 5 and *Figure* 7 for one of the initializations contain identical numbers. This suggests that the test data contains hard samples which are difficult to classify even by humans, therefore they are misclassified by both architectures. Visual inspection of the results confirmed this claim (*Figure* 8).

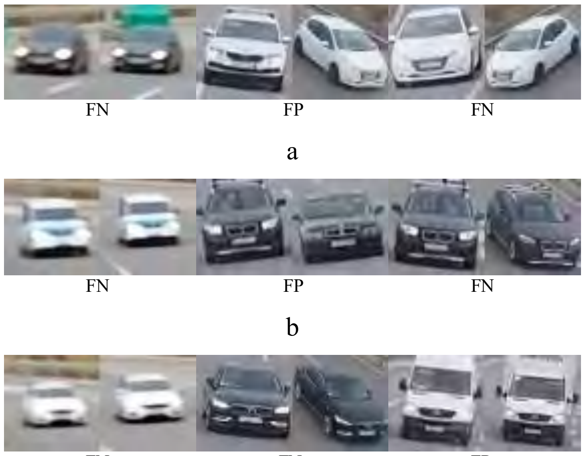


Figure 8 Classification error examples. a – Siamese network with contrastive loss; b – Siamese classifier with binary crossentropy loss; c – Siamese classifier with focal loss

VI. Conclusion

In this study, we introduced two Siamese neural network architectures, designed with a strong emphasis on computational efficiency. Both architectures demonstrate promising outcomes in terms of performance, with comparable results. Notably, the majority of classification errors were concentrated on different vehicles exhibiting similar visual characteristics, those positioned at a greater distance from the camera - resulting in reduced resolution, and instances where the cropped input images contained a significant amount of background. The future research will focus on extending tracking capabilities over extended distances, improving the recognition of vehicles from diverse viewpoints.

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Automatic private parking system using license plate recognition and car make and model recognition

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***Abstract*— In this paper we purpose an automatic gate system for parking space entry with authenticity confirmation from 2 individual modules, car make and model and license plate detection. The vehicle detection sensor identifies when cars come to a halt in front of the gate, prompting the camera to snap images of them. The approach used to segment the images in license plate detection is connected component analysis. Connected regions indicate that all pixels sharing a connection are part of the same object or entity within the image. The algorithm for detecting car make and model utilizes feature extraction methods such as the Difference of Gaussians (DoG) detector and the Scale Invariant Feature Transform (SIFT) descriptor. These techniques help identify distinctive visual features of cars, enabling accurate recognition and classification. The Euclidean distance measure is employed to find the most suitable match between a query image and those stored in the database. This comparison aids in determining the car's make and model by assessing the similarity of visual features extracted from both the query and database images. In the final stage, matching algorithms are applied to decide whether the output of the LPR and make and model detection does not conflict with the details stored in database. Access to a parking lot is granted only when specific conditions are met.**

Keywords—license plate detection and recognition, make and model, SIFT

I. INTRODUCTION

Ensuring security is paramount, particularly for accessing restricted premises. Surveillance cameras play a pivotal role by capturing digital records of individuals and vehicles entering the area. Leveraging computer vision and image processing techniques, these images and videos can be automatically analyzed. With the escalating number of vehicles, such technologies offer expedited and efficient solutions to manage security effectively.

Automatic license plate recognition (ANPR) systems have emerged as valuable technology for identifying traffic violations and exerting some control over them. Moreover, they offer added advantages such as theft prevention, access control management, and enhancing overall safety for both individuals and vehicles. ANPR systems have become ubiquitous in various public spaces like parks, shopping malls, and more, contributing to enhanced security and management. Indeed, while ANPR systems offer significant benefits, they may not always be foolproof in recognizing cars, especially in instances where forgery is possible. License plate forgery or alteration can undermine the accuracy of ANPR systems, potentially leading to misidentification or evasion of detection. As such, while ANPR technology is valuable, it's essential to complement it with additional security measures and verification techniques to mitigate the risks associated with forged or altered license plates [1]. Absolutely, relying solely on ANPR systems in high-security areas such as military compounds or governmental organizations poses risks due to the potential for license plate forgery or alteration. Integrating car make and model recognition with ANPR enhances security measures by adding an extra layer of verification. This combination not only strengthens security but also aids law enforcement agencies in investigating criminal activities involving vehicles. Additionally, in certain secure environments like airports or military installations, this technology can be employed to track employees movements, further bolstering security protocols.

In this work we purpose a smart private parking lot based on the functionalities of license plate and car make and model detection. Vehicle detection sensor is employed to detect when cars come to a stop at the gate. Following this detection, two subsequent modules capture the image of the car and conduct the necessary analysis. After extracting information such as the number plate, car make, and model, the system verifies entry by matching this data with details stored in a database. If there's a discrepancy or mismatch in the data, entry is denied as a security measure.

This paper is organized as follows: The second section describes related works, the third section introduced entry gate of the private parking lot, forth section describes purposed solution structure and the last section conclusion of the previously described work.

Figure 1: Prototype of smart gate equipped with computer vision techniques

II. RELATED WORK

Research in the field of Intelligent Transportation Systems (ITS) encompasses various techniques, including

Automatic License Plate Recognition (ANPR) and Automatic Vehicle Make and Model Recognition (AVMMR). These techniques play crucial roles in enhancing traffic management.

A. Automatic License Plate Recognition (ANPR)

The Scale Invariant Feature Transform (SIFT) is a powerful method for describing local image features, extensively utilized in various pattern recognition tasks [2]. Research, such as the work referenced in [3], often relies on SIFT features for their robustness and adaptability to scale and rotation changes in images. However, challenges such as background clutter, variations in illumination, and image blurring can significantly impact the recognition rate of SIFT-based methods. Overcoming these challenges remains a focal point in advancing the effectiveness of pattern recognition systems utilizing SIFT features. In [4], a novel approach utilizing the SIFT algorithm was proposed for license plate localization. This method identifies keypoint features in images, which are then utilized in the matching process between input images and character templates. Recognition is based on the distinct transition patterns among pixels of characters. These unique transition patterns sets of 60 Brazilian license plate images each demonstrated accuracies of 88.33% and 70%, showcasing the effectiveness of the proposed approach in license plate localization and recognition. In [5], a different approach employed a SIFT-based template matching technique for localizing Jordanian number plates. Following localization, Optical Character Recognition (OCR) was applied to recognize the characters within the segmented license plates. This combined approach leverages SIFT for accurate plate localization and OCR for character recognition, offering a comprehensive solution for number plate recognition in Jordanian contexts. In the license plate recognition method proposed by authors of [6], the initial step involves localizing blue color areas in the HSV color space. This method primarily targets the detection of standard Iranian plates. Color and geometric characteristics serve as cues for localizing license plates within the HSV image, which is divided into multiple blocks. Any tilts in the located license plate are addressed using pixel arrangement features, achieving successful detection even at angles of up to 45 degrees. In the character recognition stage, normal factoring with a similarity measure is applied, resulting in an impressive accuracy of 97%. In [7], ANPR system tailored for Indian license plates was developed, employing the template matching technique for character recognition. The segmentation stage proposes utilizing either rectangular projection of the number plate or an alternative template matching method. However, it's noted that testing was conducted on a very limited dataset consisting of only 8 images, encompassing variations in shape, illumination, view angle, distance, etc. This indicates the need for further evaluation and validation on a more extensive and diverse dataset to assess the system's robustness and generalizability.

In [8], the ANPR system employs Fourier transform to detect the inherent spatial frequency of characters in a license plate. After localizing the plates using Fourier analysis, characters are segmented based on connected components, and recognition is performed using Support Vector Machines (SVM). This approach utilizes Fourier analysis for effective plate localization and SVM for accurate character recognition, showcasing a comprehensive methodology for ANPR systems.

In [9], the license plate recognition task is tackled using the You Only Look Once (YOLO) deep learning framework. With 7 convolutional layers, the system achieves around 98.22% accuracy for license plate detection and 78% for recognition. Traditionally, ANPR systems were commonly implemented on PC-based platforms due to their processing power, enabling the handling of high-quality images within shorter timeframes. However, there's a growing trend towards considering mobile-based platforms for ANPR, indicating a shift towards more versatile and accessible solutions for automatic number plate recognition. Authors of this study [10] introduces a method leveraging a deep learning framework employing the YOLOv5 architecture to enhance car license plate recognition. To assess the efficacy of this approach, the researchers generated a custom dataset and conducted thorough experiments involving training, validation, and testing processes. This comprehensive evaluation allows for a robust assessment of the proposed method's performance and its potential for improving license plate recognition accuracy. Authors of [11] employed the YOLOv7 object detection model for effectively detecting vehicles, access badges, and license plates. Also, its adaptability allows it to be used in different countries by retraining the object recognition model to recognize the respective LPs, access badges. Despite its effectiveness, the Shine system has its limitations.

This paper [16] follows a systematic approach consisting of five steps for license plate extraction: image pre-processing, license plate location, background color recognition, character segmentation and character recognition. Using KNN like template matching technique they are recognizing Arabic number with high accuracy and makes the identification closer. They are archived a plate extraction and background color accuracy as 97.78%, Arabic number recognition with OCR as 45.56%, and with KNN as 92.22%.

B. Automatic Vehicle Make and Model Recognition (AVMMR)

Zafar et al.'s approach, as described in reference [12], presents a 2D Linear Discriminant Analysis (LDA) method for the recognition of car make and model. Their experimentation revealed that this approach outperformed Principal Component Analysis (PCA). This suggests that for the specific task of car make and model recognition, the 2D LDA method yielded superior results compared to PCA. In reference [13], a hierarchical classifier was introduced, initially determining the class of the vehicle and then proceeding to recognize the make and model within a smaller group. Their algorithm achieved an impressive accuracy of 96% on a dataset consisting of over 280 back view images of vehicles. Additionally, the algorithm demonstrated robustness to various environmental conditions such as illumination and weather changes. This highlights its effectiveness in real-world scenarios where such conditions can significantly impact performance. In [14], vehicle model recognition leveraged the geometry and appearance of car emblems within rear-view images. They employed a linear

Support Vector Machine (SVM) binary classifier with Histogram of Oriented Gradients (HOG) features. Impressively, their approach achieved an accuracy of 93.75% on a dataset comprising 1342 images representing 8 car makes and 28 distinct car models. This underscores the effectiveness of utilizing emblem information for accurate vehicle model recognition, even amidst a diverse range of car makes and models. Authors of [15] purposes a new large-scale vehicle make and model recognition dataset, DVMM which covers the most popular cars available in Europe market. The DVMM dataset encompasses vehicle images with diverse colors, captured from various viewpoints, and under a multitude of conditions, including different camera types, image resolutions, illumination conditions, and background settings. To address the challenges posed by this variability, a novel deep-learning-based Vehicle Make and Model Recognition (VMMR) framework, termed 2B–2S, has been proposed. This framework adopts a two-branch processing approach and a two-stage network training strategy, aiming to enhance the model's robustness and accuracy across the wide range of conditions present in the DVMM dataset. The authors of [17], purposed a solution with a smart camera equipped with ANPR, AVMMR, and color recognition capabilities is described. Therefore, the make and model recognition component utilizes a Scalable Vocabulary Tree (SVT) constructed from Speeded Up Robust Feature (SURF) descriptors. SVT offers an efficient and scalable approach for recognizing vehicle makes and models based on these descriptors. In [18], the research delves into the efficacy of integrating various local feature point detectors with the SIFT descriptor. The study scrutinizes the performance of these combinations across four distinct databases. Through experimental analysis, the study reveals notably superior recognition rates achieved by the combinations of SIFT with Difference of Gaussians (SIFT-DoG), SIFT with Multiscale Hessian, and SIFT with Multiscale Harris. These findings highlight the effectiveness of these particular combinations in enhancing recognition accuracy across diverse datasets.

In paper [19], authors employed frontal view vehicle images and implemented a deep learning architecture based on SqueezeNet for the development of an AVMMR system. Through extensive experimentation conducted on a dataset comprising over 291,602 images encompassing 766 classes, the system achieved an impressive accuracy of 96.33%. This underscores the effectiveness of utilizing deep learning approaches, particularly the SqueezeNet architecture, for accurate and robust vehicle make and model recognition tasks, even when dealing with a large number of classes and diverse image variations.

The authors of this project [25] have developed a License Plate Recognition (LPR) system that achieves a high recognition rate without requiring high-quality video signals from expensive hardware. They also address the challenge of car make and model recognition, enabling the search of surveillance video archives using partial license plate numbers combined with visual descriptions of vehicles.

III. Entry gate of private parking lot

In [20], an automatic gate system was proposed to manage entry control at a building gate. This system operates on a patch-based matching process, where a segment of the incoming vehicle's image, referred to as a "patch," is compared with vehicle images stored in a database. This matching process enables the gate system to authenticate the identity of vehicles seeking entry by comparing their visual characteristics with those in the database. This approach ensures secure and efficient access control, allowing only authorized vehicles to enter the premises while preventing unauthorized access. The gate control system [21] utilizes the LPD information for giving staff permissions for campus entry. The authors of [22] developed an intelligent garage system which is uses the matching information of face recognition and license plate recognition to store and retrieve cars. In [23], the development of an automated gate system was observed to rely solely on license plate recognition (LPR) technology. In the system outlined in [24], a comprehensive approach is adopted, incorporating automatic license plate recognition (ALPR), vehicle make and model detection, and under vehicle inspection technologies. By combining these methods, the system aims to mitigate the limitations inherent in individual techniques and enhance security in vehicle inspection processes.

Combining license plate recognition with vehicle make and model recognition significantly bolsters security, enabling the creation of highly secure automatic gates at entrances to restricted areas such as private parking lots, airports, military bases, campus entries etc. This fusion enhances access control, improves security screening, streamlines management, and enables comprehensive monitoring of vehicle movements, ensuring heightened security and safety within the premises. The potential benefits of using purposed system are:

- Implementing screening procedures such as manual identity card checks can lead to reduced waiting times, also provides an opportunity to gather additional information about individuals entering the parking lot.
- Collecting statistical data regarding the types of visitors and the car models used provides valuable insights into parking lot usage.
- Categorizing incoming individuals, staff, and guests allows for efficient management of parking spaces by allocating appropriate slots for each category based on their specific needs and priorities.

IV. Solution structure

Purposed system structure is depicted in the Figure 2.

A. Preprocessing phase

Dataset of all registered cars is used in the implementation and testing of our prototype. In the preprocessing of real-time captured images, the initial steps involve converting the image to grayscale and removing noise through median filtering. Subsequently, binarization is applied, followed by connected component analysis, to identify target license plates based on their distinct structural properties (Figure 3). The process of extracting Regions of Interest (ROI) involves identifying specific areas around the headlights, upper and bottom grills of the vehicle. These regions encapsulate discriminative information crucial for recognizing car makes and models. An example of the selected ROI from a sample image is illustrated in Figure 4.

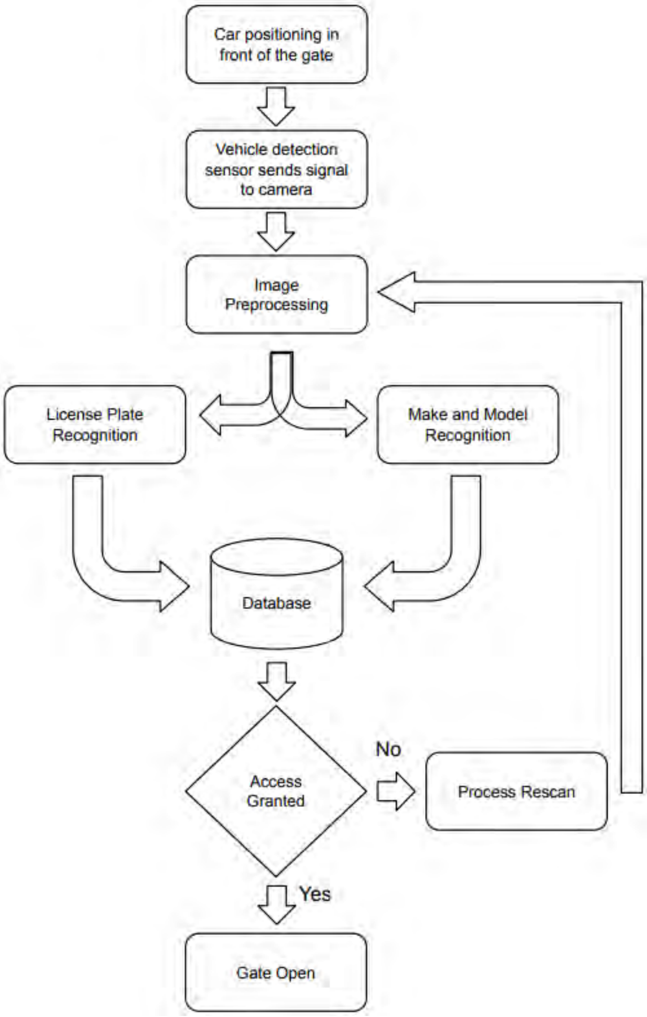

Figure 2: Purposed prototype of the parking lot system

Figure 3: License plate extracted

Figure 4: ROI representation for make and model recognition

B. License Plate Recognition

The segmentation of images employs Connected Component Analysis, where connected regions indicate that all connected pixels belong to the same object. Two pixels are considered connected if they share the same value and are adjacent to each other. This approach enables the identification of distinct objects or regions within the image based on their connectedness and pixel values. Output of the preprocessing phase, is provided as input to the next step and Connected Component Analysis (CCA) is applied on this image to bound the characters in plate. Once each character is identified during the character segmentation process, it is appended into a list. This list serves as a collection of individual characters extracted from the license plate image, facilitating further processing such as character recognition. Character extraction from the license plate is specifically tailored to read Macedonian formats. This entails designing methods are optimized for detecting and isolating characters present in Macedonian license plates. Customization ensures accurate and efficient recognition of sequence characters and numbers from Macedonian license plates, contributing to the overall effectiveness of the license plate recognition system.

C. Make and Model Recognition

The AVMMR system as described in [18] utilizes the following process:

- Detect interest points using DoG method.
- Extract SIFT descriptors from these keypoints.
- During training, compute SIFT features from images of various car make-models.
- Match query descriptors to prestored descriptors using Euclidean distance.
- Identify the best match based on the smallest distance, determining the make and model of the car.

Therefore, we made tests using the Stanford dataset, fine-tuning a ResNet-152 model specifically for European cars under various lighting conditions corresponding to different daily time slots. This dataset consists of 16,185 images representing 196 classes of cars. The data is split into 8,144 training images and 8,041 testing images, with each class roughly evenly distributed between the training and testing sets. This approach allows for comprehensive evaluation and validation of the model's performance across different lighting conditions and car classes, ensuring robustness and accuracy in car recognition tasks. We evaluated the recognition of 42 common make-model combinations found in both the dataset and the cars typically seen in Macedonia.

Table 1: Car make and number of models tested

Car Make	**Number of Models**
Audi	4
BMW	3
Mercedes	4
Skoda	4
Opel	5
Ford	3
Toyota	4
Kia	3
Fiat	2
Seat	3
Golf	4
Hyundai	3

The experiments were conducted using the samples listed in Table 1. The Region of Interest (ROI) was identified as the frontal area encompassing headlights and grills. Subsequently, all images were resized to maintain uniform dimensions. The outcomes of these experiments indicate that the best performance is observed when we are testing with the brightest images summarized in Table 2.

Since the system functions as a private parking lot, only authorized entities are permitted entry. Upon verification through LPR and cross-referencing with the database for car make and model, access is granted or denied based on credentials. If access is denied, the system allows three consecutive scans of the LPR and car make and model to mitigate potential weather deviation or system weakness. Following the third failed scan, a message will be displayed stating "Access denied for vehicle xxx with license plate yyy." (Figure 5).

Table 2: Accuracy depending on image lighting

	Accuracy (%)		
Car Make	**25% lighting**	**50% lighting**	**100% lighting**
Audi	65.32	67.17	69.09
BMW	66.45	68.3	70.22
Mercedes	66.85	68.7	70.62
Skoda	67.87	69.72	71.64
Opel	69.75	71.6	73.52
Ford	64.58	66.43	68.35
Toyota	63.24	65.09	67.01
Kia	67.54	69.39	71.31
Fiat	66.57	68.42	70.34
Seat	69.36	71.21	73.13
Golf	64.21	66.06	67.98
Hyundai	60.35	62.2	64.12

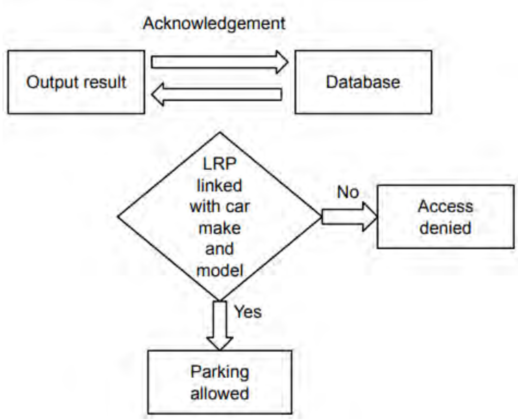

Figure 5: Car verification procedure

V. CONCLUSION

We introduced a real-time automatic gate system by integrating car make and model recognition with license plate recognition. Deploying such a gate can significantly reduce human effort and enhance security in the designated area. The expedited authentication process helps mitigate traffic congestion that may occur due to manual screening or the use of card readers.

Integrating car make and model recognition together with license plate recognition in private parking systems can ensure that only authorized vehicles are granted access. This helps in preventing unauthorized vehicles from entering restricted areas, enhancing overall security. That means significantly reducing the risk of spoofing attempts where individuals try to gain unauthorized access to a parking lot by transferring license plates to other vehicles. Because of that reasons we implement conditional check following license plate verification with the associated make and model of the vehicle. By making access conditional on both, the system becomes more resistant to spoofing attempts. Even if someone were to transfer a license plate to another vehicle, the mismatch between the make and model and the expected data would trigger an alert, preventing the system for unauthorized access.

Absolutely, this system can be readily adapted to high-security areas due to its robustness and effectiveness in controlling access and enhancing security measures. Whether it's international airports, military bases, government facilities, or other sensitive locations, the integration of car make and model recognition with license plate recognition offers a comprehensive and reliable solution for access control. Its ability to minimize human intervention while maximizing security makes it an ideal choice for safeguarding high-security areas.

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System for Visual Graphic Animation and Recognition of Macedonian Sign Language Using Machine Learning and 3D Visualisation Tools

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***Abstract* — The global difficulty encountered by hearing impaired persons around the world, including Macedonia, is limited access to adequate communication methods in education, media, and social activities. Deaf and hard of hearing persons rely on sign language as their major mode of communication, particularly with one another, yet they still encounter problems in their daily lives and interactions with others. Communication obstacles arise in a variety of contexts. The primary purpose of this research is to create a software system for standardising the Macedonian sign language (MSL) and automate its presentation and translation. The same approach is applicable to all languages around the world. In this paper, we present a promising 3D visual translation and classification tool for MSL. The limitations of the dataset introduce weaknesses in the overall results. However, the system's main goal is to enable and improve communication, ease the process of learning sign language, and offer visual tools in education and media for the hearing-impaired, which our approach facilitates.**

Keywords— Motion Capture System, Human Pose Estimation, Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs)

I. INTRODUCTION

Due to barriers to communication and limited participation in different sectors of life, the lives of hearing-impaired individuals in Macedonia are difficult, [1]. Their social integration, community involvement, and personal growth all depend on effective communication. A vital component in maintaining communication with the outside world is sign language, a system of natural language, [2].

In this paper we create a visual interpreter of Macedonian sign language (MSL), aimed at increasing the ease of communication and access of hearing-impaired individuals to knowledge by providing information in a suitable and understandable fashion. Therefore, the system is crucial in enabling education, breaking down social boundaries, and fostering general interpersonal contact. This also represents the main reason for the research, i.e. enabling deaf and hard of hearing persons to communicate through MSL should be a top priority in our society.

An inventive step toward enhancing communication and integrating hearing-impaired people into society's everyday operations is the use of visual interpreters in the media and in educational settings, [3]. With the addition of a 3D interpreter and models for identification and categorisation of signs, the software system for the standardisation of MSL will work to enhance communication and the integration of hearing-impaired individuals into various societal groups.

We consider and address two primary research ideas. Firstly, we develop machine learning (ML) models for recognition and categorisation of MSL, and secondly, we build a 3D interpreter as means of MSL standardisation.

The rest of the paper is organised as follows: Section II summarises the related work, Section III explains the experimental setup, and Section IV presents and elaborates the results, while Section V concludes the paper.

II. RELATED WORK

Researchers have developed unique computer vision approaches that increase the accuracy of 3D human pose estimation [4] and Sign Language Generation (SLG) [5] by using advanced modelling techniques adjusted to the complexities of human motion and gesture.

The authors of [6] introduce an innovative approach for 3D human pose estimation that processes the focus on directly regressing 3D joint positions and toward estimating bone lengths and orientations. They introduce a fully-connected residual network by dividing down the task, which leverages data from every frame in the film to forecast bone lengths. They also create a completely convolutional architecture with lengthy skip connections for hierarchical bone direction prediction. A more precise human pose estimation is obtained through this dual technique, which effectively provides an intermediate image that links the gap between 2D key points and 3D joint positions. In addition to establishing the framework for future studies to improve the combination of bone length and direction prediction for a more precise 3D human pose estimate, their approach emphasises the significance of investigating specific learning representations specialised to the particular anatomy of the human body.

Sign Language Generation (SLG) presents a unique challenge in computer animation since it involves the need to precisely record complicated hand gestures. Traditional procedures, as represented in [7], require costly equipment and manual labour. The study provides a first in the field: an automated SLG method that generates avatar sign postures from basic RGB photos. This approach develops a 3D pose model, SignPose, using an animated dataset of Indian Sign Language (ISL) signs and 2D pose estimation, compared to existing 3D pose estimation models that have difficulties with the unique motions of sign language. Utilising quaternions for output representation, the method entails expanding the dataset by employing "pseudo-signs" and simplifying the architecture to meet the requirements associated with the task. In SLG, SignPose performs more effectively than present models, yielding output that is more realistic and precise enough to be utilised with human avatars. The model and dataset are both publicly available to encourage additional study.

Both methods give an important step forward and emphasise the need for customised representations and structures corresponding to human anatomy's unique peculiarities and sign language motions.

III. EXPERIMENTAL SETUP

A. Dataset overview and preparation

The dataset utilised in this paper for implementing classification models and generating 3D animation is composed of videos in MSL. The video content was sourced from two free main online platforms via web scraping techniques: the website “TALKING HANDS”[8] which provides videos for each letter and word in MSL, and a YouTube channel named “We Learn Sign Language - Children's Educational Program” [9] dedicated to sign language content. Each video in the dataset represents an interpretation in MSL, performed by certified interpreters. The dataset includes videos corresponding to various letters of the Macedonian alphabet, with each letter being represented by a different number of videos.

The duration of each letter may vary depending on the interpreter, resulting in videos of varying lengths. This variability in video length introduces a challenge in processing and standardising the data for ML tasks implemented in later stages.

Table 1 Dataset overview of MSL

Letter	Number of videos
letter_2	10
letter _3	7
letter _4	10
letter _5	9
letter _6	12
letter _7	7
letter _8	7
letter _9	7
letter _10	9
letter _11	8
letter _12	11
letter _13	5

Table *1* illustrates the distribution of video material among different letters of the Macedonian alphabet. It reveals that Letter_6 has the most videos (i.e., 12), while Letter_13 has the fewest (i.e., 5). Most letters have 7 to 10 videos, suggesting a reasonably balanced sample. This distribution is essential to train and evaluate models for sign language recognition. It is important to note that only certain letters of the alphabet were selected for Table *1* due to brevity, and the selections clearly showcase the distribution of the data as remaining letters fall within the scope of Letter_6 and Letter_13.

B. Techniques used for standardisation of the MSL through the building of a 3D interpreter

MSL codification using a 3D interpreter requires overcoming mocap system challenges, integrating use of human posture estimation advantages and implementing advanced deep learning algorithms. This section provides an extensive review of different approaches.

a. Challenges of Motion Capture System

Motion capture (MoCap) innovations are essential for effectively capturing the precise gestures required for MSL interpretation, but they present numerous challenges. These technologies have to coordinate the complex patterns of sign language motions, such as fingerprinting and facial expressions, which demand a high level of precision. However, difficulties such as occlusions, where the hands overlap or move in front of the body, may prevent accurate detection. The preparation and training of MoCap systems involve multiple cameras and sensors to be exactly coordinated, keeping the process expensive and technically demanding. Additionally, raw data often comes with noise that requires major processing, expanding the complexity and the potential for error in animating a 3D avatar, therefore could restrict scalability for a wider audience.

b. Benefits of Human Pose Estimation

The implementation of human pose estimation for MSL interpretation and standardisation becomes a desirable choice considering its many benefits over motion capture techniques. Pose estimate is significantly more available and scalable than motion capture that monitors movement with specialist equipment. Considering it doesn't require an individual to be equipped with sensors or be in a controlled environment, this technology is less restrictive and allows for more natural independence and adaptability in many circumstances. Furthermore, real-time functionality of human position estimation results in it being perfect for real sign language interpretation, where immediate feedback is required. Following that, these joints are connected to form a skeleton model which represents the movement and locations of the parts of the body toward time. The data can be analysed in two ways: in 2D, that focuses on coordinates within the image plane, or in 3D, that includes depth information and offers a more precise and comprehensive representation of gestures. Afterwards, a 3D avatar is animated employing this skeleton model to ensure it matches the signing individual's extremely accurate motions and gestures.

c. Utilisation of deep learning techniques for 2D and 3D human pose estimation

In systems like sign language interpretation, deep learning techniques like Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) provide significant advances in human pose estimation. CNNs successfully extract spatial features, enabling for the specific recognition of critical locations such as hands and fingers in both 2D and 3D spaces. The temporal sequence of gestures is processed by RNNs, which might be GRUs or LSTMs, and is required for suitable representation. These techniques are scalable, using video data without a requirement for specialised equipment, thus making them for real-time processing. They often demand large, annotated datasets for training that may be time-consuming to collect, especially for less common sign languages. BlazePose and other human pose estimation systems are useful in making 3D animations because they accurately capture and analyse human movements from 2D video inputs.

C. The construction of an ML model for the recognition and categorisation of MSL

a. Video Classification with a CNN-RNN Architecture

In this paper, we address the challenge of video classification in the larger context of sign language recognition, with a particular emphasis on the MSL dataset. The primary objective is to develop an effective video classification model that can precisely represent both spatial and temporal information. Utilising the advantages of recurrent neural networks (RNNs) for temporal sequence analysis and convolutional neural networks (CNNs) for spatial processing, we implement a combination of CNN-RNN architecture to accomplish this.

The dataset consists of up of multiple videos demonstrating diverse sign language gestures; each video is an organised series of frames. We begin by creating frames from these videos with OpenCV, then apply preprocessing techniques such cropping and scaling. To extract significant spatial features from these frames, we utilise the InceptionV3 model, a cutting-edge CNN that was previously trained on the ImageNet dataset. This model provides us with detailed spatial representations from video frames that are required for accurate classification.

After generating the spatial information, we implement a gated recurrent unit (GRU) layer—a type of RNN that is efficient at detecting dependencies throughout time steps—to address the temporal part of the videos. The extracted features and labels have been created for model training by transforming the videos into fixed-length sequences, padding if required and encoding the labels into numerical format

Our testing environment includes developing the CNN-RNN model on the MSL dataset, with the emphasis on optimising the model's performance using optimal training parameters such as batch size and number of epochs. We discuss the consequences of these results, comparing them with current approaches and recommending directions for further investigation, like trying out alternative RNN models or analysing additional data sets.

IV. RESULTS

This section will present the measurements results from the experimental setup described in Section III.

A. Implementation of 3D avatar generation

This section of the paper describes the development of an automated framework for creating 3D animations of MSL represented on Fig. 1. The process begins with inputting an RGB video, which is analysed and split into individual frames.

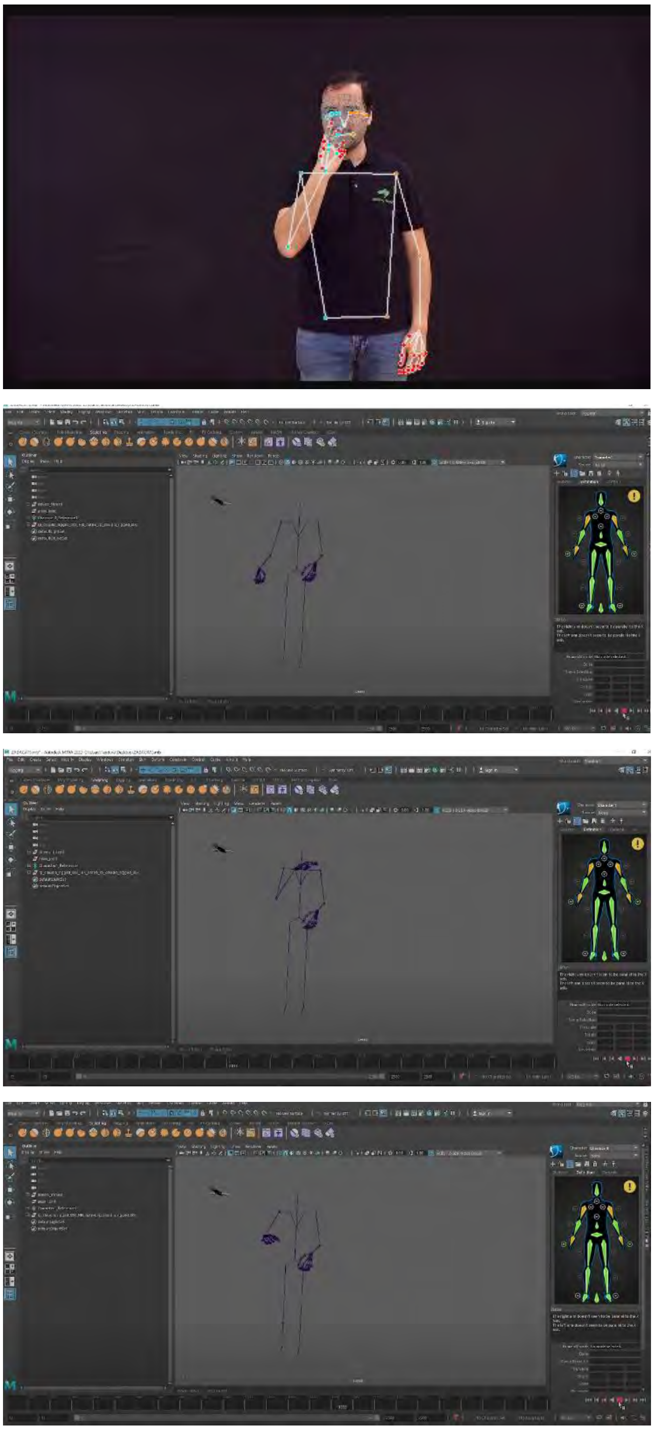

Fig. 1 The results of pose estimation, using the BlazePose algorithm, are illustrated in the first image. The remaining three frames show the output of the video.

Then, the images are processed with BlazePose or other 3D pose estimation methods, which generate joint coordinates. These coordinates are normalised and ordered to align with the skeletal structure in the 3D software Maya. Fig. *1* shows one such example. By fully automating the process, the system produces a standard .fbx file that can be directly used for animation in Maya, although manual review and adjustment of the animation are recommended due to potential deficiencies in the output data from the pose estimation methods.

B. Evaluating results from video classification with a CNN-RNN Architecture

The sequence model created for this paper leverages Gated Recurrent Units (GRU) to deal with the temporal changes of video material that has been pre-processed with Convolutional Neural Network (InceptionV3) to extract 2048-dimensional feature vectors. The model is made up of two GRU layers: the first, with 16 units, has been configured to produce sequences, while the second, with 8 units, is responsible for constructing the final hidden state. The GRU layers are followed by a dropout layer with a rate of 0.4 to minimise overfitting, an 8-unit dense layer that uses ReLU activation, and a final 12-unit dense layer that uses a softmax activation to produce class probabilities.

The model is optimised using Adam, constructed with the **sparse_categorical_crossentropy** loss function, and evaluated on accuracy. The model keeps the model with the greatest performance based on validation loss throughout training, which lasts for ten epochs with a thirty percent validation split. The trained model has a test accuracy of 8.33%.

The model's architecture, represented on Fig. *2*, shows 99,972 trainable parameters, representing that it can gain knowledge from the data. However, the test accuracy is only moderately accurate, indicating that there may be an opportunity for improvement.

Layer (type)	Output Shape	Param #	Connected to
input_layer_6 (InputLayer)	(None, 20, 2048)	0	-
input_layer_7 (InputLayer)	(None, 20)	0	-
gru_4 (GRU)	(None, 20, 16)	99,072	input_layer_6[0][0], input_layer_7[0][0]
gru_5 (GRU)	(None, 8)	576	gru_4[0][0]
dropout_2 (Dropout)	(None, 8)	0	gru_5[0][0]
dense_4 (Dense)	(None, 8)	72	dropout_2[0][0]
dense_5 (Dense)	(None, 12)	108	dense_4[0][0]

Total params: 99,828 (389.95 KB)
Trainable params: 99,828 (389.95 KB)

Fig. 2 Model Architecture for Video Classification Using a CNN-RNN Approach

This result could be the result of several factors. The dataset could present unique challenges because of the complexity of the MSL gestures, the diversity of the video content, or the small number of participants, as the detailed structure of MSL motions and the fluctuation of video content, which might impact model performance. Furthermore, a limited or low-quality dataset can negatively affect the model's capacity to generalise successfully because it may not fully capture real-world variations, resulting in lower accuracy. This can lead to less reliable feature vectors and, as a result, worse model performance.

Furthermore, the model's capacity, with only 16 and 8 units in the GRU layers, may be insufficient to handle the task's complexity. The dropout rate, coupled with a relatively small network, could affect the model's ability to learn robust features. Further research is essential for improving performance, such as experimenting with deeper or more complex models, changing the number of units in the GRU layers, increasing the dataset size, or using data augmentation approaches. Adjusting the learning rate and other hyper parameters, or investigating alternative architectures such as LSTMs or attention techniques, may also lead to better results.

V. CONCLUSION

Communication for deaf and hard-of-hearing individuals is a significant challenge in Macedonia, necessitating various methods for learning MSL and facilitating communication for people with hearing impairments within society. This paper presents a visual interpreter for MSL that helps individuals with hearing impairments overcome the barriers and obstacles they face in daily life. The visual interpreter simplifies the process of learning MSL, assisting people with hearing impairments in continuing their educational process. Introducing the visual interpreter in all areas of daily life would provide quick access to information for people with hearing impairments, helping them overcome communication barriers in all aspects of everyday life. The goal and our future work is creating a 3D application with integrated pose estimation techniques and classification models for active use, aiming for a successful representation of sign language through 3D animations and models with precise recognition and classification.

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Assistive Keyboard for Children With Ataxia

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***Abstract*—Ataxia is a neurological condition characterized by a lack of voluntary coordination of muscle movements, significantly affecting fine motor skills, making everyday tasks such as writing challenging [1]. This paper introduces an innovative split assistive keyboard designed specifically for children with ataxia to improve their typing skills and overall computer interaction. The keyboard features an ergonomic split design, allowing for custom positioning that aligns with the user's natural hand separation and movement. The keys are also larger than those on standard keyboards, reducing the precision required for keystrokes.**

***Keywords*—ataxia; assistive technology; split keyboard design; ergonomic keyboard; children with developmental disabilities; digital inclusion;**

Fig. 1. Split Assistive Keyboard.

I. Introduction

In the field of assistive technology, the quest to create inclusive tools that meet the diverse needs of users with disabilities has led to the development of innovative solutions that bridge the gap between individuals' limitations and potential. One such advance is the design of a split assistive keyboard specifically tailored for a child with ataxia–telangiectasia, a neurological disorder that significantly impairs voluntary muscle coordination [2]. Individuals with ataxia are challenged in performing tasks that require fine motor skills, such as writing, which is an essential skill in today's digital-centric world. Recognizing the unique difficulties these children face, the split assistive keyboard emerges as an assistive tool designed to ease the typing experience while also enabling greater comfort and efficiency.

This assistive keyboard is distinguished by a split design, allowing each half to be positioned according to the natural placement of the user's palms and hands, reducing the coordination effort normally required by standard keyboards [3]. This ergonomic thinking is crucial for children with ataxia, as it accommodates their limited control over muscle movements, allowing them to more effectively operate computers and digital interfaces. This keyboard is precisely crafted to meet the specific needs of its users. Offering a mix of customization, ease of use, and assistive technology, the split assistive keyboard is a testament to the power of assistive devices in transforming the lives of people with disabilities, providing them with the tools they need to communicate, learn, and thrive in the digital age.

II. Design

The design of the split assistive keyboard for children with ataxia involved a comprehensive examination of its ergonomic features, adaptability and technology integrations tailored to meet the specific needs of children who face challenges with motor coordination.

The split design is a feature that addresses the natural hand separation and positioning of users. Unlike traditional keyboards that force the user to adjust their hands to a fixed layout, a split keyboard allows for adjustment to comfortably fit the user's hand span and range of motion. This adaptability is crucial for children with ataxia, as it minimizes the effort required to touch the buttons and significantly reduces muscle strain and fatigue [3].

Button sensitivity and size are adapted to the limited control of motor functions characteristic of ataxia. For these reasons, mechanical key switches are best suited for sensitivity, ensuring that minimal force is required to register a keystroke, accommodating users with varying degrees of muscle strength and control [4]. The increased button size reduces the need for precision, making it easier for children to press the correct buttons.

The design prioritizes usability, durability and accessibility, with settings and adjustments that are easy to navigate. The aim is to encourage children with ataxia towards independence and confidence in using technology for communication and learning. From Fig. 2 it can be noted that different buttons have

FEEIT, INNOFEIT, FEEIT-FABLAB, JLAB

Fig. 2. Button layout and visual indicators.

different visual indications. The keys are grouped in different colors according to the categories: vowels - in red, consonants - in green, punctuation marks and numbers - in yellow and function keys - in blue. Such a visual indication enables faster navigation on the keyboard, which, unlike the monotonously colored ones, and according to our tests, reduces the search time by 1 to 2 seconds where ataxia is present.

III. Making of the Case

The durability and long-term structural integrity of a split assistive keyboard designed for a child with ataxia is an important feature. The unique demands placed on assistive devices—especially those intended for children with motor control challenges—require careful consideration of materials, design principles, and manufacturing techniques. For these reasons, the most appropriate choice for making a keyboard case is with a 3D printing machine, which is suitable for low-cost prototyping and low-volume production [5].

The choice of material significantly affects the durability and safety of the keyboard. For children with ataxia, materials must be non-toxic, hypoallergenic and robust. Thermoplastic polymers such as ABS (acrylonitrile butadiene styrene) and PLA (polylactic acid) are common choices for 3D printing due to their structural strength and ease of printing [6]. In our case, PLA polymer proved to have satisfactory characteristics. For parts that require more flexibility or impact resistance, TPU (Thermoplastic Polyurethane) can be used, especially in areas that are subject to frequent movement or pressure [7].

When designing a keyboard, the physical stress that will face during use must be considered. This includes taking into account the force of pressing the buttons, the possibility of drops or shocks and the stress on the connectors. Rounded corners can reduce stress concentrations that lead to cracks during a fall, and also reduce the risk of injury due to sharp edges.

In 3D printing, the orientation of a print substrate part and the settings used can affect its mechanical properties. Sections are generally stronger in the X and Y directions (along the substrate plane) than in the Z (height) direction [8]. Thus, critical components that will bear greater load or stress should be oriented to maximize strength in the required directions. Optimizing print settings to ensure good layer adhesion further improves the durability of printed parts.

Considering the individualized needs of children with ataxia, parts of the keyboard can be adjusted for ergonomics and ease of use. These parts were designed with modularity

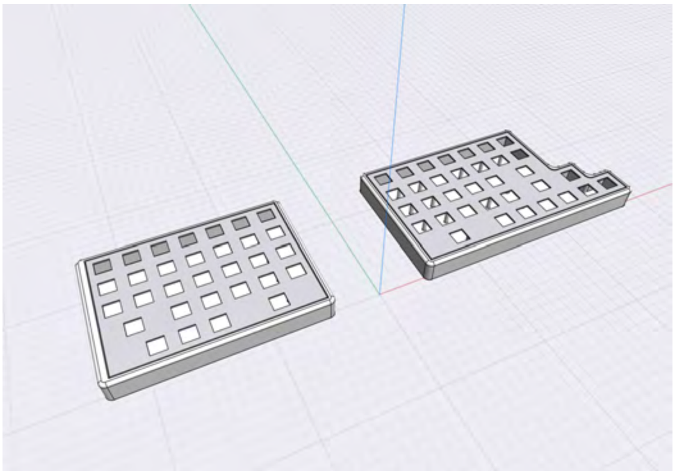

Fig. 3. Case design.

in mind, ensuring that they can be replaced without compromising the overall structural integrity of the device. Also, the height, width and weight of the same should be observed, in order to obtain the necessary ergonomics. This approach not only extends the life of the keyboard, but also allows for changes depending on the needs of the user over time.

The design of the keyboard should facilitate easy assembly and disassembly, allowing maintenance and replacement of parts. Screws are recommended as opposed to glued connections, as they allow parts to be replaced or tightened if necessary. Modular designs can also allow the keyboard to be customized or reconfigured based on the user's evolving needs. The non-slip bases prevent the two halves from moving during use, which is especially important for users with ataxia who may perform erratic movements. The lightweight and compact design improves portability, allowing the user to easily transport the keyboard between different environments such as home and school.

IV. Hardware and Software

Creating an assistive keyboard requires careful consideration of the unique hardware and software needs that meet the specific challenges these users face. Before making these kind of keyboards, it is necessary to study the hardware and software limitations in detail before making a final decision. In our process, due to the limitations, the Arduino model Arduino Micro, which is suitable for the QMK software library, were chosen as the appropriate microcontrollers.

The hardware consists of mechanical switches, on which the buttons with a larger non-standard dimension are placed. They are connected in a matrix configuration, and the communication protocol between the two halves is serial (bit banging). In our case, the first half has 5 rows and 7 columns, and the second half has 5 rows and 9 columns. When binding keys, each key should be associated with the corresponding row and column. For example, the key "A" will correspond to matrix position *[1][1]*, i.e. row 1 and column 1.

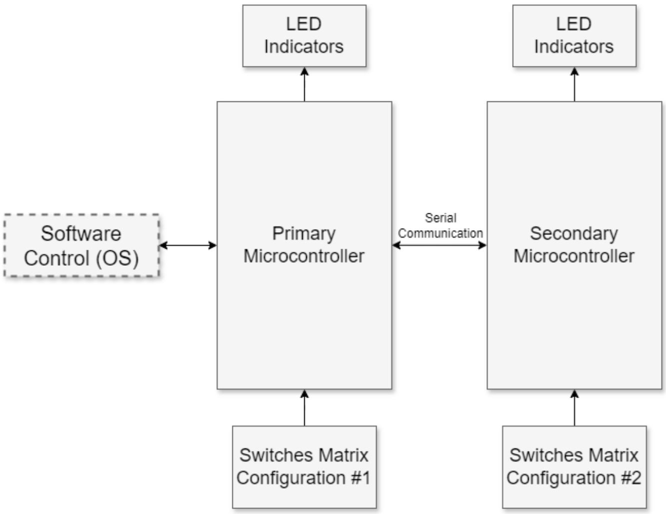

Fig. 4. Block schematic diagram.

From Fig. 5 you can see that we have added a diode to each button. The diodes are added in order to be able to press 2 or more buttons simultaneously without damaging the microcontrollers or causing a disturbance in the software.

When connecting the rows and columns to the microcontrollers, it should be noted which pins are the easiest to connect to the columns and rows, so that the wires are neatly arranged. It is also very important to note which pins are critical for serial or I2C communication (these are usually pins D0, D1, D2, D3 of the microcontroller).

The keyboard's open-source software (the QMK library) provides options for customizing and adjusting the key layout, sensitivity settings, and feedback mechanisms to suit individual preferences and needs. This level of customization ensures that the keyboard can adapt to the user's evolving skills and preferences over time.

It is important to note that the QMK library uses the microcontroller's ports, not the board's labels. For additional functionality, such as LED control, the QMK library has options that should be declared in the info.json file with the appropriate pin.

The software is designed to be compatible with various operating systems and digital platforms with the USB protocol, ensuring seamless integration with educational software, games and communication tools. This compatibility maximizes the keyboard's usefulness, making it a versatile tool for learning and everyday use.

V. Testing and Validation

Before finalizing the design, it is crucial to conduct rigorous testing to ensure that the keyboard meets the necessary requirements for strength, functionality and durability. This testing should simulate real-world use, including repeated keystrokes, shocks, and bending. Feedback from these tests can guide further design improvements, ensuring that the final product is both durable and functional.

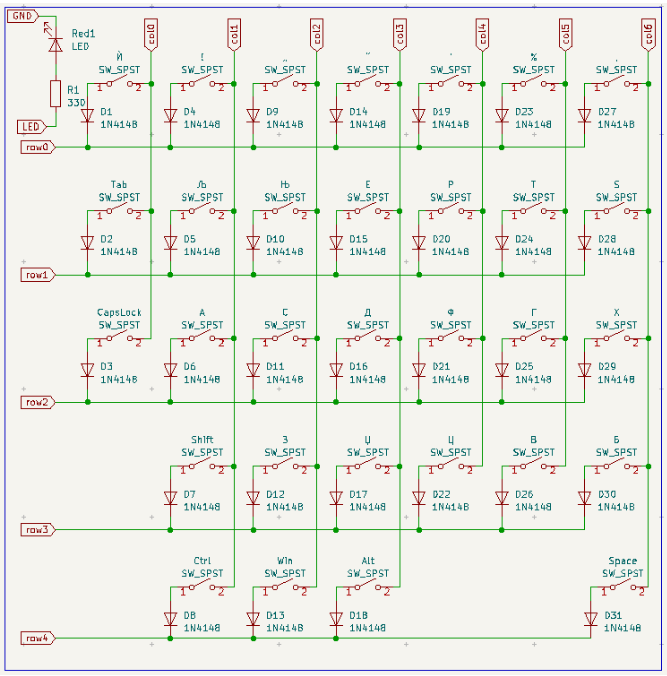

Fig. 5. Connection of mechanical switches.

For our case, we performed extensive tests on the consistency and reliability of the actuations, ensuring that minimum and variable pressure inputs are accurately registered. We subjected the keyboard to rigorous usage scenarios, strong and repeated keystrokes, to assess the durability of the keys and switches. With this we concluded that the model of the button holder was not suitable, so we revised and reinforced it in the second iteration of the printing process.

We've performed drop and physical stress tests to evaluate the keyboard's structural integrity, ensuring it can withstand accidental impacts. During this test, we found weaknesses in the placement and looseness of the hardware, which were adjusted and now work flawlessly.

We also tested the keyboard for long-term comfort through extended typing sessions, paying close attention to user feedback on hand and wrist strain. Apart from children with ataxia, the keyboard was also found to be comfortable for people without health disorders, where typing turned out to be more natural on a separate keyboard, without difficulty after a little training and maintaining a healthy sitting position. This allows us to evaluate the adaptability of the split design to promote a natural writing posture and reduce the effort required to write [3].

We've tested the keyboard's compatibility with different operating systems and devices to ensure broad accessibility. All relevant safety standards for electronic devices, for electrical safety and toxicity of materials, especially those intended for use by children, were observed.

VI. Conclusion

In conclusion, the development, testing and validation of a split assistive keyboard designed for children with ataxia represents a significant step forward in creating accessible and assistive technologies. Through meticulous design considerations focused on ergonomics, customization and adaptability, this keyboard addresses the unique challenges faced by children with motor coordination difficulties, offering them a customized solution to enhance their interaction with digital environments.

An iterative development approach, driven by direct feedback from children with ataxia, caregivers and professionals, emphasizes the importance of inclusivity and accessibility in technology design. By prioritizing these values, the project contributes to breaking down barriers to digital participation for children with ataxia, giving them the opportunity to communicate, learn and engage more effectively with the world. In addition, the lessons learned and methodologies applied in this project can serve as a blueprint for future endeavors in assistive technology, highlighting the transformative impact of thoughtful user-centered design in improving the lives of people with disabilities.

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Open ended acoustic obstacle avoidance interface for visually impaired people based on consumer grade mobile device

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***Abstract*—Obstacle avoidance is a common issue for all visually impaired. Currently methods for obstacle avoidance rely on using a white cane, guide animal or another person. However, the wide adoption of personal mobile devices opens a new avenue for combining commonly used consumer grade mobile devices with wearable obstacle avoidance systems. We present a novel method for using smart glasses paired with a smartphone for the purpose of increasing spatial awareness for the visually impaired. Furthermore, we provide an open ended sensing system whose information can be utilized in any way on a smartphone. Our glasses are equipped with three ultrasonic sensors that connects to an smartphone Android application. Based on the position and distance of detected obstacles, the phone vibrates in specific patterns, providing feedback to the user. We conducted an experiment in a common living area, in which a person needs to navigate around the obstacles placed in known positions from starting point A to the finish point B. The experiment validated the effectiveness of the developed system for the detection of obstacles.**

***Index Terms*—assistive technology, obstacle avoidance, blind, smart glasses, wearable devices**

I. Introduction

Visually impaired people struggle with leading independent lives in a society relying on visual cues. Often they need to utilize additional means such as a white cane, service dogs or another person, but none of them entirely address the landscape of issues.

According to the World Health Organization (WHO) almost 2.2 billion people face different vision impairment issues. This is more than 25% of the global population, from which 2 to 8% of the visually impaired are using white canes, and around 5% are relying on assistance dogs. Walking without sight brings the risk of frequent falls and collisions, leading to occupational or traffic-related injuries. A survey of 300 blind people found that about 40% experienced head height collisions at least once a year and 15% once a month. [1]

However, the common adoption of mobile devices equipped with a wide range of sensors and actuators and the current developments in the mobile health sector opens avenues to novel methods for assistance through assistive technology.

Our approach relies on combining a consumer-grade mobile device with wearable smart glasses featuring an ultrasonic sensor system. We want to show that glasses equipped with three ultrasonic sensors with a 60° field of view can provide sufficient obstacle detection for a person requiring assistance. These glasses, combined with a white cane, would help such people navigate in their surroundings, detect obstacles, and avoid collisions. This would help them sense their environment better and provide them with a more comfortable life.

Furthermore, passing sensor information to mobile devices allows for open-ended signal analysis and makes the entire hardware system much cheaper. We define open-endedness as the possibility to process or interpret information sensed by smart glasses in a custom way by a mobile device. We do not define what mobile device should be used, as with the Bluetooth API, glasses can be connected to anything having a compatible interface. Furthermore, information can be processed in custom ways, providing suitable information for end users. In our case, we are using the smartphone's vibration motor; however, this does not limit other system capabilities, e.g. audio cues etc.

II. Related work

There are numerous works done on the topic of wearable devices for the vision impaired, such as ultrasonic sensor glasses with built-in vibration motors [2], or depth cameras combined with smart AR glasses with audio feedback [3]. There are also simple student systems based on Arduino and cheap ultrasonic sensors that demonstrate the feasibility of designing an assistive tool for the visually impaired [4]. Some of the works include wireless connections, enhancing control over the system [5]. Further, surveys have been conducted, providing more details about the current state of research in the field of electronic aids for the blind [6].

Our design differs in that we provide an open-ended solution. By building a sensing array with Bluetooth communication, other engineers are enabled to use signals obtained by the glasses and develop smartphone based solutions for feedback and control.

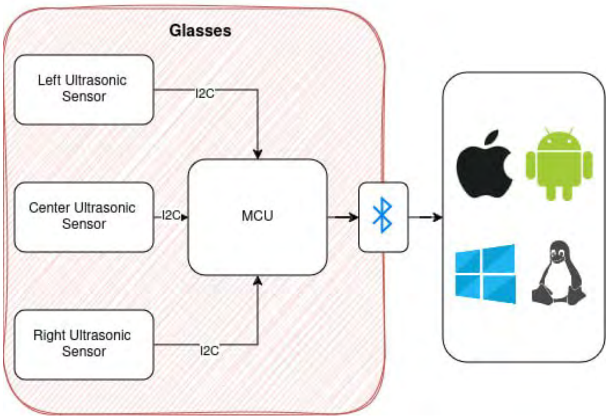


Fig. 1: Block diagram of the Vision Glasses system.

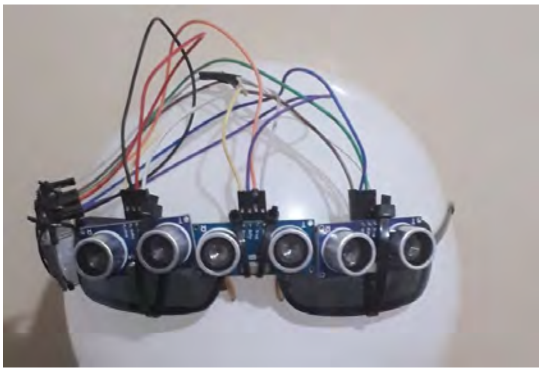


Fig. 2: Prototype of the Vision Glasses system.

III. System Overview/Design

A. Hardware

The major hardware components of the Vision Glasses system are a glasses frame, 3 ultrasonic sensors for distance detection, a battery, and an ESP32 microcontroller with Bluetooth capabilities. The block diagram is shown in Fig. 1 and the realized system in Fig. 2. The microcontroller is responsible for requesting data from the distance sensors and transmitting converted distances in centimeters to the connected Bluetooth device/system. The sensors are placed on the glasses frame in the most optimal positions to provide the highest degree of field of view. That gives the device the ability to detect if objects are appearing from the right, left, or center direction.

To complete the hardware system, the user needs to provide a consumer-grade device with Bluetooth capabilities, such as a smartphone running iOS or Android OS, or desktop device with Windows, Linux, or macOS, presuming that there is an existing application able to connect to the glasses.

B. API

The Hardware API provides a Bluetooth Low Energy (BLE) advertising service with data packed into a string for easy parsing. The data is updated every 500 ms, providing and sending a notification each time.

The data frame consists of a frame counter – counting frames since device boot-up, and distance sensor data sending data in centimeters in the following order: right, center, and left. The frame starts with a START prefix and ends with an END postfix, as shown in Table I.

TABLE I: Data Frame

Prefix	DATA1	DATA2	DATA3	DATA4	Postfix
START	RIGHT	CENTER	LEFT	COUNTER	END

C. Software

For the purpose of this research, besides the code running on the microcontroller, an Android application was developed to facilitate the required functionality of the system. The code diagram is shown in Fig. 3. This schematic can be used as a template for developing an app for our hardware and how the information obtained from the glasses can be collected and utilized. The most important aspect of the software system is that it can be deployed on any consumer-grade electronic device and is not limited by the capabilities of the glasses.

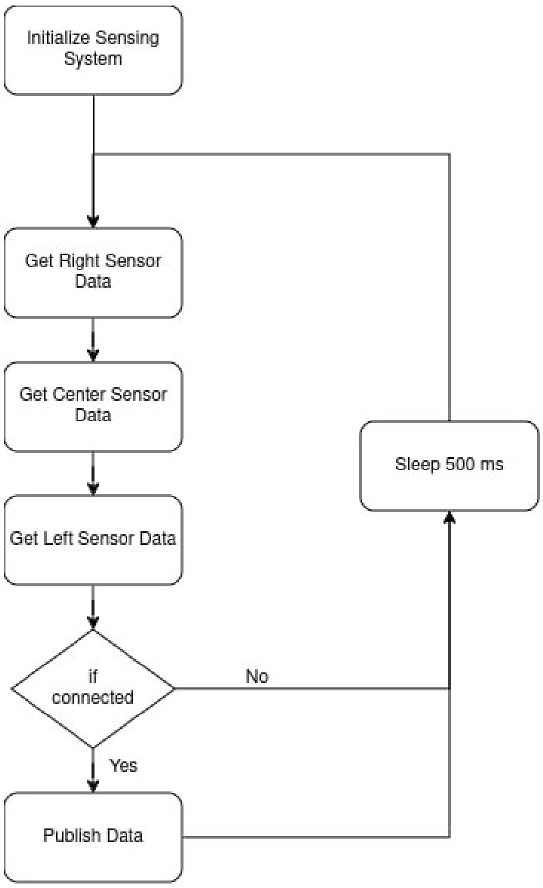


Fig. 3: Block diagram of the Android application.

To test the feasibility of using the collected data to provide feedback to the user, the smartphone's built-in vibration motor was used. As our assistive glasses can detect obstacles in three different directions, but smartphones usually are employed only with one vibration motor, a cues vocabulary was developed to distinguish between them.

To keep the vocabulary simple, only three cues were chosen: Ascending, Constant, and Descending vibration, as shown on Fig.4.

An ascending cue is when the amplitude softly rises over 500 ms. A descending cue is when the vibration abruptly starts with high amplitude and then softly quiets down over the course of 500 ms. Constant cue abruptly starts and abruptly stops with constant amplitude.

The vocabulary is assigned to directions in the following way: Left corresponds to Ascending, Center to Constant, and Right to Descending, as shown in Table II.

Android applications send signals to the vibration motor if any of the sensors detect an obstacle closer than 70 cm. If more than one obstacle is detected, the vibration motor prioritizes them in the following order: left, center, right.

TABLE II: Direction of Obstacle vs Vibration cues

Left	Center	Right
Ascending	Constant	Descending

IV. EXPERIMENTS

A. General description

The experiment was conducted in a common living area. The participant navigated a path around a room containing walls, doors, tables, and other obstacles, as well as other inhabitants. All obstacles were placed in known positions, and the participant was asked to navigate from the starting point A to the finish point B.

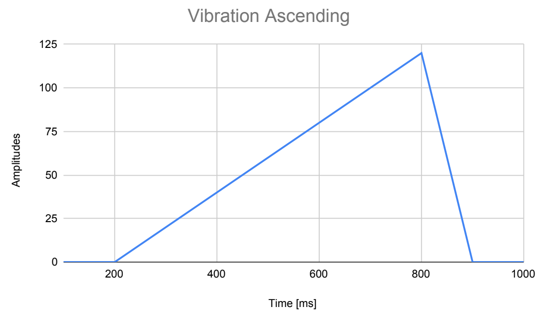
B. Specific scenario

During the experiment, the participant was faced with a simulated environment of a common living space, consisting of obstacles like walls, doors or chairs, as shown in Fig.5.

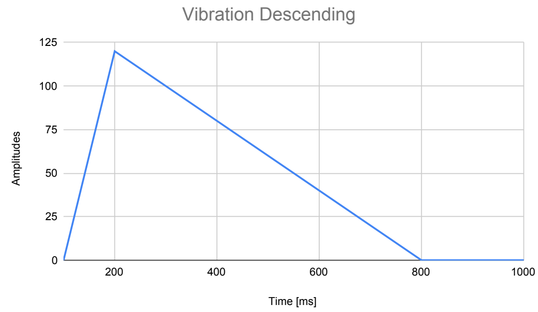
The experiment's task was to navigate from starting point A to the finish line at point B. To finish this path, the participant had to make a few turns, open the door, avoid the person behind the door, and turn to the final destination.

During the entire run, the assistive device was recording the obstacle detection signals from the three sensors shown in Fig. 6. The collision events are marked as green dots on Fig. 5.

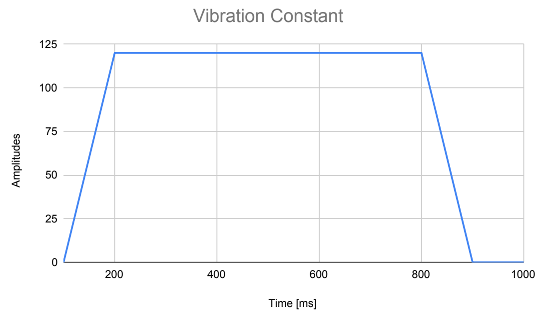
This comprehensive test scenario will allow us to assess the glasses' performance in obstacle detection. The results obtained from this scenario, along with participant feedback, are essential for the refinement and enhancement of the assistive glasses for them to be used by blind individuals, ensuring safer and more independent navigation in real-world environments.



(a) Vibration cue for left sensor.



(b) Vibration cue for right sensor.



(c) Vibration cue for center sensor.

Fig. 4: Plots of the vibration cues used by the application.

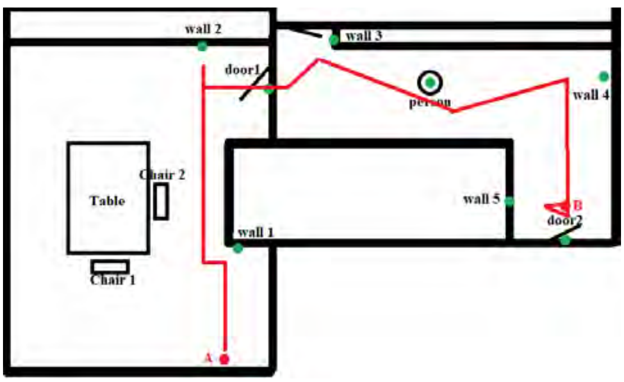


Fig. 5: The setup and path used for the experiment.

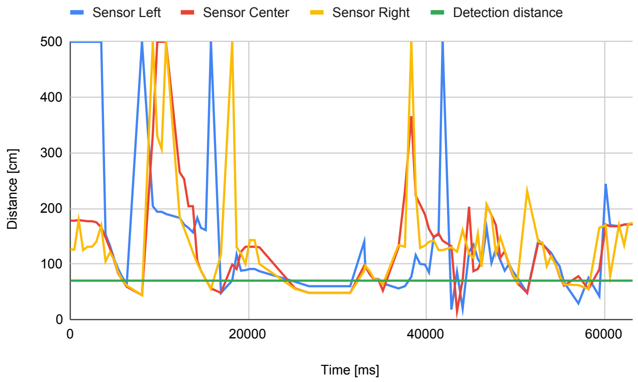


Fig. 6: Plots of the ultrasonic sensors representing measured distances over time.

V. Results and Analysis

Analysis of the data from the experiment indicated that the sensor in fact reacted correctly in all scenarios, providing vibrations and readings, as can be seen in Fig.6. By analyzing the data, we can see that the first collision event caused both the left and center sensors to activate. The second event, the wall just before the door, caused all sensors to be activated, and after the participant took a turn right to face the door, all sensors reacted again.

The opening of the door kept the right sensor activated. Then the wall after the door was detected by all sensors, and next the person alerted the right sensor. The next wall was caught by all sensors, and while turning right, the left and middle sensors kept being active.

Then, when the next door was approached, all sensors detected it, so by turning right again, all sensors were activated until the participant turned right for 90° to face the open area.

VI. Conclusion

Building assistive technology that can be integrated with consumer-grade electronics is a feasible approach. It decouples the computing part from the sensing and actuating part of the device. This allows for designing assistive hardware and applications as two separate components which are interoperable with other devices available on the market.

We present a system for obstacle detection that can be used by the blind and vision impaired to navigate their surroundings. We evaluate the performance of the system in an experimental setup emulating real world deployment. The results obtained by the experiment show that using separate consumer grade device for computing and decision making allowed for successful navigating during the obstacle run. This validates our system as an effective assistive device.

Additionally, the device itself can provide different types of cues, not limited to only assistive hardware, but having access to a whole range of other sensors. With such a device, it is possible to develop a sufficient vocabulary of cues for providing real-time feedback to the user.

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Exploring Pigmented Skin Mole Borders: Minkowski Dimensions in Malignancy Detection

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***Abstract*—Malignant pigmented skin tumors (melanoma malignum) are one of the most aggressive skin carcinomas with high metastatic potential, regional and general. It has a rising incidence, which is explained by ozone depletion and the consequent increase in UV radiation. One of the criteria used to assess this type of tumor is the B-characteristics i.e. the boundary of melanoma. The visual distinction in smoothness between normal and abnormal tissues or cells has prompted the use of fractal dimension as a diagnostic tool. Typically, normal tissues exhibit lower complexity, reflected in a lower fractal dimension, while abnormal tissues display higher complexity, indicated by a higher fractal dimension. In this study, we analyze the Minkowski dimension of mole borders and their inner structures. Our results indicate that malignant moles possess a higher fractal dimension compared to benign moles, suggesting that fractal dimension analysis can be an effective method for differentiating between malignant and benign tissues.**

***Index Terms*—Malignant pigmented skin tumors, melanoma malignum, image processing, Minkowski dimension**

I. Introduction

The Minkowski dimension (MD), also known as a Box-counting dimension, a fractal dimension introduced by mathematicians Hermann Minkowski and Georges Bouligand [1], can be used in the mathematical analysis of different pigmented skin moles due to its ability to measure roughness, a typical characteristic of malignant skin tumors. Malignant skin tumors exhibit infiltrative, invasive, and destructive growth. They are poorly demarcated, spread to neighboring organs and tissues, metastasize, and recur. These tumors are composed of atypical and anaplastic cells. Malignant skin tumors can be classified as pigmented (melanoma malignum) and non pigmented (basocellular carcinomas and squamocellular carcinomas). Melanoma malignum is one of the most aggressive skin carcinomas with high metastatic potential, regional and general. Melanoma malignum is a malignant skin and mucous membrane tumor originating from epidermal melanocytes, the junctional component of a cellular nevus, or, rarely, from a blue nevus. Malignant melanoma, the most aggressive of all skin cancers, has a rising incidence, which is explained by ozone depletion and the consequent increase in UV radiation. On the other hand, skin melanoma can be prevented, and if diagnosed early, it can be cured in a high percentage of cases. The highest incidence of cutaneous melanoma is reported in Queensland, Australia, where the annual incidence is 55 per 100,000 inhabitants. The world-standardized rates for annual incidence are 2.7-6 per 100,000 inhabitants for men and 4.6-8.5 per 100,000 inhabitants for women. Additionally, 18% of patients with melanoma are between the ages of 15 and 39. It occurs more frequently in females, particularly in younger age groups [2].

Because of the seriousness of this type of cancer, it is crucial to detect it as early as possible. As previously mentioned, malignant tumors are poorly demarcated, and this characteristic can be used to determine whether a tumor is malignant or benign. We specifically used the Minkowski dimension to measure the local dimension of the pigmented mole. We conducted two measurements: one considering the entire mole with its interior, and the other considering only its border. Both sets of results were distinguishable from those obtained when we analyzed benign tumors. Specifically, malignant tumors yielded significantly higher dimensions. Using this approach, it is possible to roughly estimate whether a skin mole is malignant or benign.

The criteria used to assess the type of tumor is ABCDE characteristics of melanoma [3]. A stands for "asymmetrical" form (melanoma malignum is often asymmetrical); B stands for "border" (melanoma malignum typically has irregular border); C stands for "color" (when more than one color or different shades from one color are present, the mole is considered to be suspicious); D stands for "diameter" (diameter of melanoma malignum is usually greater than 6mm); E stands for "evolution" (how the previously normal mole is evolving, i.e. changing its color and shape). In this paper, we mainly focus on the boundary characteristics, although we also consider the mole's inner.

The paper is organized as follows. In Section II we give a short overview of the research done in this area. In Section III, we define the Minkowski dimension and describe the sets whose dimension will be determined. Section IV includes the dataset along with the methodology we employed. In the subsequent Section V, Statistical Analysis and Results, we discuss the hypothesis tests and the obtained results. This section is followed by discussion and conclusion.

II. Related work

Medical images often exhibit irregular and fragmented contours, which makes fractal geometry, rather than Euclidean geometry, a more suitable tool for their description and characterization. In another study [4], a set of 100 images of melanoma and non-melanoma moles were analyzed. Specifically, it targeted the B-characteristic, expecting higher fractal dimensions for the contours of melanoma malignum. The visual difference in smoothness between normal and abnormal tissues (or cells) motivated the use of fractal dimension as a diagnostic tool: normal tissues are supposed to have lower complexity (lower fractal dimension), while abnormal tissues are supposed to have higher complexity (higher fractal dimension). However, descriptive statistics revealed that the fractal dimension did not provide a clear classification or systematization of the moles.

Another significant approach to classify skin lesions as malignant or benign involves using color photographic slides of the lesions, image processing techniques, and an artificial neural network classifier [5]. Quantitative image analysis measures a series of candidate attributes expected to contain sufficient information to differentiate melanomas from benign lesions. Finally, the selected features are fed into an artificial neural network for classification.

Despite the previous work, relying on the border [4] and the other using artificial neural network [5], in our research, we also focus on the irregular and poorly defined borders with their inner as well. We also decided that it would be more efficient to use statistical methods, such as Kolmogorov-Smirnov test and Student's t -test in order to determine if there is a significant difference between the means of the two groups and how they are related.

Using the ABCDE criteria, we analyze the moles to determine their malignancy. Unlike previous studies that found no significant difference in fractal dimensions between melanoma and non-melanoma moles, our study aims to demonstrate that the border irregularity measured by the Minkowski dimension can provide a clear distinction between benign and malignant moles. By focusing not only on the borders' fractal characteristics, but also on their entirety as well, we seek to improve the accuracy of melanoma detection and classification.

III. Fractal Dimension

Fractal dimensions provide a quantitative measure of complexity and irregularity in geometric shapes and patterns. Unlike traditional Euclidean dimensions, which are integer values (e.g., a line is 1-dimensional, a plane is 2-dimensional), fractal dimensions can be non-integer values, reflecting the intricate detail present in fractal shapes. It describes how a fractal's detail changes with the scale at which it is measured.

There are several techniques for calculating fractal dimensions [6], such as:

- Minkowski dimension (or box-counting dimension). This method involves covering the fractal with a grid of boxes and counting the number of boxes that contain a part of the fractal. The dimension is determined by analyzing how this number changes as the size of the boxes is varied.

  Let S be a subset of a metric space (such as $\mathbb{R}^n$). For each $\varepsilon > 0$ let $N(\varepsilon)$ denote the minimum number of non-overlapping n-dimensional boxes of side length ε necessary to cover S. By n-dimensional box of side length ε, we mean a translated copy of the n-fold product of intervals $[0, \varepsilon]^n \subset \mathbb{R}^n$. The upper Minkowski dimension of S is
  $$\overline{D}(S) = \limsup_{\varepsilon \to 0} \frac{\log N(\varepsilon)}{\log\left(\frac{1}{\varepsilon}\right)},$$
  and the lower Minkowski dimension is
  $$\underline{D}(S) = \liminf_{\varepsilon \to 0} \frac{\log N(\varepsilon)}{\log\left(\frac{1}{\varepsilon}\right)}.$$
  If
  $$\overline{D}(S) = \underline{D}(S),$$
  then the common value is denoted $D(S)$ (or just D if there is no possibility of confusion) and called the Minkowski dimension of S.

  In short, if the Minkowski dimension of a set S exists then the formula used to determine the Minkowski fractal dimension D is:
  $$D = \lim_{\varepsilon \to 0} \frac{\log N(\varepsilon)}{\log\left(\frac{1}{\varepsilon}\right)}, \tag{1}$$
  where $N(\varepsilon)$ is the minimum number of boxes of side length ε is required to cover the analyzed set S.
- Hausdorff Dimension offers a mathematically more rigorous approach that defines the dimension based on the measure theory. It considers the size and distribution of the fractal's constituent parts.

Fractals model broken, jagged, complex, wiggly, and rough shapes. But some shapes are rougher and more complex (e.g., coastlines) than others. The fractal dimensions mentioned above are both used to quantify this roughness and complexity. The higher the dimension, the higher the roughness, the higher the complexity [1]. The problem we want to assess in this study is the shape of a skin mole and measure its roughness. This will help determine whether a malignant or benign tumor is in question.

The earliest known measure of the roughness of an object is the Minkowski dimension (also known as Minkowski–Bouligand dimension and box-counting dimension) [6]. In practice, calculating the Minkowski dimension of a fractal object directly is extremely difficult because its measure is not always a certain value but variable in an interval. In our case, we adopted the box-counting dimension [7]. The MATLAB code we used in order to calculate the dimension of the moles is by the equation (1).

IV. Dataset and Methodology

We used an original dataset containing 100 photos, out of which 38 malignant skin tumors, and the other 62 benign skin tumors. They were obtained using the FotoFinder dermatoscope [8] in the city hospital "8-mi Septemvri" in Skopje, North Macedonia. The instances were later diagnosed by a medically trained person, a dermatologist. After the classification, the dataset analysis continued with a preprocessing sequence implemented to remove noise and undesired structures from the images. Namely, some of the images contained vignettes and other irregularities, such as hairs. To overcome this, we used Paint 3D, more specifically the Eyedropper tool to select the color of the skin and then using the Marker or the Brush, the irregularities were covered. This process can be seen on Fig. 1 and Fig. 2. The processing resumed with the following steps [9]:

- Loading the Photo in MATLAB: Each photo was imported into MATLAB for subsequent analysis.
- Converting the Photo to Binary Format: The photo was converted from RGB format to binary format. The parameters used for conversion were: Input image (img) and Luminance Threshold. Input image is the RGB image that is being converted. It contains color information in three channels: red, green, and blue. Luminance Threshold is the threshold value used by the im2bw function to convert the image to binary format. Pixels with a luminance (brightness) value greater than the value provided will be converted to white (1), and pixels with a luminance value less than or equal to the value provided will be converted to black (0).
- Adjusting Grayscale Threshold: We adjusted the grayscale threshold to optimize image segmentation. The function rgb2gray(img) converts the original RGB image 'img' to a grayscale image. This function removes the color information, retaining only the luminance (brightness) values. This section of the code adjusts the image to grayscale format by reducing it from three color channels (RGB) to a single channel representing brightness.
- Applying Inverse Function: An inverse function was applied to convert the binary formatted photo, swapping white pixels with black and vice versa, as seen on Fig. 3.
- Performing Image Erosion: Image erosion was conducted to enhance the extraction of the mole boundary, Fig. 4.

Observe that some steps in the processing, like removing the noise and erosion, are decreasing the fractal dimension (Minkowski dimension as well as Hausdorff dimension).

Following these preprocessing steps, we obtained two types of photos suitable for different analytical techniques. That is one photo representing the mole with its inner and the other representing only the mole's boundary. Then, we applied the Minkowski dimension function [10] to analyze each type of photo.

This methodological approach allowed us to effectively analyze and compare the structural complexity of malignant and benign skin tumors based on their Minkowski dimensions. We put together a table consisting of three columns representing the tumor type (malignant or benign), its Minkowski dimension (mole together with its inner), and the Minkowski dimension of the border of the mole, respectively. There are 100 rows, each of them representing the dimensions and type of a different mole.

V. Statistical Analysis

This section will represent an extensive statistical analysis of the dataset containing information about skin moles, specifically focusing on the Minkowski dimensions of the mole with its inner and also a mole regarding only its border. They are categorized by their class labels 'Malignant' and 'Benign'.

A. Descriptive Statistics

We began by computing basic descriptive statistics for the Minkowski dimensions across the entire dataset. The mean, standard deviation (SD), and quartile information provided initial insights into the distribution and variability of these dimensions. The results are shown in Table I.

TABLE I: Descriptive Statistics

	Mean	SD	Max	Min
Benign (inner)	1.4158	0.0997	1.5599	1.1536
Benign (border)	0.9925	0.0671	1.1315	0.8292
Malignant (inner)	1.559	0.088	1.7184	1.3585
Malignant (border)	1.105	0.0575	1.2307	0.9905

B. Correlation Analysis

Scatter plots were used to visualize the relationship between the Minkowski dimensions of the moles' borders and the Minkowski dimensions of the borders and their inners. The scatter plot shown in Fig. 5 indicates a distinct separation between benign and malignant tumors, with malignant tumors generally having higher values for both calculated Minkowski dimensions (Minkowski dimensions of the moles' border and the Minkowski dimension of the mole's border and its inner). This visual pattern supports the use of these features in distinguishing between the two classes.

In the scatter plot shown in Fig. 5, we can notice that there are benign moles with higher dimensions (of the border and

Fig. 1: Original photo.

Fig. 2: Brushed up photo.

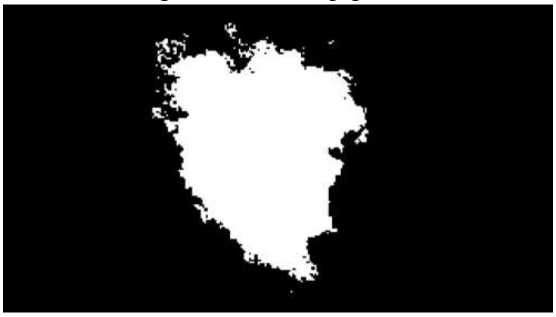


Fig. 3: Inverted binary photo.

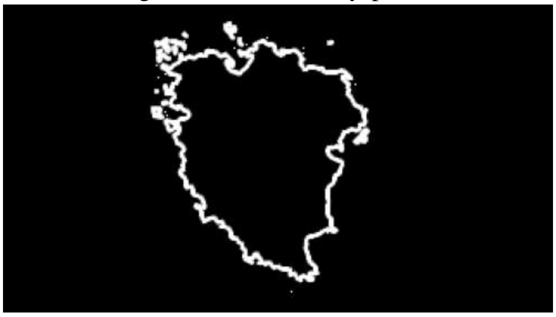


Fig. 4: Boundary of the mole.

the border with its inner part), as well as malignant moles with small fractal dimensions. Such moles are shown in Fig. 6 and Fig. 7.

We also considered a machine learning method. Because it is a binary problem, the model provided good results. The ROC curve will be presented below in Fig. 8. Our dataset can undergo a prediction method to evaluate the type of tumor. Our problem is of binary classification type because the outcome variable can be one of two possible types. We wanted

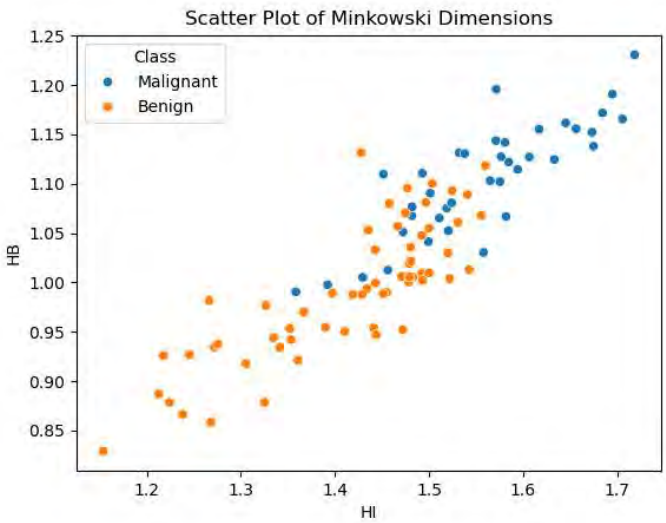


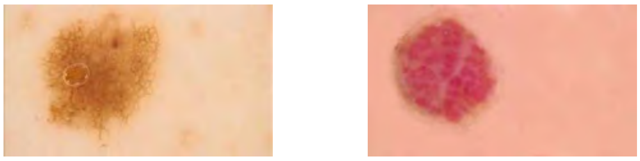
Fig. 5: Scatter plot of Minkowski Dimension (Mole with its inner (HI) vs. Border (HB)).

(a) (b)

Fig. 6: Malignant moles with small fractal dimension. (a) Blue nevus, malignant if found in a specific location on the body. (b) Malignant due to its asymmetry, pseudopods, and uneven color.

to predict the likelihood of a malignant tumor based on its Minkowski dimensions. Therefore, we used the sigmoid [11] function to map any real-valued number into the range $[0, 1]$. The model achieved an area under the Receiver Operating Characteristic curve of 0.95, indicating good predictive performance.

The Receiver Operating Characteristic (ROC) [12] curve shown in Fig. 8 visually represented the trade-off between true positive rate (sensitivity) and false positive rate (1 - specificity) across different thresholds. The ROC curve bows



(a) (b)

Fig. 7: Benign moles with higher fractal dimension. (a) Seborrhoeic keratosis. (b) Hamangioma.

towards the upper left corner, suggesting a model with high sensitivity and specificity. The area under the curve (AUC) is 0.95. Considering that a value of 0.5 means random guessing and a value of 1.0 represents perfect classification, the result displays a reasonable distinction between the two affected classes. This result has proven to be encouraging for our next, more profound mathematical analysis.

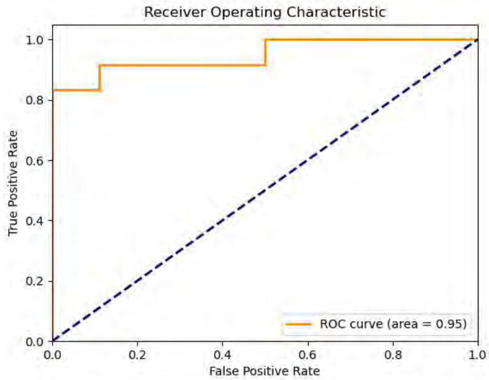


Fig. 8: ROC curve

C. Comparative Analysis

In this section, we make further analysis of the suggested methods. Fig. 9 and Fig. 10 show the boxplots of the Minkowski dimensions of benign and malignant tumors when mole with the inner and the border of the mole are considered, respectively. When moles with their inner are analyzed the boxplot (shown on Fig. 9) indicates a slight overlap in the interquartile ranges between benign and malignant tumors, suggesting potential differentiation based on this dimension. We can notice one data point lying outside the range of most of the data. However, the T-test results discussed later in this section show a significant difference between benign and malignant tumors. Despite the outlier, the overall trend remains clear.

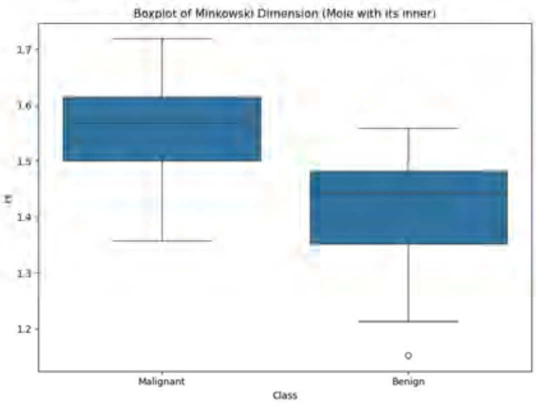


Fig. 9: Boxplot of Minkowski Dimension (Mole with its inner).

When borders of the moles are analyzed, we obtain similar results, the boxplot shows distinguishable differences in the distribution of border dimensions between the two classes. The boxplot is shown in Fig. 10.

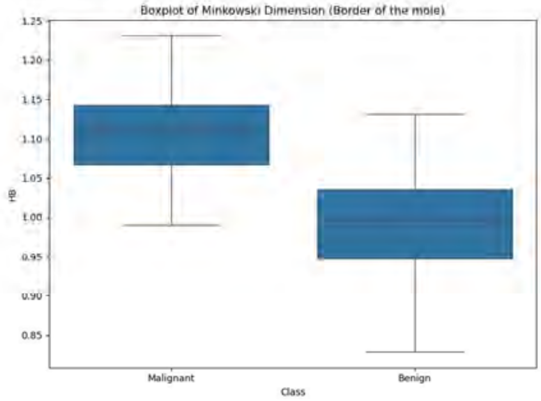


Fig. 10: Boxplot of Minkowski Dimension (Border of the mole).

Both visualizations indicate that there is a difference between the Minkowski dimensions of benign and malignant moles. To statistically validate the differences observed in the boxplots, we conducted hypothesis tests with the Null hypothesis

H_0 : *There is no difference in the Minkowski dimension between the groups (benign and malignant moles),*

and a significance level $\alpha = 0.05$. Performed Kolmogorov-Smirnov test [13] report that the analyzed data (Minkowski dimension of the moles' borders) is normally distributed (the corresponding p-value is 0.200), and therefore for this data we perform a T-test. When the border with the inner is analyzed, the Kolmogorov-Smirnov test reports a p-value of 0.015, which indicates that the data do not follow the normal distribution. Therefore, in this case we performed a nonparametric test to compare two groups of independent variables, known as Mann-Whitney test [13].

- When the Minkowski dimensions of the moles with their inner are compared, the Mann-Whitney U test yielded a significant difference (p-value = 0.000) between benign and malignant tumors, which confirmed the distinct mean values.
- When the Minkowski dimensions of the borders of the moles are compared, there is also a significant difference in border dimensions between the two classes ($t = -8.618$ and p-value = 0.000).

The 95% confidence interval for the mean of the Minkowski dimension of moles' borders are $[0.97541, 1.00951]$ for benign moles and $[1.08662, 1.12443]$ for malignant. Similarly, the 95% confidence interval for the Minkovski dimension of the moles' borders and its inner are $[1.39043, 1.44108]$ and $[1.52983, 1.58749]$, for benign and malignant moles respectively.

VI. Conclusion

In this paper, we analyzed the Minkowski dimensions of moles recorded with a FotoFinder dermatoscope. We analyzed the dimensions of the moles' borders and the dimensions of the borders with their inner part. The results suggested that there is a significant difference in the mean of the dimensions. Therefore, this technique can be used as a support for diagnosing melanoma. As the results suggested there are moles whose dimensions do not follow the result obtained here (see Fig. 5, 6, and 7). This is expected as melanoma is diagnosed according to ABCDE criteria, and in this case we are dealing only with the B-criteria.

VII. Acknowledgement

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Health Risk Prediction for Children Built on a Combination of Heterogeneous Datasets

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***Abstract*—Health risk prediction tools for children are important to identify those at risk in order to start timely interventions. However, they currently do not exist, so the SmartCHANGE project is developing cardiometabolic health risk prediction models for children and youth. This is a difficult task because there are no datasets tracking individuals from childhood to sufficiently old age with an appreciable disease prevalence. We, therefore, combine longitudinal and cross-sectional datasets containing different risk factors. We fill out the datasets with missing variable values by imputation, and by predicting variables that are missing in some datasets from the variables in overlaps between datasets. This enables the prediction of risk factors up to age 55. At that age, we feed the risk factors into existing risk prediction models for cardiovascular disease and diabetes. Given the nature of the problem and the available data, it is difficult to evaluate whether the resulting risks are correct, but preliminary results indicate they are reasonable.**

***Index Terms*—incomplete data, limited label access, real-world applications, life-long learning**

I. INTRODUCTION

Statistical and even machine-learning tools for predicting health risk are increasingly established, especially for cardiovascular risk – many health professionals, for example, use the SCORE2 model [1] developed by the European Society of Cardiology. However, such models for children do not exist. This is because the non-communicable diseases these models are predicting are far in the future for most of them, so developing risk-prediction tools is technically difficult, and the need does not appear great. However, health behaviors that eventually lead to disease begin at a young age, and even physical disease precursors are evident in some cases. Evidence points to childhood and adolescence as an ideal period for risk-lowering strategies based on behavior modification [2]. Identifying children who should be targeted by such strategies is surprisingly difficult, though. This is why the SmartCHANGE project [3] is developing a model and tools for predicting cardiometabolic risk for children and youth.

To predict the risk of non-communicable diseases for children, one would ideally want a dataset that contains a broad range of risk factors going from a young age (when we want to make the prediction) to an old age (when the diseases typically occur) for the same individuals. However, compiling such a dataset would require tracking many people over many decades. Consequently, ideal datasets for our purpose do not exist, however, many relevant datasets for risk prediction do exist. Our objective is to combine such heterogeneous datasets in order to build a risk prediction model. In this paper, we describe the first attempt at this, in which we use four datasets. We identify their overlaps, sometimes by generalizing some variables. We then use models trained on these overlaps to generate synthetic values for datasets that do not contain certain variables, similar to some imputation approaches. We use this completed dataset to forecast some of the variables – the risk factors – in middle age. We finally feed these risk factors into established models designed to predict the 10-year risk of cardiovascular disease and type 2 diabetes.

The rest of the paper is organized as follows. In Section II, we briefly review related work on risk prediction models, imputation and synthetic data generation. In Section III, we present the datasets used in the paper. In Section IV, we proceed to describe our risk prediction modeling pipeline, followed by the results in Section V. With Section VI, we conclude the paper and provide some ideas for future work.

II. RELATED WORK

Several risk scores were developed and are currently used for predicting cardiovascular risk [1], [4]–[6] and diabetes [7]. Some of the most popular scores were developed and validated even on multiple cohorts [1], [8]. However, these cohort datasets are homogeneous in the sense that they contain all the variables of interest at ages of interest. This means that predicting risk from them is relatively straightforward, whereas in our case each dataset is different and not sufficient to predict risk on its own.

Imputation of missing data is a crucial step for robust predictive models in health studies. A common approach to imputation is joint modeling, which specifies a multivariate distribution for all variables, but can be complex to implement with diverse datasets. Fully Conditional Specification, on the other hand, imputes missing data using a series of univariate conditional models. This method is more flexible than joint modeling, but may face theoretical limitations due to potential model incompatibility [9].

Synthetic data generation similarly plays a significant role in medical research, primarily addressing challenges related to data privacy and scarcity. Generative Adversarial Networks and Variational Autoencoders are popular methods for generating synthetic data. These methods are particularly useful for creating synthetic data that maintains complex relationships between variables, however, such methods also require large

TABLE I
SELECTED DATASETS

Name	SLOfit	LGS	YFS	AFINA-TE
Origin	SI	BE	FI	PT
Age range	5 - 20	5 - 25	0 - 60	5 - 25
Longitudinal	Yes	Yes	Yes	No
Num. of people	280165	17991	3596	1632
Num. of measurements	3121399	31127	32364	1632
Num. of variables	13	80	24	59
Missing values	2.55%	16.25%	39.49%	33.53%

TABLE II
PRESENCE OF VARIOUS VARIABLES OF INTEREST ACROSS SELECTED DATASETS

Attributes	SLOfit	LGS	YFS	AFINA-TE
Age	✓	✓	✓	✓
Sex	✓	✓	✓	✓
Height	✓	✓	✓	✓
Weight	✓	✓	✓	✓
Waist circumference		✓	✓	✓
Fitness	✓	✓		✓
Resting heart rate		✓	✓	✓
Systolic blood pressure		✓	✓	✓
Diastolic blood pressure		✓	✓	✓
Glucose				✓
Total cholesterol			✓	✓
HDL			✓	✓
LDL			✓	✓
Physical activity		✓	✓	✓
Smoking		✓	✓	
Diet			✓	

amounts of data for training, which can be difficult to obtain [10]–[12].

III. DATA

The datasets used in this work are presented in Table I. From the datasets we decided to keep specific 16 variables, either because they are incorporated into the existing risk prediction models we utilize or because they are essential for establishing connections between datasets; the presence of variables in each of the datasets is shown in the Table II.

The SLOfit dataset is a dataset based on a school-based fitness monitoring program in Slovenia for children aged 6 to 19. It aims to improve physical education by systematically evaluating students' physical development, supported by national school legislation. Schools annualy measure body height, weight, triceps, skinfold thickness, and motor abilities through eight fitness tests [13].

The Leuven Growth Study of Belgian Boys [14] dataset (LGS) was obtained between 1969 and 1974, with the aim of describing the physical fitness of Belgian boys aged 12 to 18 and gathering longitudinal data on their growth. Measurements include physical growth, biological maturity, motor performance, sports practice, and sociocultural characteristics.

The Leuven Growth Study of Flemish Girls dataset (also abbr. LGS) [15] was obtained from 1979 to 1980. Its focus was the assessment of the physical fitness of Flemish girls aged 6 to 18. Data collected includes physical fitness tests, anthropometric measures, somatotype ratings, biological maturity, sociocultural factors, sports skills, sports practice, hygiene, and eating habits.

The Cardiovascular Risk in Young Finns Study dataset (YFS) [16] is a collection of measurements from 1980 to 2020, with the aim of exploring early cardiovascular disease risk factors in youth. The data includes measurements of children, but also of adults, at later numerous follow-ups. Data collection includes questionnaires, physical measurements, and blood tests, focusing on variables like serum lipoproteins, insulin, inflammation markers, obesity indices, blood pressure, lifestyle factors, and socioeconomic status.

The AFINA-TE dataset [17] is part of an intervention program aimed at promoting physical fitness, activity, and nutritional knowledge among children and adolescents. Conducted in the district of Porto, Portugal, the study involved participants aged 12–18, split into an intervention group and a control group. Data collection included accelerometer measurements of physical activity and the Nutrition Knowledge Questionnaire to assess dietary habits.

IV. METHODOLOGY

A. Preprocessing

Initially, units of measurements of the same variables were standardized across datasets. Multiple measurements of a single variable at the same measurement point (e.g., systolic blood pressure) were next combined by calculating their mean to provide a consistent single measure. Smoking status codes, which differed between datasets, were aligned. Additionally, in the SLOfit dataset we excluded all data rows that had more than one-third of their attributes missing and then sampled 20,000 unique participants from the dataset. This was possible due to the substantial size of the dataset. The resulting dataset, consisting of 217,843 data points, was consequently more robust and comprehensive.

B. Individual dataset imputation

The imputation of missing values within each dataset was performed uniformly. The initial imputation sweep utilized only fully observed variables, such as height, weight, sex, and age, as features for models used to impute missing values in other variables. Variables were imputed based on the order of their ratios of non-missing values: those having the highest ratio were selected first. Once a variable was imputed during the sweep, it was considered complete and used in subsequent imputations.

The models that we used include Gradient Boosting, Linear, Ridge and Logistic Regression, ElasticNet, Random Forest and Gaussian Process Classifiers. The performance of a model was evaluated using 5-fold cross-validation. For classification models, accuracy was used as the scoring metric, acknowledging the limitations of accuracy for imbalanced datasets. For regression models, mean absolute error (MAE) was used. The model with the best cross-validation performance was then retrained using all available data points of the target variable and employed to predict the missing values.

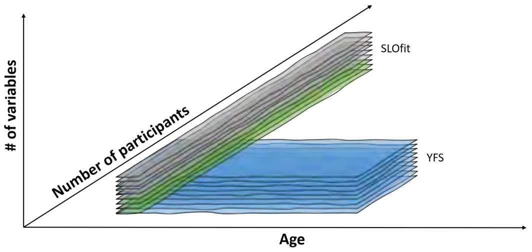

Fig. 1. Overlap of variables in SLOfit and YFS datasets across the age range. The SLOfit dataset shows a partial overlap of variables with the YFS dataset for certain age ranges. Models are trained on the overlapping variables to predict the variables present in YFS but missing in SLOfit (grey).

While imputation helps to address the issue of missing data, it also carries potential risks. The imputed values may not always accurately represent the true distribution of the data, especially if the missing data is not random. This could lead to biases in the model predictions and reduce how well the results apply to other situations. Moreover, imputed data may introduce artificial correlations between variables, potentially misleading the model's understanding of genuine relationships. To mitigate these risks, we performed a second sweep to refine the dataset further, training only on each variable's non-imputed (ground truth) values. In this iteration, all of the input columns were considered complete, utilizing the entire set of variables for imputation. This time, models were trained again using the ground truth values but with the newly imputed values from the first sweep included in the dataset, providing a more comprehensive dataset for the imputation process.

C. Synthetic data generation

At this point all the missing values from each dataset were imputed. However, subjects from different datasets still had different variables. The task of the next step was to generate synthetic data: to predict variables observed in some datasets, but completely unobserved in some other datasets.

To this end we first modified similar variables across different datasets to make them (roughly) equivalent, to achieve greater overlap between the datasets, which in turn resulted in a more precise data generation process. The following variables from SLOfit or LGS datasets were declared equivalent:

- Shuttle run times from the LGS datasets and 60-meter dash from the SLOfit dataset.
- Sitting arm reach measure and the standing bow variable. Bow, in this case, is the subject performing a standing front fold as far as possible.
- Vertical jump and the standing long jump.
- Leg lifts and torso lifting exercise.
- Sum of skinfold and triceps skinfold.

Equivalent variables were next converted to the same scale, namely to z-scores, where the z-score of a variable is defined as (variable value – mean) / standard deviation.

Next we combined all the datasets into one large dataset consisting of any overlapping variables and target variables. Figure 1 illustrates combining SLOfit and YFS datasets. We then repeated the imputation processes as described in section B, though with the already imputed values from the previous section also taken as the ground truth.

D. Individual forecasting

After the generation of synthetic data we obtained a merged dataset with no missing values. This enabled us to train machine learning models capable of forecasting the variables from a childhood to adulthood and to, subsequently, use the forecasts as inputs to the publicly available models for the predictions of health risk. The age of a child was chosen to be 14, a typical age of a child still in school, whereas the age of an adult was selected as 55, the oldest age supported by our data.

The first approach of forecasting the variables works more on an individual level, whereas the second method estimates the distribution of the whole population in order to predict the variables of an individual. In the first approach we decided, since no measurements exist for the same people at ages both 14 and 55, to split the entire forecasting into forecasting from 14 to 18 and then from 18 to 55, for which data is available. Here we implemented two fully connected neural networks, each applied on a separate time frame, with 27 inputs and 26 outputs per network. There is one less output than input, since we are not predicting the person's sex. Both networks have one hidden layer with 27 neurons, which use the "ReLU" activation function, whereas the output layer uses a linear activation function. During the training of the neural networks we used mean squared error as the loss function.

E. Population-based forecasting

Individual forecasting requires data from the same person from start to end age. While we have some data close to this ideal (Subsection IV-D), we have even more data on different people at different ages, which makes it possible to consider how variable values change over time in whole population. Predictions of future values for a specific person can then be obtained by estimating where in the general population the person should "lie" in the future. Such forecasting is less personalized, but also less susceptible to unexpected behaviors for atypical individuals.

In the first step we choose an age timespan for which we want to forecast the unknown values. We opted for the timespan that starts at the age of 5 and ends at 55 years of age, since these two ages correspond to our earliest and latest measurements. For each variable, we next estimate the initial or crude population means and standard deviations at ages for which we actually have the data. For each such age, we first collect the corresponding measurements. If the number of measurements is too low for a relatively reliable estimation of mean and deviation, we keep including neighboring ages until the criterion of enough observations is achieved. The criterion for a numeric variable is at least 500 measurements, whereas, for the categoric variable, one must collect at least 10 measurements for at least 2 classes (categoric variables can have very low number counts for some of their classes). At this point we calculate the initial mean and standard deviation of the obtained measurements.

In the next step we smooth the obtained estimates and fill in the missing values at the unknown years with the following procedure. The entire age timespan is split in any possible combination of two or three distinct subintervals, such that they cover the whole timespan. Any combination for which any of the subintervals does not include at least 20 % of age points from the first step is immediately rejected since fitting a function on such a small number of ages will not yield stable approximations. For each remaining combination we next estimate how well it fits the previously obtained means and deviations, by fitting each of the linear, quadratic, exponential, power and logarithmic functions on the intersection of each subinterval with the ages from the first step. The error of the fit of a combination (including the choice of the fitting functions) equals the sum of the absolute errors at all the age points from the first step. Next, we select the combination that achieved the lowest error and estimate the final population means and standard deviations on the whole age timespan.

For a given person we forecast the future values of a given variable via the use of z-scores. Naturally, to "reverse" the z-score value back to the original range, one reverses the order and multiplies the z-score value with standard deviation, and then adds the mean. In order to forecast the future values of a variable at a given "present" time, we first select the most recent three (or less, if the person does not have enough observations) z-scores from the past and average them. We then make a very rough assumption that this person will also have such a z-score in the future. Finally, at a chosen age in the future, we reverse the z-score back to the usual range by using the estimated mean and standard deviation at that age. We decided to only forecast future values based on the last three z-scores because the earlier measurements, in general, are not as relevant as the most recent.

F. Risk prediction

In this study, models SCORE2 and QxMD are employed to assess the risk of cardiovascular disease and type 2 diabetes. These models are selected due to their robustness and widely recognized efficacy in predicting the likelihood of developing these chronic conditions. Incorporating both SCORE2 and QxMD models allows for a comprehensive evaluation of cardiometabolic risk factors, enabling healthcare practitioners to make informed decisions regarding patient management and intervention strategies.

The Cardio-Vascular Diseases Risk Calculator – SCORE2 [1] model, developed by the European Society of Cardiology, is utilized to estimate the risk of cardiovascular events over a 10-year period. It incorporates variables such as age, sex, smoking status, blood pressure, and lipid profile to calculate the risk score. Additionally, SCORE2 considers regional variations in risk factors to provide more accurate predictions tailored to specific populations.

The Diabetes Risk Calculator – QxMD model [7], a comprehensive tool for clinical decision support, is employed to evaluate the risk of developing type 2 diabetes mellitus. This model integrates risk factors of age, BMI, family history, physical activity level, and dietary habits.

V. Results

For simplicity, we are presenting results for the variables incorporated in the SCORE2 and QxMD risk prediction model (with minor exceptions, such as the use of steroids, which cannot be predicted properly from the available data). In Table, III, results for imputation and data generation are presented. Variables Height and Weight are included in all datasets and are used as input to predict other variables. With the exception of Smoking, the errors of the remaining variables are not very large. We will consider making Smoking less fine-grained in the future, as the risk prediction models into which we are feeding it actually do not require the kind of granularity we have at the moment.

TABLE III
Mean absolute error for imputed data and for synthetic data.

	MAE	**Rel. Error (%)**
Height [cm]	Included in all datasets	
Weight [kg]	Included in all datasets	
SBP [mmHg]	3.92	3.2
Total cholesterol [mmol/L]	0.184	3.5
HDL [mmol/L]	0.082	6.44
LDL [mmol/L]	0.111	3.7
Smoking [1-9]	1.39	41.8

Tables IV and V present results for individual forecasting for age 18 from age 14 and age 55 from age 18, respectively. The errors of the first stage of forecasting are very low, as expected, considering the short time period. The errors of the second stage are higher, but we still judge them relatively low, with most being lower than the errors of the imputation. Smoking is again problematic, while the other variable with a high error is Weight. It is not clear why this is the case, but we hypothesize that many adolescents at age 14 are still undergoing puberty, which is a time of large body changes, making reliable forecasting difficult.

TABLE IV
Error metrics for individual forecasting to age 18 from age 14.

	MAE	**Rel. Error (%)**
Height [cm]	3.11	1.8
Weight [kg]	4.79	7.3
SBP [mmHg]	1.46	1.3
Total cholesterol [mmol/L]	0.05	1.1
HDL [mmol/L]	0.02	1.5
LDL [mmol/L]	0.05	1.7
Smoking [1-9]	1.01	46.9

In Table VI results for population-based forecasting for age 55 are shown. Most of the errors are larger than with individual forecasting, which is in line with this method being less personalized. Weight is forecast more accurately here,

TABLE V
ERROR METRICS FOR INDIVIDUAL FORECASTING TO AGE 55 FROM AGE 18.

	MAE	Rel. Error (%)
Height [cm]	3.47	2.0
Weight [kg]	13.60	16.6
SBP [mmHg]	2.39	2.0
Total cholesterol [mmol/L]	0.10	2.3
HDL [mmol/L]	0.08	6.1
LDL [mmol/L]	0.17	6.1
Smoking [1-9]	1.72	98.2

though. In the future, we may combine both methods or use the more accurate one for each variable.

TABLE VI
ERROR METRICS FOR POPULATION-BASED FORECASTING UP TO AGE 55.

	MAE	Rel. Error (%)
Height [cm]	1.62	0.9
Weight [kg]	10.58	12.3
SBP [mmHg]	10.91	9.0
Total cholesterol [mmol/L]	0.64	12.2
HDL [mmol/L]	0.21	16.3
LDL [mmol/L]	0.51	16.8
Smoking [1-9]	2.26	67.9

Rigorous evaluation of risk prediction, which is our ultimate objective, requires data on actual disease. While we are in the process of obtaining such data, we currently do not have it, so as a preliminary evaluation, we selected four tests persons with different levels of risk. The upper part of Table VII shows their health parameters, which serve as input data. Persons 1 and 2 are healthy, with person 2 having most parameters more desirable, although peson 1 is better with respect to HDL cholesterol. Persons 3 and 4 are unhealthy, with person 3 having even less desirable parameters than 4. So the expected risks are Person 2 < Person 1 < Person 4 < Person 3.

The upper part of Table VII shows the risks of the test persons, and Figures 2 and 3 present the probability of developing cardiovascular disease and diabetes, respectively, by using the data generated with population-based forecasting. One can see that the predicted risks are indeed ordered as expected. More specifically, for persons 1 and 2, the cardiovascular risk at a young age is relatively low, less than 0.5%. As they age, their respective risk curves also begin to rise relatively slowly, which is to be expected since those persons are relatively healthy. On the other hand, person 3 and 4 are not healthy at age 14 and already start with the risk of around 2.5% and 1.25%, respectively, moreover, as they age, their poor health increasingly manifests as disease risk, and thus also their respective risk curves start increasing significantly.

Looking at the diabetes risks, we can see that the pattern is roughly repeated. Person 1 and 2 start with a very small risk at the age of 15; moreover, over time, their curves also increase relatively slowly. However, persons 3 and 4 at age 14 already start at a very worrying risk probability at roughly 32% and 11%. Similarly, as in the case of cardiovascular risk, as they age, the risks increase more rapidly for persons 3 and 4 compared to persons 1 and 2. While the onset of diabetes tends to be earlier than that of cardiovascular disease, and so it is appropriate that the diabetes risks are higher, our prediction of diabetes risk is probably too high. A possible explanation is that there are not many people similar to Person 3 and 4 in our datasets, resulting in less accurate prediction. This is partially because much of our data from younger ages was collected several decades ago (otherwise, we could not have data for the same individuals up to age 55), and adolescents at that time were overall healthier than today.

TABLE VII
INPUTS FOR SCORE2 MODEL FOR FOUR PEOPLE AT AGE 14, AND THE PROBABILITY OF DEVELOPING CARDIOVASCULAR DISEASE (CVD) AND TYPE 2 DIABETES (T2D) BETWEEN AGES 55 AND 65.

	Person 1	Person 2	Person 3	Person 4
Age	14	14	14	14
Gender	M	F	M	F
BMI	20	19	30	29
SBP	110	107	139	135
Total cholesterol	4.0	3.5	6.0	5.0
HDL	1.5	1.3	1.0	1.0
LDL	2.0	1.5	4.0	3.5
Smoking	Never	Never	Yes	Occasionally
Risk for CVD at 55	3.0 %	2.8 %	18.7 %	11.8 %
Risk for T2D at 55	10.0 %	4.6 %	85.0 %	70.2 %

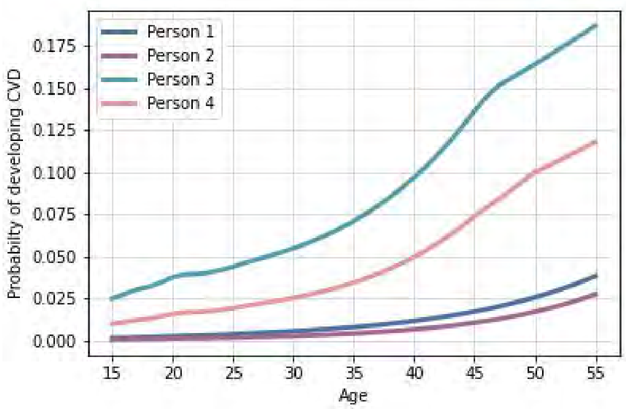

Fig. 2. 10-year probability of developing cardiovascular disease (CVD) by using data generated with population-based forecasting.

VI. CONCLUSION

In the paper we presented a methodology of health risk prediction for children, which combines multiple heterogeneous datasets with existing risk-prediction models for adults. After preprocessing, we imputed missing data within each dataset. We then combined datasets and generated values of variables that were not present in all datasets from the variables in their overlaps. Afterwards we used two methods for predicting risk factors at age 55 from those at age 14: one that relied on individual data spanning the prediction age range, and a more

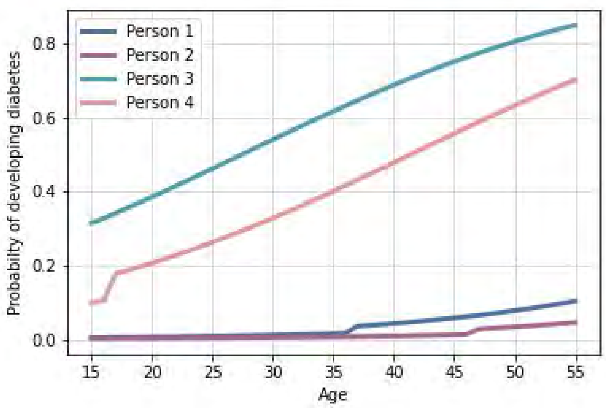

Fig. 3. 10-year probability of developing type 2 diabetes by using data generated with population-based forecasting.

general one that relied on population data. Finally we fed the forecase risk factors into SCORE2 and QxMD models for cardiovascualr disease and diabetes, respectively.

Our results show that the errors in imputation and synthetic data generation are low, suggesting that even with limited dataset overlaps, the generated data provide a solid foundation for forecasting. The forecasting methods performed well, with the personalized approach showing slightly better accuracy. Although rigorous validation of risk predictions is ongoing, the preliminary results are promising, indicating that our approach could improve the identification of at-risk children beyond current methods such as BMI.

In this work, we relied primarily on biological features common in established risk prediction models, which tend to indicate risk when it is already apparent. Future work will focus more on behavioral features, like diet, physical activity, and fitness, which can signal risk earlier than biological markers. This shift will help us better predict high-risk individuals who appear healthy but engage in risky behaviors that could lead to future health problems.

Moving forward, we will incorporate more datasets, refine our methodology, and conduct a more rigorous evaluation. Our ultimate goal is to develop a comprehensive neural network model that fully leverages all available datasets, which will require innovative architecture and training techniques.

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Recognizing Finger Flexions From EMG Signals Using Wavelet Transform and Machine Learning

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Abstract— **Wavelet transform is a mathematical tool for analyzing data where the signal values vary at different scales, such as in electromyographic signals (EMG), so it is widely used in EMG signal processing systems. In this paper we present the possibility of using wavelet transform on EMG signals which are measured with two sensors placed on the forearm of eight examinees performing individual flexion of the fingers of the palm and fist. The selection of the appropriate mother wavelet and appropriate level of decomposition is performed by implementing several wavelets from the Daubechies family with four different levels of decomposition and according to the results obtained after training the models, for the final solution we use db1 wavelet with second level of decomposition. To generate useful features from the wavelet coefficients, we use frequency domain features, which are further used as input features for training and testing the machine learning models. Classification algorithms such as Random Forest, Support Vector Machine, K-nearest neighbors, Decision Tree and Extreme gradient boosting (XGBoost) are implemented on the feature set. With evaluating and comparing the classification performance of different machine learning algorithms, we highlight the improvement in accuracy and robustness achieved by combining wavelet transform and feature extraction in electromyographic signal analysis.**

Keywords— electromyographic signals, wavelet transform, feature extraction, machine learning

I. INTRODUCTION

The hands are vitally important part of who we are and the activities that we take. They are among the most complex tools we possess and because of that reason amputees experience difficulties in their everyday life. A prosthetic arm is an effective solution to overcome these obstacles. With the purpose of automating the control of prosthetic arms for more efficient use, electromyographic signals and machine learning models play a vital role in the refinement process. The statistics, which are maintained by the health organization Amputee Coalition, show up to 3 million people who have an upper limb amputation. Around 1.4 milion people have forearm amputation, while 700 000 people have upper arm amputation, 200 000 people have shoulder amputation, 100 000 people have palm amputation. [1]

The field of prosthetic arms has seen remarkable progress, evolving from basic designs to sophisticated, functional devices that aim to restore greater functionality and natural movement to individuals with upper limb deficiency. In today’s prostetic devices, more light and durable materials such as plastic, aluminum, titanium and silicone are found, and the biggest difference is that these prostheses are mostly electric. In a world where there are many people with missing limbs, companies strive to produce prosthetics that people can afford, as current prostheses have a high purchase price. The integration of machine learning into prosthetic arms has enormous potential to improve functionality, comfort and overall usability for people with upper limb deficiency, promising more natural, intuitive and personalized control over these devices.

Processing electromyographic (EMG) signals with wavelet transform is a process that has already been successfully applied in some cases for the classification of finger movements obtained from measurements taken from forearm muscles as in [2], [3],[4] and [5].

The authors of [2] use multiple machine learning algorithms to predict the flexion of individual fingers, as well as certain combined flexions, by using two EMG sensors placed on the forearm. The data is first preprocessed by extracting necessary time and frequency domain statistical features, and is then sent to each classifying algorithm individually. The best result of 96.6% was achieved with the XGBoost algorithm, followed closely by Extra Trees at 95.4% and Random Forest at 95.2%.

The authors of [3] achieve an accuracy of around 95.5% with a neural network with six hidden layers with 32 neurons per layer. The data are collected with the help of two surface electrodes that are placed on the forearm of eight subjects and the database contains individual and combined movements of the fingers of the hand. After applying a wavelet transform to the data, where db1 is used as the mother wavelet with the second level of decomposition, they extract temporal features, where there are 12 time domain conventional ones that are used frequently and 5 new ones that increase the classification accuracy. In [4] the authors get their measurements from a volunteer performing six daily upper extremity movements and two forearm muscle channels. EMG signals were recorded on two muscles of the volunteer's right forearm with two pairs of surface electrodes. After the EMG signals have been obtained, they apply a wavelet transform to the data and they try several wavelets in order to determine which one gives the best results and at what level accordingly. With the reconstructed EMG signals and subsets of wavelet coefficients they extract features that will be used in the classifier. They use mean absolute value and mean square root as the most famous characteristics. The results show that only EMG features extracted from reconstructed EMG signals from first level and second-level detail coefficients provide an improvement in class separability in the feature space.

The main goal of this paper is to process EMG data using wavelet transform before training different machine learning models to recognize the movements that the person using the prosthetic arm attempts to make. The main emphasis is placed on the wavelet transform in order to see if it improves classification results.

II. DATA ACQUISITION

The dataset that is used and processed in this paper is from [6]. The measurements are performed on eight subjects, six men and two women aged between 20-35 years who perform the necessary finger movements. The three electrodes are placed on the flexor digitorum profundu muscle located on the lower part of the forearm, and on the extensor digitorum communis muscle located on the upper part of the forearm, while the third electrode is the reference electrode, as shown in Fig.1. After the signals were collected from the electrodes they were amplified using a Delsys Bagnoli-8 amplifier with a total gain of 1000. Furthermore, a 12-bit analog-to-digital converter (National Instruments, BNC-2090) was used to sample the signal at 4000 Hz.

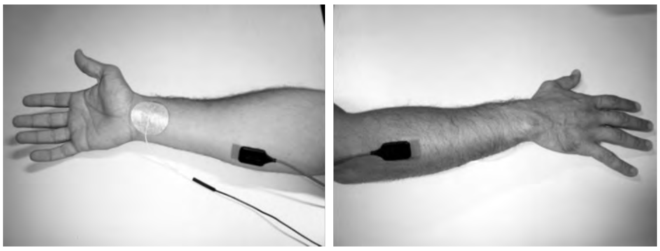

Figure 1 The placement of the three electrodes

III. DIGITAL SIGNAL PROCESSING

The data needs to be preprocessed and prepared before a classifier can be trained and tested in order to achieve more accurate classification. Preprocessing of EMG signals includes several basic steps to ensure the reliability and accuracy of the collected data for further feature extraction and signal classification. The first step is signal filtering, where the data is filtered with two types of filters. The first one is a bandpass filter with a finite impulse response that is used to filter signal frequencies in the interval of 20-450 Hz, because that interval carries the majority of the information. The second one is a notch filter which is used to remove the noise from the electrical network at 50 Hz.

After the data has been filtered, the next preprocessing step represents segmentation. Segmentation improves features extraction capabilities, reduces signal complexity, improves model training and one of the most important reasons in this paper is that users of the prostethic arm do not feel the delays in movements. The smallest acceptable delay that would not be felt by users is approximately 250ms, so accordingly one segment duration is 250ms, with the sampling frequency being 4kHz, so there are 1000 data in one segment.

IV. WAVELET TRANSFORM

The wavelet transform is a mathematical tool used in signal processing and analysis to decompose signals into their constituent components at different scales. The wavelet transform uses wavelets that are small, localized and oscillating functions that differ in scale and frequency. These wavelets are shifted and propagated through the signal, capturing both frequency and time information, allowing for a more detailed representation of signals with transient or non- stationary characteristics [7]. A family of wavelets can be constructed from a function $\Psi(x)$, also known as a "mother" wavelet has finite energy as well as zero mean value. The "mother" wavelet is chosen based on the characteristics of the signal or image and the nature of the application for which the transform is being used. The "daughter" wavelets $\Psi^{a,b}$ (x) are formed by displacement (b) and contraction (a) of the "mother". Equation (1) defines the "daughter" wavelets.

$$\Psi^{a,b}(x) = \frac{1}{\sqrt{a}}\Psi\left(\frac{x-b}{a}\right) \tag{1}$$

There are different families of wavelet functions such as: Haar, Daubechies, Symlet, Coiflet, Morlet etc. In this paper, we use discrete wavelet transform due to the possible options of choosing level of decomposition on the original signal in order not to overload the computer power. During the process of choosing an appropriate "mother" wavelet, it is necessary to understand their properties such as: symmetry, orthogonality and regularity. Regarding the properties possessed by the families of wavelets, we test the wavelets from the Daubechies family as the most compact. We test all of the wavelets starting from db1-db7 with corresponding levels from first to fourth and the best results and the chosen wavelet is db1 with second level of decomposition. The wavelet that we use is shown in Fig.2.

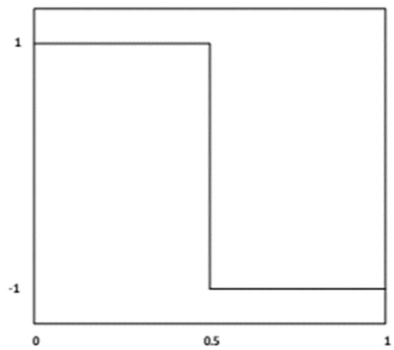

Figure 2 Wavelet db1 or Haar

Table 1 shows the results of testing different wavelets and levels of decomposition. The reason why the Table only shows results with second level of decomposition is by far having the best results out of all the other levels. It is evident that db1 with second level of decomposition is therefore the best choice to use for further feature extraction.

TABLE I. Results of different wavelets with second level of decomposition

Wavelets	**Level**	**Result**
db1	2	84.5%
db2	2	79.34%
db4	2	80.08%
db7	2	82.18%

V. FEATURE EXTRACTION

Feature extraction in machine learning involves transforming raw data into a reduced set of meaningful features that capture essential information while discarding unnecessary or irrelevant details. Feature extraction aims to improve model performance, reduce computational complexity and enable more effective learning by focusing on the most informative aspects of the data. Through techniques such as statistical measures, analysis in the time or frequency domain or advanced methods such as feature extraction based on deep learning, this process generates compact yet informative representations of the data.

The EMG characteristics can be analyzed in time domain, frequency domain and time-frequency domain. The illustration of signal characteristics in relation to frequency is the representation of frequency domain. The frequency spectrum of some signal shows what frequency that signal relies on.

Within this paper we use the frequency domain features, these are often used in signal processing, machine learning and other fields to analyze and classify signals based on their frequency content. The reason behind the widespread use of frequency domain features is the Power Spectral Density. The frequency domain features that are used for input features are:

- Power Spectral Density (PSD), which measures the power distribution across different frequency ranges in a signal, and is used to analyze the frequency content of a signal and identify dominant frequencies. Here we calculate PSD by using Welch's method, where x(n) represents the EMG signal value in a segment n and N represents the length of the segment:

$$PSD(f) = \frac{1}{N}\left|\sum_{n=0}^{N-1} x(n)e^{-i2\pi fn}\right|^2. \quad (2)$$

- Entropy, which measures the disorder or randomness in the PSD distribution. Higher entropy indicates greater randomness in the frequency components:

$$Entropy = -\sum_i P_i \log_2(P_i). \quad (3)$$

- Dominant Frequency, which represents the frequency at which the signal power is the highest.
- Mean Frequency, which is the calculation of the average frequency of the signal:

$$Mean\ Frequency = \frac{\sum_{i=1}^{N} e_i Q_i}{\sum_{i=1}^{N} Q_i} \quad (4)$$

- Max-Min Drop Ratio, which is the ratio of the average value of the mean power density and the minimum value of the power density.
- Variance of Frequency, which represents the spread or dispersion of frequencies in the spectrum.
- Total power, which represents the total power or energy contained in the signal at all frequencies.

Fig. 3 respectively presents graphs plotting the approximate coefficient and the two levels of detailed coefficients for one electrode during thumb movement.

After forming the dataset comprised of the extracted features from the wavelet coefficients, we apply standardization procedure to further improve the performance of the models.

VI. CLASSIFICATION AND RESULTS

Before classification, the dataset was divided into training and testing sets. The training set consisted of 90% of the total dataset (6,480 data points) and the testing set comprised the remaining 10% (720 data points). The training set was used for training the algorithms through stratified 10-fold cross- validation. The testing set was reserved for the final evaluation on previously unseen data. Five different algorithms were used for classification:

- K- Nearest Neighbors,
- Support Vector Machine,
- Decision Tree,
- Random Forest,
- Extreme gradient boosting (XGBoost).

The F1 score of each of the five algorithms is presented in Fig. 4, where we can observe that the best performer is XGBoost, while the worst is K- Nearest Neighbors. For each of the algorithms, hyper-parameter optimization was applied by grid search. With different hyper-parameters, with different values, we will show the chosen ones for each of the algorithms:

- K- Nearest Neighbors, we use the Manhattan distance and 10 neighbors,
- SVM, we use the regulation parameter with value 100 and Gaussian kernel,
- Decision Tree, we use maximum depth of 25,
- Random Forest, we use 1000 trees,
- XGBoost, we use 1000 trees and learning rate of 0.1.

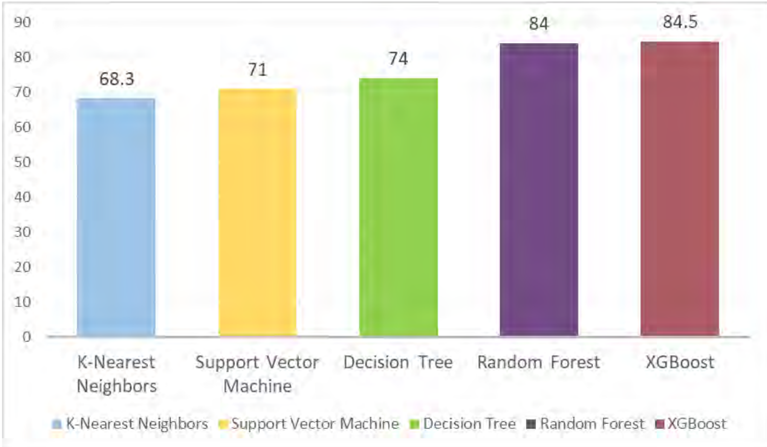

Figure 4 After classification results with F1 metric with frequency domain features

VII. DISCUSSION

Despite the fact that our machine learning models have achieved good results thus demonstrating a solid foundation, there are areas that can be improved upon. With additional work and fine-tuning, we can address some of the current errors and enhance the model's overall performance.

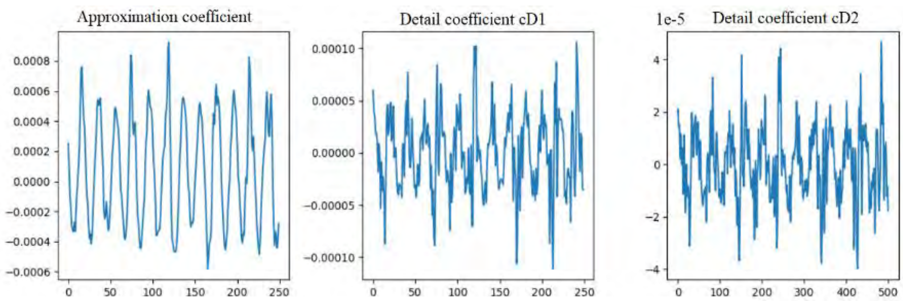

Figure 3 Plots of the approximate coefficient and two detail coefficients

To get a better visualization of the results and errors that occurred during training, we used confusion matrices that numerically show how many classes of each type are correctly predicted, how many classes are incorrectly predicted and also show exactly where the classification errors occur. The confusion matrix is presented in Fig.5, the machine learning model that is used is XGBoost. From the observation, it can be concluded that most of the movements are correctly classified with some slight deviations, most of which occur in the middle finger, while smaller errors are made in the thumb and index finger and the most accurately classified is the little finger. From the matrix it can be observed that when the actual movement is the thumb, the classifier misclassifies it as flexion of the index finger.

An important enhancement to our approach involved the use of wavelet transform, which significantly influenced the results by providing better performance. Wavelet transform is a powerful signal processing technique that decomposes a signal into components at various scales, allowing for the extraction of both time and frequency information simultaneously. This is particularly beneficial for analyzing EMG signals, which are non-stationary and exhibit variations over time. By applying wavelet transform, we were able to capture more relevant features from the EMG signals, leading to improved classification accuracy.

However, it is important to note that the results can have errors due to several factors. Some of these external factors can’t be controlled and they will be present even when the prosthesis would be used by humans. Variations in the anatomy of the hand, such as differences in hand size, muscle structure and thickness of the forearm of the examinees can impact the consistency of EMG signal patterns. Additionally, the method by which EMG signals are measured, including electrode placement, skin conductivity and signal acquisition techniques can introduce variability. The type and quality of instrumentation used to measure EMG signals including sensor sensitivity and signal processing algorithms, also play a crucial role. And last, but not least the anatomical nature of fingers. The distribution and density of muscle fibers, as well as the location and alignment of tendons, can vary greatly between individuals, resulting in differences in how electrical activity is generated and transmitted. These anatomical differences can cause variability in the EMG signals captured from different subjects, making it challenging to develop a one-size-fits-all model. By understanding and accounting for these anatomical variations, we can improve the accuracy and reliability of EMG-based assessments and applications.

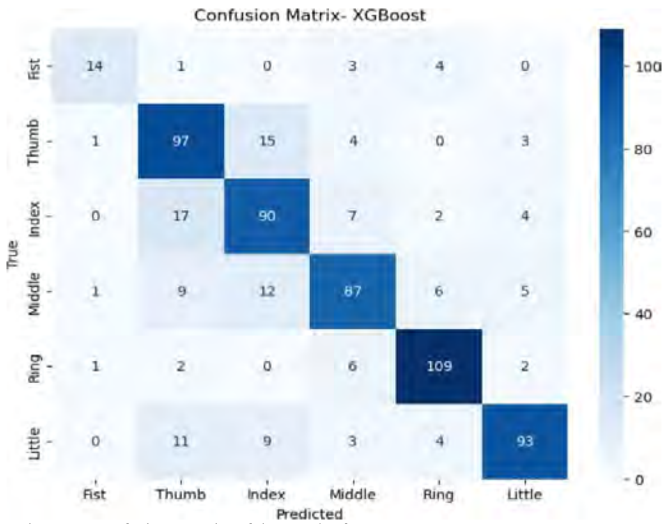

Figure 5 Confusion Matrix of the results from XGBoost

VIII. Conclusion

In this paper we have presented the results of using wavelet transform in the process of classification of EMG signals for finger flexion in order to discover new insights on how the results would be improved with its use. The paper focuses on the analysis of six different movements, five individual movements and a fist, which were measured by surface electromyography, properly filtered, segmented and standardized. After preparing the dataset, we obtained the wavelet coefficients using the Daubechies wavelet db1 with level 2 of decomposition. From these coefficients, we extracted frequency domain features such as Power Spectral Density (PSD), Dominant Frequency, Mean Frequency, Entropy, Max-Min Drop Ratio, Variance of Frequency and Total power, that later on we use as input features to train and test the machine learning models. By comparing multiple algorithms we have decided that XGBoost proved to be best, such as choosing db1 with second level of decomposition and the frequency domain features the by achieving a score of 84.5%. This result is a good achievement, but can be further improved by using additional hyper-parameter optimization and implementing more detailed feature engineering that would allow for the extraction of more relevant information taken from the data. What remains for discussion and for future work and improvement is the investigation of the application of a neural network with different architectures in order to enable the maximum utilization of the wavelet coefficients for even better results in signal classification. The neural network should achieve an easier, faster and more refined implementation of the model in different real situations in terms of time, accuracy and usability.

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Gesture control robotic arm using flex sensors

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I. INTRODUCTION

Robotics are increasingly becoming a common presence in business, industry, medicine, and military fields, with their complexity continually growing. Advances in mechatronics have made robots more adaptable and lifelike, thanks to the development of sensors and motors with highly sophisticated designs.

Robotic arm applications demand sensors with high degrees of repeatability, precision, and reliability. Flex sensor is such a device, which accomplish the above task with great degree of accuracy. For the main robotic arm operations (pick and place) to be efficient, a microcontroller environment is necessary. Generally, there are two basic ways to controlled the robotic arm wired and wireless. Both technologies have some advantages and some disadvantages as wired circuit is complex and have cannot be controlled from the long distance but it does not require extra batteries as required for wireless system. Wireless systems also have external interference whereas wired system is less interference. The cost of wired system is much less than the wireless system.

Today, most multi-fingered robotic hands are employed in service robots, human-friendly robots, and personal robots. In manufacturing and other fields requiring precision and dexterity, stable gripping and delicate manipulation with a multi-fingered robotic hand are becoming increasingly essential.

In this paper, a design and implementation of a gesture control robotic arm using flex sensors is presented. A robotic hand is designed to perform operations by imitating the movements of a human hand, as illustrated in Figure 1. The robotic arm is able to grip objects of various sizes and weights through wired communication by using a wearable controller glove that consists of five flex sensors. The necessary materials for the implementation include 5 servo motors, 5 flex sensors, an Arduino Uno, and a fishing line. This designed work is an educational based concept.

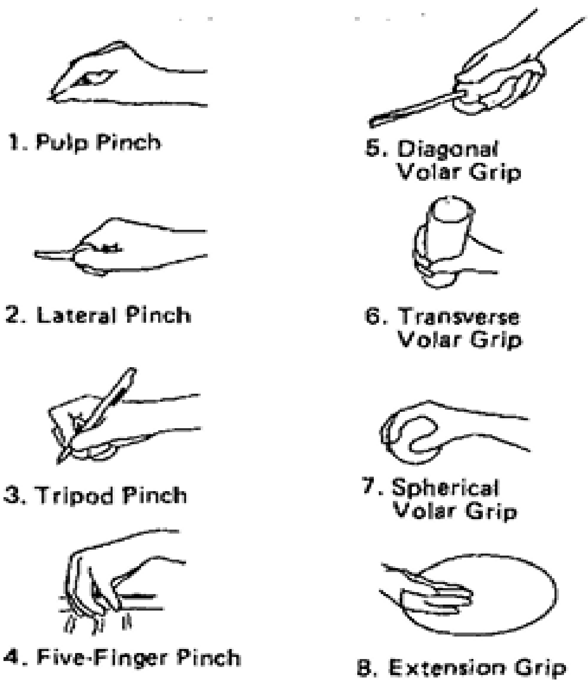

Figure 1. Different grips a human hand can execute

II. METHODOLOGY

The proposed robotic hand has three basic parts: a forearm, five fingers, and a palm, all manufactured using 3D printing technology. The process begins with the design phase, carried out using SolidWorks software, followed by 3D printing of the parts, and finally, assembling them and connecting the whole system. Each finger, except the thumb, is constructed from three phalanges, which are connected by 2mm aluminum wire and secondary adhesive. The wheel is linked to the tendon, while the pin is fixed to support the hinge. The palm is a single component with a complex design, serving as the central connection point between the fingers and the forearm. It features grooves to guide the tendons from the actuators located in the forearm. These grooves ensure that the tendons for each finger do not interfere with each other and constrain their movement to specific areas, simplifying movement control. The forearm is composed of two main sections, each containing three parts securely fastened with screws. Figure 2 shows the shape of the forearm and the complete palm. The Tendon-Driven Mechanism (TDM) relies on wire steering over pulleys. It is used to construct a lightweight spatial arm, automated hands, a suspended rapid framework, and a humanoid robot. The driving force is transmitted to a series of joints through the pulleys.

Figure 2. 3D robotic arm

III. COMPONENTS

The human hand is a complex structure involving several essential components for performing actions, including bones, muscles, tendons, and nerves. To execute a grip, these components must not only be active but also collaborate with each other. In a robotic hand, the necessary components for grip execution include servo motors for precise control of finger movement, flex sensors for detecting joint angles and adjusting finger positions, a tendon-driven system to simulate tendon movement and generate gripping force, control software for processing sensor data and managing servo motors, structural components such as aluminum wire and adhesive for constructing and stabilizing the fingers, and wiring and connectors for integrating all components and providing electrical power and signals.

A. Flex sensor

The flex sensor is a variable resistor, where the degree of bend in the sensor determines its resistance, as shown in Figure 3. The resistance variations are recorded digitally, and this data is translated into degrees of rotation for the servo motors.

Figure 3. Variable resistance depending on bend

To read data from a flex sensor, a voltage divider is implemented to enable analog-to-digital conversion on the Arduino UNO. The voltage divider provides a varying voltage output to the Arduino UNO, which changes proportionally to the varying resistance of the flex sensor, as described by Eq. 1. R_2 is the resistance from flex sensor, R_1 is a static resistance from a resistor, Vin is the input voltage and Vout is the voltage going to the Arduino pins.

$$V_{out} = V_{in} \circ \frac{R_2}{R_1 + R_2} \qquad (1)$$

The flex sensor consists of several key components: a substrate material, usually made of flexible polyimide or polyester, provides the base; conductive ink or resistive material, printed on the substrate, changes resistance when the sensor bends; leads or connectors, which are metal strips or conductive paths, connect the resistive material to an external circuit; a protective layer coats the sensor to shield it from physical damage and environmental factors; and terminals, or end connectors, interface the sensor with electronic circuits. Together, these components detect and measure bending, translating it into an electrical resistance change.Using the flex sensors, the servo motors can be controlled from 0° to 180°. The relationship between the flex sensors placed on the bracelet and the angle values of the servo motor corresponding to each finger is shown in Table 1.

Finger	Flexion Angle	Resistance value
Thumb finger	0º 90º 180º	13.4 KΩ 16.5 KΩ 20.1 KΩ
Index finger	0º 90º 180º	15.8 KΩ 17.7 KΩ 26.3 KΩ
Middle finger	0º 90º 180º	13.7 KΩ 17.2 KΩ 23.6 KΩ
Ring finger	0º 90º 180º	14.1 KΩ 16.9 KΩ 22.4 KΩ
Little finger	0º 90º 180º	14.3 KΩ 18.6 KΩ 24.1 KΩ

Table1. Flexible sensor angle-resistance static characteristic (lookup table)

A. Servo motor

Servo motors (Figure 4) are often used with microcontrollers for precise positioning and control of the rotation angle. They are small, lightweight, and capable of accurate movements, making them ideal for various projects.

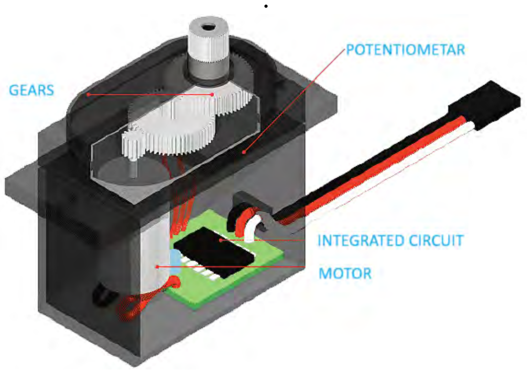

Figure 4. Components of servo motor

A servo motor consists of several key components: a DC motor that provides basic rotational movement, a gearbox that reduces the motor's speed and increases torque, a potentiometer that detects the current position of the motor shaft and provides feedback to the control circuit, and a control circuit that manages the position of the motor based on input signals.

Pulse Width Modulation (PWM) is a method for controlling servo motors, where the width of the pulse in the electrical signal directly affects the rotation angle of the motor. Figure 5 presents some examples of the generated PWM signals for controlling the rotation angle of the servo motor.

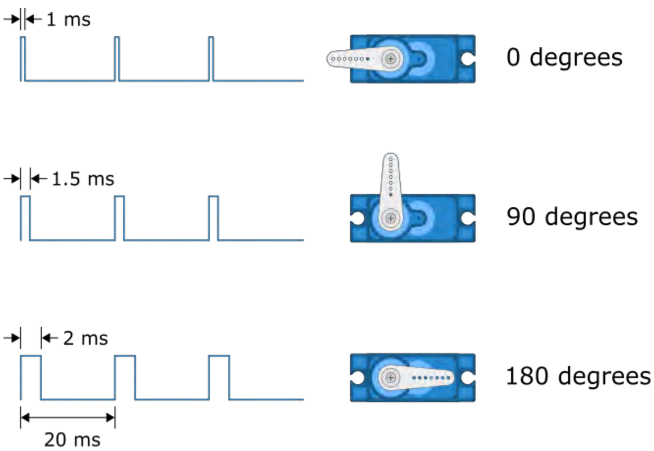

Figure 5. PMW signals with varying duty cycles

IV. Circuit Diagram

The robotic arm control system is a complex integration of software and hardware components that enable precise control and manipulation of the robotic arm. The interaction of flex sensors with Arduino represents an excellent way to create interactive projects. Using these sensors and proper Arduino programming, applications can be developed to measure flexibility and movement in various fields, such as robotics and medical technology. Figure 6 shows the complete block diagram.

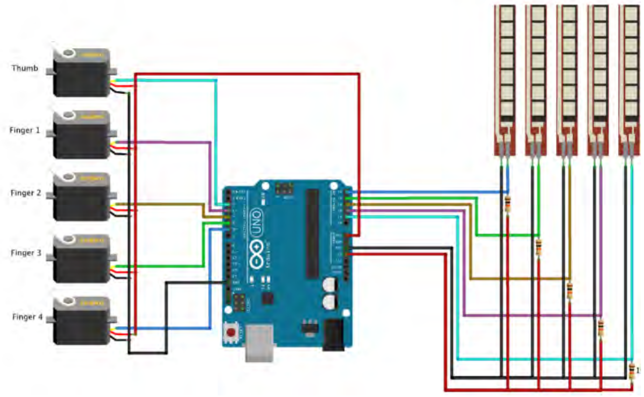

Figure 6. Complete circuit block diagram

V. Block Diagram

The code is designed for controlling servo motors via flex sensors, which are mounted on a glove to control the robotic arm. As can be seen from the Figure 7, at the begin, the sensors and servo motors must be defined to get in the setup-move servos loop.

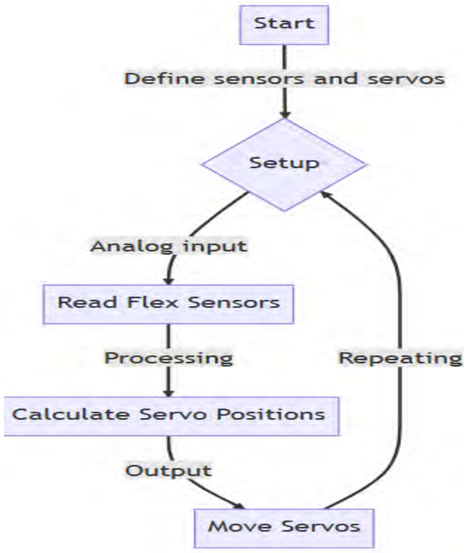

Figure 7. Main block diagram for the code

VI. Test and Results

The testing was divided into two groups: imitation of human fingers and grasping lightweight objects, including those with both soft and rough structures. Figures 8 and 9 show the results from various tests. As observed, the robotic hand performs tasks like grasping different objects (a ball and a plier) with high accuracy (Figure 8) and precisely mimics the signs executed by the control glove (Figure 9).

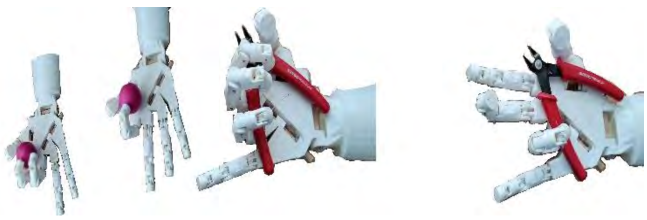

Figure 8. Results from grasping objects

Figure 9. Results from the imitation of a known finger gesture

VII. Conclusion

The robotic arm was designed as a part of the diploma work. Based on the testing results, one can conclude that the robotic arm it is a fully functional robotic arm, capable of accomplishing tasks like grasping small objects and sign mimicking with satisfactory precision. The flex sensors on the glove used by the operator had to be adjusted several times to fit securely on the glove, enabling the achievement of the desired servo motor angle range. After adjustment, the performance of the flex sensors was good but not perfect. The glove was not ideal due to its fixed size and adjustments when worn, which affected the bending of the flex sensors. Additionally, the bending angle of the flex sensors varied depending on the user. A suggested improvement for the robotic arm is to replace the wired communication by wireless and to enhance the palm of the robotic arm which requires further research.

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Design and implementation of a laboratory-scale photobioreactor

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***Abstract*— Photobioreactors have been a relevant field of study in the area of biotechnology in recent times. Although they are almost always implemented on a large scale, photobioreactors for experimental laboratory use are on the rise. In this paper, we present a simple approach for designing modular and programmable laboratory-scale photobioreactors. Since the optical requirements are proposed in the form of Photosynthetic Photon Flux Density, a unit usual for the field of biotechnology, they are first converted to more standard radiometric and photometric units. Given the available choice of electronic components, we design a lighting system that satisfies the given requirements. The design process is split into two parts: a numerical model for calculating the lighting distribution on a surface and the design of the electronic system. The numerical model uses the light-emitting diode parameters, geometry, and light propagation laws to approximate the illumination at a point. The electronic system requires optimal arrangement of the diodes, the choice of appropriate bias resistors, a microcontroller, and transistors for regulation of the intensity and timer. The final design proved that the process of implementing a photobioreactor is not a simple task, and there are many sources of error to factor in.**

Keywords—photobioreactor; lighting; phototroph bacteria; microcomputer system; light-emitting diodes;

I. Introduction

A fundamental aspect of nature is the interaction between light and microorganisms through various processes such as photosynthesis, phototaxis, and photomorphogenesis. Light and its effects on microorganisms have been studied for some time now, especially from the perspective of improving environmental conditions in various biotechnology-adjacent industries. The field of biotechnology is growing rapidly as a result of the increased demand for its products while trying to keep the negative effects on the environment to a minimum. Nowadays, a good portion of the technologies and products utilized in this field are readily available, which offers an easier gateway to research and experimentation in the areas of biotechnology. The need for innovative approaches towards improving the efficiency and specificity of the systems used in biotechnology grows bigger every day. As such, designing a system that can maintain the needed conditions in a controlled environment accurately in order to stimulate growth and maximize waste usage is an important problem in this field. The availability of simple but powerful electronic systems for control enables the fast development and deployment of experimental platforms that can be used in both academia and potentially in industry, if the design proves feasible.

One of the platforms of this kind are photobioreactors, which utilize natural or artificial light sources to facilitate the metabolism and growth of various microalgae and phototrophic bacteria. In order to improve their efficiency, the effects of different light parameters on the cultivated organisms, such as wavelength, intensity, and light-dark cycles, ought to be studied. Photobacteria are one of the key players in modern methods for wastewater treatment, a serious concern in the food, textile, and many more industries, which in turn produce valuable biomass and photopigments such as carotenoids while reducing the effects of the wastewater. As such, improving the process of wastewater treatment by optimizing the conditions for photobacteria is of paramount importance.

With that being said, the centerpiece of a photobioreactor is the lighting system. Today, affordable and powerful microcontrollers offer simple yet precise control of the parameters of lighting systems, making photobioreactors even more suitable for experimentation and research. Many recent studies have tackled this problem from different perspectives. For example, one study has shown that infrared irradiance intensity has a positive effect on the growth of purple photobacteria [1]. Effects on biomass yield, valuable substance production, and pollutant removal in photobacteria have been noticed as a result of changing between light and dark cycles in given time intervals [2]. The efficiency and specificity of these lighting systems can also be improved by tailoring the light spectrum to the absorption spectrum of the cultivated microorganisms [3]. It must be noted that implementing artificial lighting comes at a cost. Although there are the aforementioned benefits, they might not always outweigh the energy used, especially not in large-scale cultivation [4]. This is why numerous photobioreactor designs opt for light-emitting diode (LED)-based light sources, considering their narrow spectrum band, which can fit easily into the needed photosynthetic absorption spectrum, high efficiency, compactness, and low heat emission [5] [6] [7] [8].

While designed lighting systems are rarely a one-size-fits-all solution and are usually implemented as specifically as possible, in this paper we approach the problem with a more general design as a priority. Instead of implementing multiple systems for different experiments, we propose a single programmable system built around certain prerequisites: light intensity control, timer control, and shape modularity for both rectangular benchtop shakers and cylindrical bioreactors.

With that being said, the path for exploring the effects of light on the microbial metabolism is open and leading towards more fine-tuned solutions, which would pose a step in both the knowledge and utilization of photobacteria for environmental and sustainable goals.

II. Design of the Lighting System

The design process stems from the optical requirements proposed for the lighting system. In order to estimate the options for a physical implementation, numerical calculations must be done first. In our case, the following parameters needed to be fulfilled: three separate sources of light with dominant orange, green, and infrared spectrums, each within a given Photosynthetic Photon Flux Density (PPFD) range. Since the PPFD is not a radiometric unit, it needs to be converted to irradiance in order to have comparable units later on.

TABLE I. LED PARAMETERS

	G-RND01-LED5 (Green)	O-RND01-LED3 (Orange)	TSUS5402 (Infrared)
Dominant wavelength [nm]	520 ± 20	610 ± 20	950 ± 25
Luminous intensity [cd]	39 @ 20mA	3.8 @ 20mA	/
Radiant angle	Narrow	Medium	Wide

To make the conversion between the PPFD and irradiance, we need the wavelengths λ of each LED provided in Table I. By using (1) and the sum of energy of all photons in unit time falling on a surface area, we can calculate the needed irradiance for each LED provided in Table II. The other two factors in the equation are the speed of light *c* and Planck's constant *h*. It's important to note that every parameter used in the calculations is based on the available LEDs, which was the first limitation in fully optimizing the design.

$$E = c \cdot h / \lambda \qquad (1)$$

In order to proceed with the calculations for the lighting distribution, the radiometric and photometric units need to be bridged, hence the conversion from luminous intensity (I_v) to radiant intensity (I_e). Our simulation approach utilizes the diode parameters (in the radiometric domain), geometry, and electromagnetic wave propagation laws as simplified as possible, while still maintaining accuracy.

TABLE II. PPFD AND IRRADIANCE RANGES

	Green	Orange	Infrared
PPFD [μmol/m^2 s]	90 ÷ 100	25	90 ÷ 100
Irradiance [W/m^2]	20.724 ÷ 23.027	4.907	11.334 ÷ 12.604

The infrared LEDs already have their radiant intensity on the datasheet (since they don't emit visible light), whereas for the orange and green LEDs, given their datasheet parameters for luminous intensity in candela, we convert them to radiant intensity in Watts over steradian. The conversion is done by using the following equation [9]

$$I_e = I_v / K_m \cdot V(\lambda) \qquad (2)$$

where K_m is a constant named photometric conversion factor and V is the spectral sensitivity factor of the eye for daylight viewing, a dimensionless function of the wavelength. The values for K_m, V, and I_e are given in Table III.

TABLE III. LED RADIANT INTENSITIES

	G-RND01-LED5 (Green)	O-RND01-LED3 (Orange)	TSUS5402 (Infrared)
K_m [lm/W]	683		
$V(\lambda)$	0.7617	0.5279	/
Radiant intensity [W/sr]	0.074965	0.010539	0.02

Besides the nominal radiant intensity, we need to factor in the radiation diagram too in order to calculate the irradiance E from a single or multiple diodes on an equidistant flat surface. In these calculations, the variable parameters are the smallest distance between the lighting system and shaker/bioreactor, the distance between two neighboring diodes, and the type of diode used (its nominal radiant intensity and radiation diagram).

The angle between the point of interest and a diode is calculated using right triangle geometry. Using this angle, we look up the relative intensity of the different types of LEDs according to their radiation diagram. The incident angle α is one factor of proportionality in calculating the irradiance of a point. To simplify things, we assume the illuminated surface is Lambertian. Consequently, we can use Lambert's cosine law to account for the incident angle α and radiation distribution of the diode.

Another factor of proportionality is the distance between the LED and the point of interest on the surface, denoted by d. It is well known that light propagation obeys the inverse square law, which states that the intensity decreases with the square of the distance between the source and the point at which we calculate the irradiance. Combining these two factors with the nominal radiant intensity I_e, we arrive at the equation for the irradiance at a single point from a single diode E, given in (3). The irradiances are calculated for every combination of points and diodes and are summed, or integrated in a continuous case, per point at the end, giving us the total irradiance at every point on the surface. By graphing this, we can inspect if the irradiance is uniform along the surface and also see if we meet the criteria for irradiance given in Table II.

$$E = I_e \cdot \cos(\alpha) / d^2 \qquad (3)$$

With this numerical model, we can now simulate the irradiance for different combinations of diodes. Because this step of the design process can lead to absurd results, we must limit some of the parameters and take the electronic design into consideration, as symmetry in the electronic design is of great importance. As such, we consider the illuminated area to be 50 centimeter long, coming from the 45-centimeter length of the platform of the shaker and the ±2-centimeter movement of the platform itself. Because of this, the LEDs must be distributed along a at least 55-centimeter-long strip. Another thing to be noted is the divisibility of the number of diodes of the same type, considering they need to be split into identical branches that are biased to the needed current. In our case, we chose the number of diodes to branch ratio of 3, 4, and 5 per type of LED. For the nearest distance between the diode and illuminated surface, we chose 7 centimeters in order to calculate the irradiance at a distance with a small overhead, while still having the option to bring the system closer to the platform if an increase is needed. After trial and error and taking the electronic design into consideration, the following parameters were chosen: length of the strip l=55.5 cm; distance between green LEDs d_{gr}=1.65 cm; number of green LEDs N_{gr}=27; distance between orange LEDs d_{or}=1.9 cm; number of orange LEDs N_{or}=25; distance between infrared LEDs d_{ir}=2.5 cm; number of infrared LEDs N_{ir}=21. The irradiance distributions, along with the irradiance requirements from Table II. of each spectrum are presented in Figs. 1-3 below. The excess length of the strip accounts for the lower intensities at the edges.

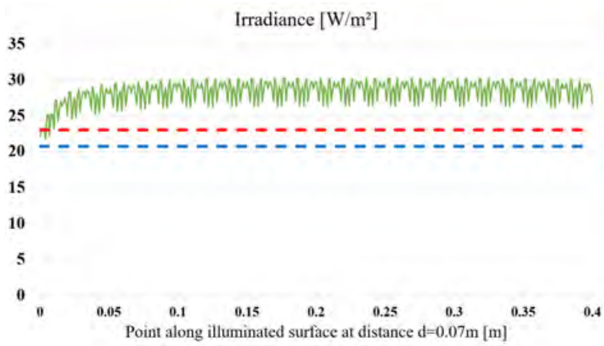

Fig. 1. Irradiance distribution of green LED array.

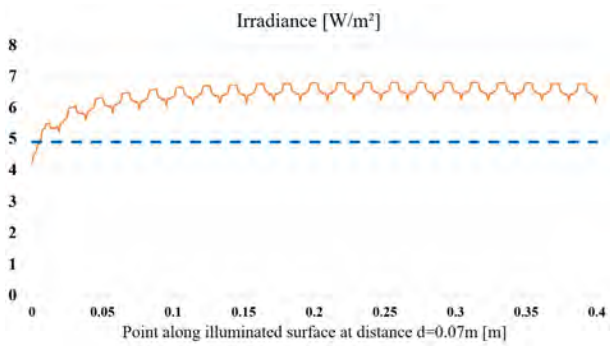

Fig. 2. Irradiance distribution of orange LED array.

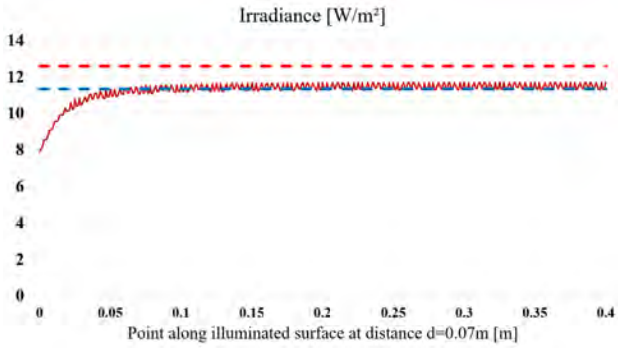

Fig. 3. Irradiance distribution of infrared LED array.

Fig. 1-3 show the simulated irradiance for each LED type. It is noticeable that the irradiance distributions are not ideal, but they are optimized in the sense of lowering cost, LED availability, and simplifying design and assembly. Choosing the optimal light distribution is usually done with probabilistic models [10] [11], but limitations in the electronic and housing design required a trial-and-error approach. The green LEDs, with their narrow angle of radiation, are the outliers since their irradiance distribution is not very uniform. Although it can be flattened by increasing the distance between the LEDs and the platform, it comes at the cost of lower irradiance. These calculations are made using the nominal parameters of the diodes; the corrections and fine tuning of the lighting system are done in the electronic design. Accounting for an increase in the distance, we opted for a slight increase from the nominal radiant intensity for the infrared diodes, while the green and orange LEDs are reduced to 90% and 83% of their nominal intensity, respectively, due to exceeding the needed ranges by a significant margin. The LED parameters are interpolated from the datasheet graphs, which might bring in additional errors. The biasing voltages, currents, and resulting intensities, considering an ideal characteristic of the LEDs, are given in Table IV.

TABLE IV. OPERATING LED PARAMETERS

	G-RND01-LED5 (Green)	**O-RND01-LED3 (Orange)**	**TSUS5402 (Infrared)**
Voltage [V]	3.148	1.9	1.3125
Current [mA]	17.4	14.7	120
Radiant intensity [mW/sr]	/	/	24
Luminous intensity [cd]	35.1	3.154	/

The final design consideration is choosing the arrangement of the LEDs in the circuit. A power supply of 12 V was chosen, considering the forward voltages of the LEDs. The process of arranging the LEDs proved to be iterative, as later on other limitations arose in the physical implementation related to current and power dissipation. Ultimately, the arrangement of the LEDs is as follows: 4 branches of IR diodes with 5 diodes in each; 5 branches of orange LEDs with 5 diodes in each; and 9 branches of green LEDs with 3 diodes in each. With this arrangement in mind, the needed resistors for biasing and power dissipation in each branch are given in Table V.

TABLE V. RESISTOR PARAMETERS

	G-RND01-LED5 (Green)	O-RND01-LED3 (Orange)	TSUS5402 (Infrared)
Resistance [Ω]	147	170	45.31
Resistor power dissipation [mW]	44.51	36.735	625.5

III. PHYSICAL IMPLEMENTATION AND CONTROL OF THE SYSTEM

Since modularity was one of the requirements for the lighting system, the first step in the physical implementation was choosing the shape of the LED housing. Because benchtop shakers are usually flat, a solid strip with the LED matrix on it would work. But the bioreactors have a cylindrical shape which needs to be enclosed by the lighting system for maximum efficiency, and that's why the design needs to be modular [6]. Instead of a solid single-piece strip, we divide it into three parts, which can be rearranged as a flat strip or in a π-shape, enclosing and focused towards the center of a cylinder. The 3D model of the design is shown in Fig. 4.

Because the system is assembled manually, imperfections in the component placements are expected. As the cultivated organisms are continuously mixed inside the equipment, the effects of the imperfections are expected not to be as adverse.

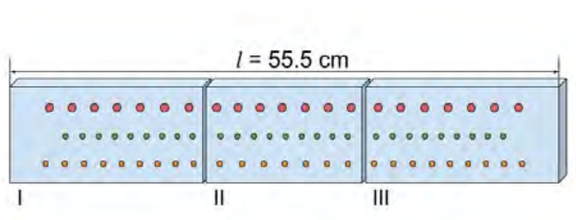

Fig. 4. 3D model of the LED housing.

After the assembly of the LED matrix, the choice of resistors followed. Since the exact calculated resistances aren't feasible to implement, the options closest to the calculated values were considered. Due to the relatively high power draw of the infrared diodes given in Table VI, the power rating of the resistors in the infrared branches needs to be adequate.

A problem occurred during the measurement of the actual voltage drops and currents of the LEDs with the first calculated resistances. Due to the random nature of the LED parameters and their high tolerances, many of the LED branches didn't have the expected voltages and currents when measured. This required a change in the resistors used in the LED branches. The first and revised resistors used are given in Table VI. Finally, the system also required a controllable intensity of the diodes and the duration of the on-off cycles. The intensity control is done via pulse-width modulation (PWM) by adding a controllable metal-oxide-semiconductor field-effect transistor (MOSFET) at the end of each LED array, although there are other available options such as potentiometers. The model of the MOSFETs used is BUZ11.

TABLE VI. RESISTORS USED IN THE PHYSICAL IMPLEMENTATION

	G-RND01-LED5 (Green)	O-RND01-LED3 (Orange)	TSUS5402 (Infrared)
Resistors I.[a] [Ω]	1×150	1×169	4×182[b]
Resistors II.[a] [Ω]	1×150	1×110	4×169[b]

a. Every resistor used has 1% tolerance and 1/4W power rating

b. *Resistors are connected in parallel to meet power rating*

This MOSFET is beneficial because it has a low drain-to-source on-state resistance, which doesn't disturb the electrical parameter calculations for the LED arrays as much. The PWM and on-off timer are controlled via an Arduino UNO R3 microcontroller connected to the gate of the MOSFETs. To protect the microcontroller from drawing too much switching current, a 100 Ω gate resistor is used, and another 10 kΩ pull-down resistor is connected to ground to ensure the MOSFET is fully off [12]. The PWM frequency of the used microcontroller is 490 Hz, and the timer feature is fully implemented in software. The light intensity and timer are reprogrammed every time it is needed or set up via buttons if a programming device isn't available. The code consists of inputs for the intensity of each LED array (8-bit unsigned integer) and inputs for the on-off cycle durations. If programmed directly, the desired value for each input is changed in the code and the system is programmed, whereas if the buttons are used, the appropriate array is selected with one button, with the selected array being indicated by blinking.

The system is powered via a 12 V, 3 A DC power source, which provides power to both the lighting system and the microcontroller via a barrel jack. Given the maximum power draw for both of the elements, 3 A is more than enough to feed them both. The microcontroller can also be powered via USB. Fig. 5 shows the diagram of the lighting system where the circuits for the LED arrays are similar to those shown in Fig. 6. Fig. 7 shows the final implemented system while in use.

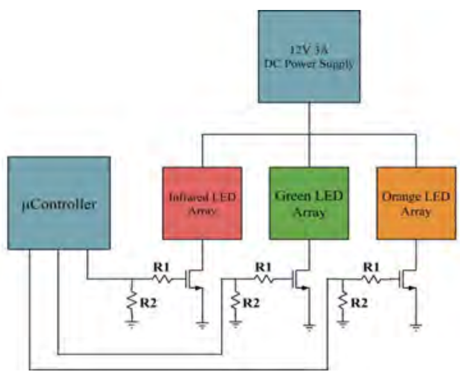

Fig. 5. Top-level diagram of the lighting system.

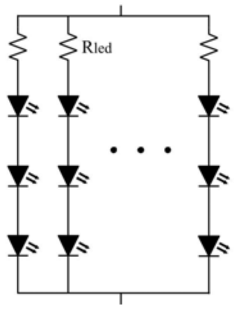

Fig. 6. Example of the LED array configuration. (*Rled is the appropriate Table VI. resistor.)*

Fig. 7. The lighting system used with a benchtop shaker.

IV. MEASUREMENTS

Measurement of the optical performance of the lighting system was done with a digital light meter, limited to only measuring the visible part of the spectrum (green and orange LEDs); the infrared irradiance wasn't measured due to the lack of measuring equipment. Multiple measurements were done at a distance of 7 centimeters, which was the distance used for the calculations, and the range of the measurements is given as a result. An interesting anomaly was noticed, as one third of the system, marked with I on Fig. 4, has a higher intensity than the other two thirds, marked with II and III. This can be credited to accumulated errors from the assembly process and the high variance of the LED parameters. It must be noted that if the system is used to illuminate a benchtop shaker, this might result in visible differences in the growth of cultures on different sides of the shaker. The results from the measurements are presented in Table VII.

TABLE VII. LIGHT INTENSITY MEASUREMENTS

	G-RND01-LED5 (Green)	**O-RND01-LED3 (Orange)**
Irradiance I [W/m^2]	35.56 ÷ 38.44	4.438 ÷ 4.715
Irradiance II-III [W/m^2]	30.75 ÷ 34.60	3.744 ÷ 4.022
Irradiance simulation [c] [W/m^2]	23.31 ÷ 27.153	5.154 ÷ 5.59

[c.] Shown in Fig. 1-3

V. CONCLUSION

Designing laboratory-scale systems that are costly at a larger scale, such as photobioreactors, is of great importance for experimenting, researching, and discovering advancements that could transfer to industry-scale designs, improving their efficiency.

In this paper, we designed a cost-effective photobioreactor for studying the effects of orange, green, and infrared light on the metabolism and growth of various photobacteria.

Simulated calculations were used to dimension the system according to the required parameters in a physical design, mainly based on geometry, electromagnetic, and optical laws.

The system employs LED arrays for lighting and a microcontroller connected to MOSFETs for regulating the parameters of the light. These features are key in many of the photobioreactor designs used for research.

Measurement results show that the green light is significantly stronger than designed, while the orange light is slightly below the calculated values. Although this might not be a practical problem, since the intensity can be regulated in a multitude of ways, it shows how prone the design and manufacturing processes are to various types of errors. Starting from the limited choice of components, their non-ideal production process, assumptions for simplifying the calculations, observational errors, and many more factors that all play a role in the final product.

Designing electronic systems is more often than not an iterative process, which takes up a large portion of the time. Luckily, the adjustments needed to correct the systems usually don't cost a lot of time and money for smaller designs.

Instead of trading off between certain aspects while designing, a more robust lighting system can be designed if we introduce a bit of complexity. Namely, using a feedback loop with sensors for adjusting the needed light intensity, covering the LED matrix with diffusers for a more uniform light distribution, or adding a modular power supply to which additional LED arrays can be added are some upgrades that can be done in the future to improve the existing design.

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Integrated Hybrid Manufacturing: Design, Control and Implementation of a Dual-Function CNC Machine

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***Abstract*—Hybrid manufacturing, integrating additive and subtractive technologies, represents a significant advancement in modern production systems. This paper explores the development of a dual-function CNC machine capable of both 3D printing and milling operations. The mechanical construction details a versatile platform designed for printing various materials and machining metals, wood, and plastics. Control system architecture highlights precise servo motor control, PID-regulated extrusion, and robust communication protocols. Firmware implementation on an STM32F767 microcontroller ensures efficient command processing and motor control, optimizing performance through preemptive computation strategies. This comprehensive integration enhances manufacturing flexibility, efficiency, and part quality across diverse applications.**

Keywords*—hybrid manufacturing; additive manufacturing; subtractive manufacturing; CNC machine; CNC milling; dual-function machine; 3D printers

I. Introduction

Research in hybrid production, which combines subtractive and additive technologies in a single machine, is ongoing, though commercial applications are still limited. One approach involves additional machining during specific stages of the 3D printing process to enhance part quality. These machining sequences depend on tool size and workpiece shape. Another significant method involves CNC machining of each printed layer of the model, demonstrating a tenfold improvement in part wall roughness. This method uses specialized software for slicing the piece and generating the G-code for both machining and 3D printing [1].

Additive manufacturing, a key technology of the 21st century, is often combined with subtractive manufacturing to create hybrid systems capable of producing complex parts, such as 3D-printed sensor systems. Conventional hybrid manufacturing typically requires separate CNC machines for additive and subtractive processes, which presents certain disadvantages. Integrating both processes into a single CNC machine offers higher accuracy, reduced production time, and lower costs [2]. For instance, using fused layer modeling (FLM) as an example, a general approach for incorporating additive manufacturing processes into CNC machine tools demonstrates the resulting CNC architecture and its functionality.

The development of hybrid multi-tasking machine tools, which integrate additive manufacturing with CNC machining, addresses the need for reduced manufacturing costs and in-process time while maintaining high added value. By incorporating Laser Metal Deposition with traditional turning and milling capabilities, these machines enable near-net shape production followed by high-precision finish machining. This integration is particularly advantageous for small-lot production of difficult-to-cut materials, such as aerospace alloys and high-hardness materials, as well as high-precision medical device components [3].

Additive manufacturing, characterized by layer-by-layer material deposition, has gained significant traction in production processes due to its myriad advantages. Reviews of additive manufacturing detail its evolution as a prominent technology and discuss various phases [4]. Emphasis is placed on the significance of part orientation, build time estimation, and cost computation. Challenges associated with different additive manufacturing methods have prompted consideration for hybridization with subtractive manufacturing to address imperfections, highlighting future research directions.

Recent advancements in hybrid manufacturing have revolutionized the production of complex parts previously challenging with traditional methods. A noteworthy innovation is a cost-effective, fully automated multi-axis hybrid CNC machine for non-metallic parts [5]. This machine integrates a six-axis CNC machining center with a six-axis extrusion 3D printer, capable of processing polymers and specialized materials like carbon fiber reinforced filaments. Employing Finite Element Analysis (FEA), the design optimizes structural strength and reduces component costs while demonstrating minimal deformation and high safety factors under heavy loads, validating its industrial potential. This development highlights hybrid manufacturing's capability to enhance efficiency and reduce costs in producing high-performance components.

Additive manufacturing with fused filament fabrication (FFF) offers rapid prototyping, design flexibility, and cost efficiency, making it a disruptive technology compared to traditional subtractive manufacturing. However, the achievable accuracy of current FFF printers is limited, prompting research into factors affecting print quality. Experimental tests such as circularity testing, operational vibration analysis, and repeatable

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positioning accuracy measurement reveal that servo motors outperform stepper motors in terms of vibration reduction and positioning accuracy. The findings highlight that while motor choice has a limited impact on surface quality, movement-induced vibrations significantly affect print outcomes [6].

Optimizing Cartesian 3D printer design requires precise estimation of natural frequencies. Methodologies based on the Euler–Lagrange formalism, as introduced by [7], provide crucial insights into selecting optimal axis positions and linear drives. Validation against finite element analysis and experimental data underscores the method's reliability in supporting emerging 3D printing technologies.

Innovations in 3D printing extend to printed circuit boards (PCBs), where high accuracy is paramount to avoid electrical faults. A novel neural network-based error correction method detects and repairs defects in real-time during printing. By integrating high-resolution cameras and convolutional neural networks, this approach ensures reliable circuitry by identifying and rectifying connection breaks automatically [8].

Furthermore, an integrated mechatronic approach is pivotal in designing machines tailored for metal injection molding (MIM), distinct from traditional 3D printers. Customized designs, drives, and controls optimize extrusion rates and acceleration curves specific to MIM requirements. This approach, exemplified in [9], not only enhances workspace efficiency but also serves as a test platform for refining MIM process parameters, showcasing its potential for advancing additive manufacturing applications.

Dynamic errors in CNC machines often surpass quasi-static errors at high processing speeds, significantly affecting the quality of the machined surface. These errors, defined as deviations of the actual displacement of the CNC machine head from the reference displacement during movement, are addressed by focusing on the control unit that generates signals for the servo motors and performs interpolation of all axes [10].

Advancements in CNC interpolators have been pivotal in the implementation of computer numerical control. Initially relying on simple linear parametrization, interpolators evolved from complex hardware to powerful and flexible software, enabling the machining of intricate shapes and contours. Advanced parametric curves such as cubic splines, B-splines, Bezier curves, and NURBS now provide enhanced contouring accuracy, precision, and smoothness [11].

Conventional tool paths for CNC machines often face limitations due to velocity and acceleration discontinuities at segment junctions; however, a proposed geometric corner smoothing algorithm using quintic B-splines ensures G2 continuity transitions and optimal curvature geometry, controlling cornering errors and generating a smooth, accurate feed profile in real-time. A unified framework for calculating B-spline curves approximates micro-lines into which the tool path is divided, with an extended bi-chord error test selecting dominant points to construct the initial B-spline curve, thereby improving machining efficiency and maintaining surface quality by reducing the number of control points [12]. Evaluations of a NURBS interpolator using recursive equations instead of traditional Taylor's expansion demonstrate reduced feedrate errors and calculation time, proving it faster and more accurate for CNC systems [13].

A dual-Bézier path smoothing algorithm for five-axis tool paths addresses first-order discontinuity at segment junctions, enhancing path smoothing, speed consistency, and trajectory accuracy through adaptive feedrate scheduling [14]. An adaptive real-time NURBS curve interpolation method for a 4-axis polishing machine tool integrates pre-interpolation calculations and an adaptive interpolation algorithm, validated through simulations and experiments to enhance CNC system performance [15]. A robust trajectory generation scheme using a Finite Impulse Response (FIR) filter minimizes residual vibrations caused by rapid accelerations, achieving smoother surface finishes and improving machining accuracy without extending cycle times [16].

II. Mechanical Construction of The Machine

The proposed innovation is a dual-function CNC machine designed for both milling and 3D printing. It is capable of 3D printing various plastic materials such as PLA, ABS, PET, and carbon fiber, and milling different types of metal, wood, and plastics. The machine features a fixed table with a movable tool head that operates in three-dimensional space. The mechanical construction is depicted in Figure 1.

Hybrid production in its initial version is sequential, allowing for 3D printing of a part first, followed by milling to achieve specific forms. Future versions will integrate hybrid processes during production. The current model employs a simple method for changing tools. The spindle (1), used for milling (subtractive production), is fixed due to its heavy weight, while the extruder (2), used for 3D printing, is removable with two screws and a cable connector. This allows for easy switching between milling and printing.

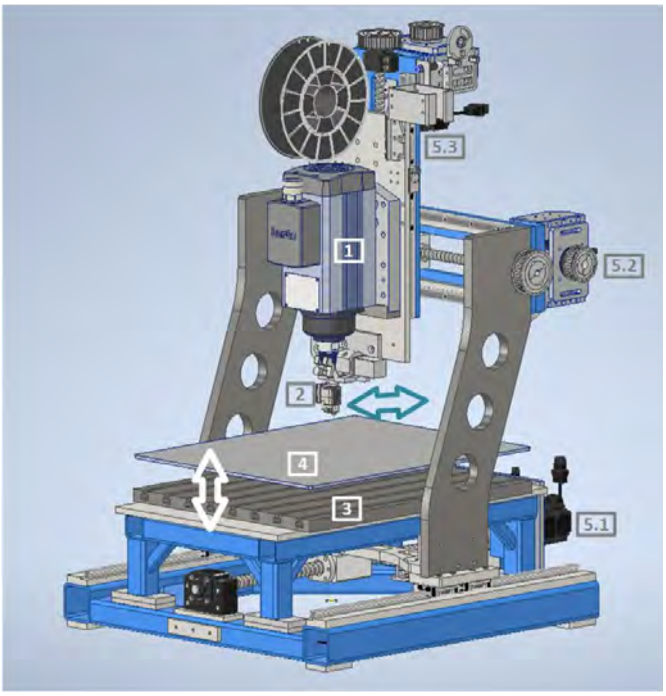

Figure 1. JLABsmartCNC 3D Model.

The machine has different types of working tables for printing and machining. For machining, a massive T-slot table (3) is fixed on the machine. For printing, a lightweight table (4) with a heater is placed on the T-slot table using magnets and connected via a connector.

The machine's axis movements are driven by three servo motors (5.1; 5.2; 5.3), each with a power of 400W and corresponding drivers. Each axis is equipped with double limit switches at both ends, totaling twelve limit switches. The first switch is inductive and integrated into the software, while the second is a mechanical switch that breaks the power supply to the driving power unit, enhancing reliability.

III. Control System Architecture

The electronic control unit (ECU) of the machine is illustrated in the block diagram shown in Figure 2, detailing its connections with sensors and actuators.

The machine's power supply is split into two parts: a 24-volt supply for the ECU and system sensors, and separate supplies for motors and heaters. Despite each motor and heater having its dedicated power line, they are all activated simultaneously by a main contactor. Activation of the motor power supply requires prior activation of the control unit power supply. Mechanical limit switches at each axis end and an emergency switch ensure safety by cutting off power to the actuators when triggered.

Communication between the ECU and Delta servo drives utilizes I/O communication and a high-speed differential line driver for precise control of step pulses and motor directions. The Delta servo motors operate in a closed-loop system with a resolution of 1µm. For the Z-axis, a pneumatic brake is implemented to prevent it from falling due to the weight of the Z-axis and spindle when the motor is off; this brake engages when the motor is turned off and disengages when activated.

The extruder consists of three primary components: the extruder motor, a heater for material melting, and an NTC sensor for temperature feedback. Operating within a temperature range of 20°C to 300°C, the extruder requires a specialized circuit for precise temperature measurement using two branches with different resistance values for the NTC sensor. Branch switching is automated by the software. The extruder heater, selectable between 12 volts or 24 volts via jumpers on the ECU, employs PID temperature regulation for accuracy.

The extruder motor is a stepper motor with 200 steps per revolution, enhanced by a gear reduction unit with a 1:13.76 ratio, resulting in a resolution of 88064 steps per revolution after microstepping with 32 microsteps. With a 12 mm material pulling gear diameter, the circumference is:

$$\text{Diameter} \times \pi = 12 \times 3.14 = 37.68 \text{ mm} \qquad (1)$$

Thus, the theoretical pulling resolution is:

$$\frac{37.68mm}{88064steps} = 0.428\mu m/step \qquad (2)$$

The spindle motor, a 4kW induction motor from Hertz, is controlled by a Yaskawa GA50 VFD drive. Automatic tuning optimizes motor parameters stored within the VFD control system. Communication between the VFD and ECU occurs via

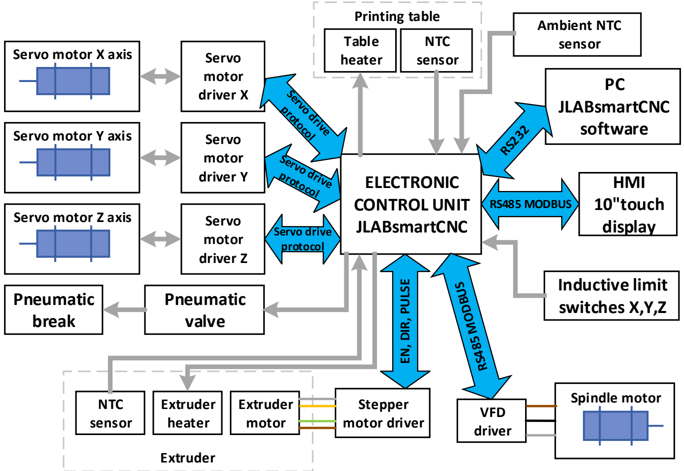

Figure 2. JLABsmartCNC Control System Architecture.

RS485 MODBUS, with the ECU as master and the VFD as slave.

Inductive limit switches with conditioning circuits are connected to the ECU, utilizing highest-priority interrupts in the software for enhanced reliability. An HMI display serves as an intuitive user interface, providing complete control over the machine's functions. The graphical user interface (GUI) is user-friendly and communicates with the ECU via a separate RS485 MODBUS, with the HMI acting as the master and the ECU as the slave. Additionally, PC software has been developed for comprehensive control of printing and machining processes, communicating with the ECU via RS232 using a protocol specifically designed for JLABsmartCNC.

An ambient temperature sensor continuously monitors the environmental temperature critical for maintaining high-quality printing. Insufficient temperature prompts warnings. The printing table includes a 220 VAC 800W silicone heater and an NTC sensor. PID regulation, like that of the extruder but with unique coefficients, ensures optimal printing conditions.

IV. Firmware Architecture and Implementation

The heart of the electronic control unit (ECU) is an STM32F767 microcontroller based on the Cortex M7 core. The firmware for this system is developed using the STM32Cube IDE. Figure 3 illustrates the upper-level architecture of the firmware.

The system avoids using an RTOS (Real-Time Operating System) to ensure precise timing and eliminate latency introduced by the RTOS. In the block diagram shown in Figure 3, the "other tasks" block encompasses all communications and commands from the HMI or PC. This block includes functions for managing USB sticks or SD cards, such as reading, writing, and file operations. For simplicity, these activities are grouped together in one block to emphasize the primary focus on motor drive algorithms.

When the machine is in printing or machining mode, the system continuously checks for new commands from the USB, SD card, or PC software. Users can choose one of these options to send G-code to the machine. Once the machine enters the

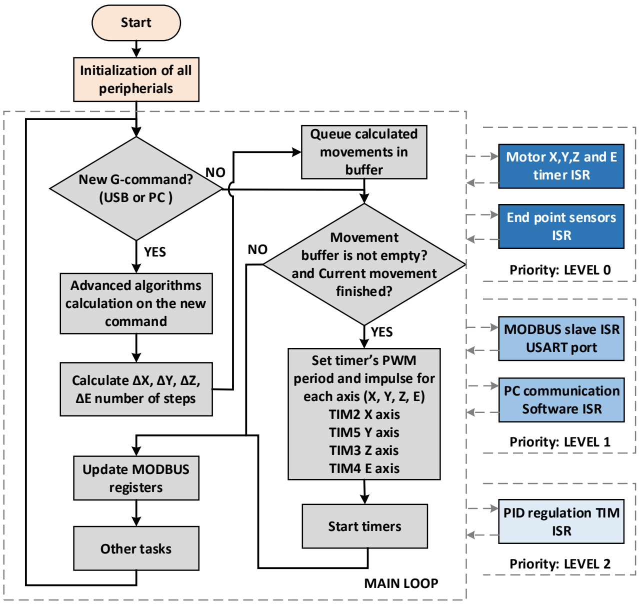

Figure 3. Firmware Architecture.

printing or machining state, the control unit processes any new commands using advanced algorithms and queues them in the movement buffer. These algorithms calculate the next distances, speed profiles, and acceleration and deceleration profiles.

If the movement buffer is not full and the current movement is finished, the system retrieves the next movement from the buffer, sets the appropriate timer periods and impulse widths, and starts the timers. The timers operate in PWM mode, generating interrupts at each impulse to decrement the number of steps. When the number of steps reaches zero, the interrupt service routine (ISR) automatically stops the timer. Each axis uses a different timer: Timer 2 for the X-axis motor, Timer 5 for the Y-axis motor, Timer 3 for the Z-axis movement, and Timer 4 for the E-axis movement.

The servo motors have a resolution of 1 µm, meaning each impulse from the ECU results in a 1 µm displacement of the axis. With a maximum motor speed of 3000 RPM and a displacement of 5 mm per rotation, the maximum axis movement speed is:

$$V_{max} = 3000rev/min \times 5mm/rev = 15m/min \qquad (3)$$

$$V_{max} = \frac{15m/min}{60s} = 250mm/s = 250Ksteps/s \qquad (4)$$

Thus, at maximum speed, the timers generate interrupts every:

$$T_{servo\_tim\_peirod} = \frac{1s}{250000steps/s} = 4\mu s \qquad (5)$$

The code execution in each ISR for the motor timers lasts 74 clock cycles in most cases, with 94 clock cycles required when the motors are turned off. The maximum latency for the ISR, from the timer interrupt generation to the first ISR instruction execution, is 12 clock cycles in the worst-case scenario [17][18]. With an MCU frequency of 216 MHz, the ISR execution time, including latency, is:

$$T_{servo\_tim\_ISR} = (2 \times 12 + 74)clk\ cyc \times \frac{1}{216MHz} \qquad (6)$$

$$T_{servo\_tim\_ISR} = 454ns \qquad (7)$$

For the maximum motor speed, the ISR utilization for three servo motors is:

$$Utilization_{servo} = 3 \times \left(\frac{T_{servo\_tim\_ISR}}{T_{servo\_tim\_period}}\right) \qquad (8)$$

$$Utilization_{servo} = 3 \times \left(\frac{0.454\mu s}{4\mu s}\right) = 0.34 \qquad (9)$$

For the extruder motor, the maximum extrusion speed is 60 mm/sec with a resolution of 0.428 µm/step. Thus, the number of steps per second at maximum speed is:

$$\frac{Steps}{second} = \frac{60000\mu\frac{m}{s}}{0.428\mu\frac{m}{step}} = 14018\ steps/s \qquad (10)$$

This means the extruder timer generates interrupts every:

$$T_{ext\_tim\_period} = \frac{1s}{14018steps/s} = 71.3\mu s \qquad (11)$$

Since the ISR for the extruder motor is similar to the servo motors, the execution time is:

$$T_{ext\_tim\_ISR} = T_{servo\_tim\_ISR} = 454ns \qquad (12)$$

The ISR utilization for the extruder motor at maximum speed is:

$$Utiliz_{ext} = \frac{T_{ext\_tim\_ISR}}{T_{ext\_tim\_period}} = \frac{0.454\mu s}{71.3\mu s} = 0.0064 \qquad (13)$$

In practice, the motors will typically operate at 70% of their maximum speed, reducing the utilization proportionally for the servo motors:

$$Utilization_{servo,nom} = 0.34 \times 0.7 = 0.238 \qquad (14)$$

For the extruder motor, the nominal speed is 50% of the maximum speed because the highest speed is only used for material retraction. Therefore, the utilization for the extruder motor at nominal speed is:

$$Utilization_{ext,nom} = 0.0064 \times 0.5 = 0.0032 \qquad (15)$$

The total ISR utilization for all motors at nominal speeds is:

$$Utilization_{motor} = 0.238 + 0.0032 = 0.2412 \qquad (16)$$

The PID regulation system uses a timer that generates an interrupt every 10ms. The ISR for the PID regulation lasts 1000 clock cycles, resulting in an execution time of:

$$T_{PID\_ISR} = 1000clk\ cyc \times \frac{1}{216MHz} = 4.6\mu s \qquad (17)$$

The PID ISR utilization is:

$$Utilization_{PID} = \frac{T_{PID\_ISR}}{10ms} = \frac{4.6\mu s}{10000\mu s} = 0.00046 \qquad (18)$$

For MODBUS and PC communication, the average command length is 40 characters at a transmission speed of 115,200 bps. This translates to:

$$\frac{Bytes}{second} = \frac{115200bps}{8} = 14400\ Bytes/s \qquad (19)$$

Interrupts are generated for each received character, with each ISR lasting approximately 110 clock cycles. For the entire command (40 characters), the last interrupt lasts 1500 clock cycles due to command execution. The total ISR execution for one command is:

$$T_{comm\_ISR} = 39 \times 110 + 1500 = 5790clk\ cycles \qquad (20)$$

The average frequency of commands is every 10ms, so the ISR execution time is:

$$T_{comm\_ISR} = 5790clk\ cyc \times \frac{1}{216MHz} = 26.8\mu s \qquad (21)$$

The communication ISR utilization is:

$$Utiliz_{comm} = \frac{T_{comm\_ISR}}{10ms} = \frac{26.8\mu s}{10000\mu s} = 0.00268 \qquad (22)$$

Since both MODBUS and PC communication are handled similarly, the total communication utilization is:

$$Utilization_{comm,total} = 2 \times 0.00268 = 0.00536 \qquad (23)$$

The total system utilization, considering nominal motor speeds and other ISRs, is:

$$Utiliz_{tot} = Utiliz_{mot} + Utiliz_{PID} + Utiliz_{comm,tot} \qquad (24)$$

$$Utilization_{total} = 0.24702 \qquad (25)$$

The remaining free time of the microcontroller, which is more than sufficient for calculating advanced control algorithms for kinematics, ensures precise and smooth movements of the CNC machine. Rather than performing these calculations between each movement, the system preprocesses and stores the results in the movement buffer. This preprocessing approach enhances efficiency and ensures that all necessary calculations are completed ahead of time, allowing the system to execute movements seamlessly and without interruption. By leveraging the free time for these computations, the microcontroller can maintain high precision and performance throughout the operation of the machine.To achieve precise control, different priority levels are assigned to the interrupts. The motor timers and endpoint sensors have the highest priority (level 0),

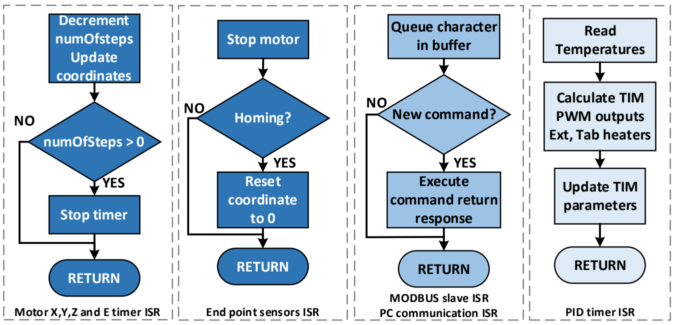

Figure 4. ISR implementation.

communication interrupts have level 1 priority, and the PID interrupt has level 2 priority. Interrupts with lower priority can be interrupted by those with higher priority. The implementation of the ISR is shown in Figure 4.

Finally, it is important to note that the endpoint sensor interrupts during the printing or machining process do not occur. They are only triggered during the homing process at the beginning to find the machine's zero.

V. Conclusion

The integration of additive and subtractive manufacturing in a dual-function CNC machine demonstrates substantial advancements in manufacturing technology. By combining precision control mechanisms, versatile material capabilities, and sophisticated firmware architecture, the system achieves high accuracy and operational efficiency. Future developments may focus on enhancing hybridization during production processes and optimizing control algorithms to further streamline operations. This research underscores the potential of hybrid manufacturing to revolutionize industrial production by offering cost-effective solutions for complex part production across various industries.

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Modern SCADA Solution for Mitigation of Water Losses in Water Distribution Network

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Abstract*— This paper explores the optimization and management of a water distribution network using a SCADA system integrated with DMAs (District Metered Areas) and PMAs (Pressure Management Areas) to improve hydraulic characteristics. The study demonstrates the importance of early fault detection, real-time monitoring, and effective pressure management within high-pressure zones to reduce water loss, enhance operational efficiency, and extend the lifespan of infrastructure. It recommends future improvements, including the addition of a new PMA to further regulate pressure, reduce faults, and decrease water consumption. By implementing these strategies, the network can achieve significant financial and environmental benefits, ensuring sustainable and efficient water supply management.

***Keywords*—PLC, SCADA, RTU, Water distribution network, District metered area, Pressure management area etc.**

I. Introduction

Water supply systems date back to ancient times, with examples like Persian qanats, Roman aqueducts, and the Machu Picchu water system. Modern developments began in the 17th century, highlighting the evolution of water infrastructure [1]. Maintaining these infrastructures requires calculating and determining the pressure and flow in water supply pipe networks has been, is, and will be of great importance and interest, both for the people responsible for designing, constructing, and maintaining public water distribution networks, as well as for the end consumers themselves.

The "Smart Water Save" project, targeting the Prespa region and encompassing Prespes in Greece and Resen in North Macedonia, aims to reduce water losses. The project was initiated due to the significant discrepancy between pumped water and household usage, as revealed by water bills, which damages underground water sources. The water supply network suffers extensive losses due to pipeline deterioration and illegal connections for agricultural irrigation. It has been estimated that both sides of the lake experience around 50% water loss from the total pumped or delivered water. This necessitates more energy for water purification, increasing greenhouse gas emissions linked to energy use and production.

Water leakage in pipeline networks is most often caused by the inability of the residual resistance of the pipe to withstand the water pressure, which causes small cracks or holes in the pipes. To solve this problem, two solutions will be proposed:

- Reducing the pressure in the pipes;
- Replacing the old, worn-out pipes in the system with new ones.

Managing water pressure in supply networks involves effective strategies to reduce water leakage caused by undetectable pipe damage, thereby lowering the risk of new cracks and extending the pipes lifespan. Water leakage in pipes is directly proportional to water pressure, so reducing the pressure will decrease water leakage.

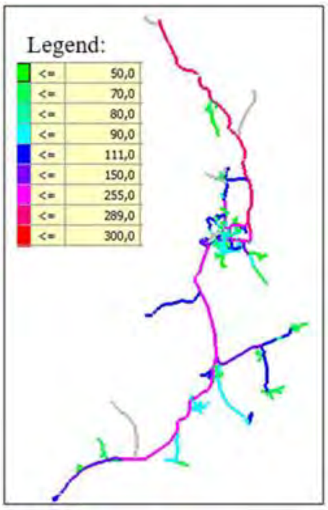

Figure 1 Pressure map of the WDN [1]

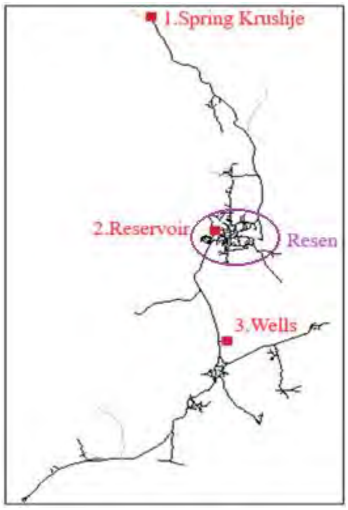

Figure 2 Crucial points of the WDN [2]

The main goal of this project is to reduce the inefficiencies of both water supply systems through the implementation of a SCADA (Supervisory Control and Data Acquisition) system. This system aims to monitor the pressure and flow in the pipes in real-time. It will collect data that will be used for subsequent analyses. Monitoring will involve gathering data from sensors placed at specific measurement points via wireless communication, as shown in Figure 6 Placement of the 19 measurement points. This approach will enable the detection of "critical points" and regionalize potential pipe damage, as well as calculate the total water leakage from the pipes. These critical areas will be replaced with new pipelines, ensuring the prevention of major damages and water losses in the future.

Further, in this paper, the concepts of pressure management like DMA and PMA will be shown in chapter II, and then in chapter III the actual state of the water supply system will be shown. In chapter IV the modeling principles and the analysis of the expected results will be discussed, and the implementation of the physical layout and SCADA architecture and SCADA system will be shown in chapter V. Finally, in chapter VI the conclusions for the implemented and expected state of the system will be drawn, and some recommendations for further work will be given.

II. CONCEPT OF PRESSURE MANAGEMENT

Nowadays, with increasing demands for water resources, it is vital to conserve and save them, with aim to avoid overburdening the water sources. Water resource management primarily aims to reduce pressure to the lowest possible operating point while ensuring adequate water supply to the network. Reducing pressure significantly decreases leakage in the pipeline, resulting in substantial resource and economic savings.

Pressure management requires adequate knowledge of the system, including consumer usage patterns, pressures at different network points, network losses, terrain configuration, and even the capacity of potable water sources. While defining the concept may seem straightforward, having a general overview of the system is not as effective as utilizing a modern monitoring system like SCADA. SCADA systems can enable the proper implementation of proven pressure management concepts, such as reducing water consumption, establishing District Metered Areas – DMAs, and pressure management areas PMAs. These zones can then be integrated into the overall management system.

A. DMA

In a water supply network, forming DMAs (District Metered Areas) involves designating certain sectors or areas where the end supply points have similar hydraulic characteristics and are in close proximity. This approach also allows for zoning based on topographical elevation. The division is done using valves at points where two isolated measurement zones meet or by interrupting the pipelines at these points. The resulting DMA zones enable the monitoring of water entering and exiting these measurement zones, allowing for the determination of water loss in a given zone.

Through the established DMAs, water flow entering the zone can be monitored and compared to the flow at the end consumers. Any discrepancies can indicate a defect or water theft in that zone. Analyzing the flows in the DMAs provides a realistic picture of the network conditions within the zones, particularly by observing the state of the zones during periods of low consumption and low flows but high pressure, typically at night. A difference in flow during these times would indicate a possible defect in that zone. Proper utilization of DMAs helps maintain water leakage from the supply network at a low level, allowing for quick intervention and replacement of worn-out infrastructure.

Overall, DMAs are a springboard towards creating an economically efficient and environmentally friendly water supply system, as they provide insights into Non-Revenue Water (NRW) and ensure consistent water supply through zoning by elevation, maintaining constant pressure for end users. DMAs also facilitate defect resolution by allowing immediate isolation and repair without disrupting other zones water supply. Managing water supply systems through isolated measurement zones is a highly advanced concept, widely accepted as standard practice globally. [2]

B. PMA

Certain implemented DMAs in the water supply network may not always achieve consistent pressure, or the consistent pressure may be too high. To address such cases, PMAs (Pressure Management Areas) are introduced, which are upgraded DMAs equipped with appropriate pressure management equipment. Zones at lower elevations often experience significant pressure fluctuations, linked directly to consumption. At night, water consumption is low, resulting in high pressure, while during the day, consumption increases, and pressure can drop below the optimal level for network operation. These fluctuations can cause expansion and contraction of pipes and joints, leading to leaks. DMAs alone may not effectively solve this issue.

To tackle this problem, PMAs are implemented, featuring Pressure Reducing Valves - PRVs. PRVs automatically reduce high inlet pressure, maintaining the desired pressure within the zone despite changes in pressure or flow. PMAs improve on DMAs by not only reducing NRW but also ensuring better pressure consistency. However, the high investment and maintenance costs of PRVs are a drawback. Overcoming this involves considering the long-term benefits of the investment [2].

C. DMA & PMA in SCADA

Implementing PMA and DMA concepts in water supply networks would significantly enhance operational efficiency and ensure consistent water distribution to end users, offering substantial economic and environmental benefits. The benefits of PMAs and DMAs are maximized when locally managed using automated controllers. Using controlling PRV valves instead of static, mechanical ones further reduces pressure, defects, and leaks. Controllers can employ PID (Proportional, Integral, and Derivative) control, optimized with algorithms based on hydraulic models or daily consumption patterns. [3]

However, local control of PMAs and DMAs does not guarantee overall network stability. Sudden, significant demand changes at distribution endpoints can cause system response delays and large fluctuations. Major consumers such as industrial complexes, fire hydrants, operator errors, and pumps in high elevation zones can cause such fluctuations. Integrating PMAs and DMAs into a SCADA system allows for better monitoring and management, preventing fluctuations in main supply lines. [3]

Integrating valves, pumps, reservoirs, and sensors from PMAs and DMAs into a cohesive SCADA system, with well-designed algorithms based on a thorough understanding of the hydraulic model, allows for micro-adjustments within zones. This management approach balances network pressure and prevents hydraulic shocks, reducing pipe damage and leaks.

III. State of the Water Supply System in Resen

The goal of this paper is to demonstrate the implementation of a SCADA system in a real water supply system. It will cover hydraulic aspects, including the system's condition, physical characteristics, models, and strategies. Additionally, it will explain the mechanical features, management of the system, the SCADA system's communication, and architecture.

The water supply system of the town of Resen, also known as Krushje-Resen-Sirhan, serves the local population in Resen and 17 other surrounding settlements with drinking water, managed by the public utility company "Proleter." This system comprises a network of pipelines totaling 97 km in length. Constructed in the 1980s, the current network consists of 67% PVC pipes, 23% HDPE pipes, 8% asbestos, and only 2% ductile iron, as shown Figure 1 [2].

Figure 2, illustrates the water supply system of Resen and its three crucial points essential for ensuring continuous and adequate water flow and pressure:

- The Krushje spring, located at 985 meters above sea level, has a capacity of 35 liters per second.
- The Resen reservoir, located at 934 meters above sea level, stores excess water during the day to be reused at night. Its location and role make it functional both as a pre-settlement and post-settlement reservoir.
- The wells near the village of Carev Dvor, used during summer when water demand increases. Three deep wells, equipped with three pumps, can provide an additional flow of up to 30 liters per second. These wells boost flow and pressure in the network, particularly for southern villages. Excess water is stored in the Resen reservoir when demand is met.

According to data from JKP "Proleter," the system is gravitational, flowing naturally from north to south. However, geographical variations, especially in the city of Resen, cause pressure differences. Higher areas (900 meters) experience lower pressure, while lower areas (875 meters) face higher pressure, leading to potential pressure differences of several bars. This discrepancy complicates the supply of consistent pressure and increases the likelihood of defects in lower areas due to high pressure.

According to calculations in [2], based on available data, the invoiced water quantities for households and commercial properties suggest a norm of 100 [l/day/per], which is acceptable. However, calibration measurements reveal that the actual norm is higher, at 150 [l/day/per], reflecting the system's true state.

IV. Modeling and Analysis of the WDN

A. Modeling

To perform a hydraulic analysis of a water supply system, a reliable mathematical model is essential. The model of the system is acquired by using modern EpaNET software package and data from crucial measurement points of the system, by solving nonlinear systems of equation, after that the model can be accurately calibrated to reflect the system's real state. The calibration process involves using least squares method for optimizing and adjusting the model based on measured data, such as geodetic height, pipe profile, pressure, water flow, and timestamps, ensuring the model closely matches actual conditions. This calibrated model can then be used for various analyses and optimizations. Data for this system is obtained from continuous measurements of pressure and flow at several points, as shown in Figure 3 [2].

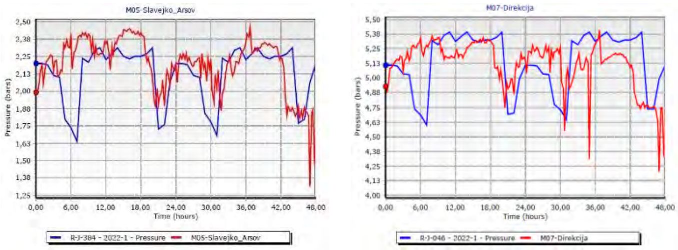

Figure 3 Comparison between real data (RED) and calibrated model (BLUE)

The graphs above illustrate the differences and deviations of the model compared to the real state of the system. According to [2], the calibrated mathematical model appropriately reflects the system's actual condition and remains within acceptable deviation limits. In other measurement points, the dynamics of the calibrated mathematical model correspond well with the real system's dynamics. Although there are noticeable spikes in the graphs, these should not be considered for calibration. Instead, the general dynamics of the system should be calibrated to avoid increasing the model's sensitivity in general cases.

B. Analysis

The analysis of the water supply system focuses on how consumption changes with pressure levels. Three scenarios are considered: the first reflects the current system state, the second introduces two pressure zones (high and low) based on identified high-pressure areas from the first scenario, and the third enhances the second scenario by adding two new PMAs with PRVs.

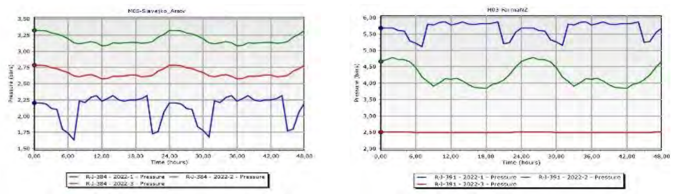

Figure 4 Model results (blue-scenario 1, green-scenario 2, red-scenario 3) [2]

To obtain a general picture of the system's dynamics, measurement points are selected at various locations and pressure zones, tracking pressure changes over 48 hours. The obtained data represent a set of information for the measurement point, such as its geodetic height, pipe profile, pressure, total volume of water passed, current flow rate, timestamp of the record, etc. This helps observe the differences and dynamics in the models from different scenarios and their impact on pressure at these points. The pressure changes for the three scenarios are shown in Graphs 11-14, with node positions in Figure 4.

1) Scenario 1 – Current situation

To establish a good reference point for comparing the proposed scenarios, the current state of the water supply system must be identified and modeled, determining all its hydraulic characteristics. This allows identifying system deficiencies that need resolution and recognizing system strengths. Using the geographical characteristics mentioned earlier, computer simulations can set up measurement nodes within the water supply system. These nodes help identify high-pressure zones, and the obtained information can be used to reduce this high pressure, thereby proportionally decreasing water loss [2].

The network in this scenario experiences high pressure ranging from 5 to 7 bars, with a water consumption rate of 70.82 l/s. In Resen, due to its geography, high areas experience low pressures (2 to 3 bars), while lower areas have much higher pressures. To address this, high and low-pressure zones are established.

2) Scenario 2 – High and low-pressure zones

This scenario is based on the previously explained isolated measurement zones, or DMAs. It is the most economical solution, requiring minimal modifications and being easy to implement. Two pressure zones—high and low—are proposed. The high zone is influenced by the pressure from the Krushje spring, extending from Krushje to the higher parts of Resen. The reservoir in Resen, located in the higher areas of the town, acts as a "low pass filter" for pressure, nullifying the pressure influences from the Krushje spring. This allows new pressure boundaries to be set for the low zones of the city, creating the new low-pressure zone.

In the first scenario, pressures ranged from 5 to 7 bars. After implementing the second scenario, pressures are reduced to between 4 and 5.5 bars. The expected pressure in the low zones of the city accounts for the elevation difference of 50 to 60 meters between the reservoir (934 m ASL) and the lowest parts of the city (875 m ASL). Simulation results for the reduced pressure in the nodes of the low zone are shown in Appendix 3, with an average pressure reduced from 5.5 to 4.9 bars, equating to a 10.3% pressure reduction. Calculations in [2] result in 14.2% decrease in network defects, 2.06% reduction in user water consumption, 10.3% reduction in water losses, and the total water consumption in the system for this state is 53.92 l/s, representing an approximately 24% reduction compared to the current state [2].

3) Scenario 3 – PMA

To improve the given system, the next step is to introduce PMAs by installing PRVs to regulate the pressure in the high and low zones. Building on the previous scenario, two PRVs will be placed according to the DMA established in the second scenario, with their positions shown in Figure 5. Since the connected buildings are mostly houses with low height, the output pressure at the regulators is set at 2.9 bar, ensuring adequate pressure for firefighting requirements [2].

Figure 5 Placement of PRVs in the city of Resen [2]

Comparing this to the previous scenarios, where the first scenario had pressures ranging from 5 to 7 bar with an average of 5.5 bar, and the second scenario had pressures from 4 to 5.5 bar with an average of 4.9 bar, scenario 3 shows pressures between 2.5 and 3.5 bar with an average of 3.1 bar, representing a significant reduction. This amounts to a 37.9% pressure reduction compared to scenario 2 and a 44.4% reduction compared to scenario 1.

Such a reduction in pressure results in improved water supply and reduced consumption. According to [2], based on the computed results in 26.5% decrease in network defects, 3.8% reduction in user water consumption, and 18.9% reduction in water losses.

It is important to note that the initial state of the system assumes most of the defects have been resolved and total water consumption has been reduced. In scenario 3, total water consumption is 50.78 l/s, representing a 6% reduction compared to scenario 2.

V. Implementation

A. Physical layout

The implementation of the project involves gathering data from 19 different locations distributed across the water distribution network as shown on Figure 6. Given that this network primarily consists of off-grid manholes, the following solution was implemented: pressure is measured at 17 locations, flow rate is measured at 2 locations on the main water distribution pipeline from the water spring Krushje and the water wells at Carev Dvor, and water level is measured at 2 locations in the reservoirs at Carev Dvor and the city reservoir. Out of these, 12 locations are powered by an off-grid solar panel. Furthermore all of the locations are monitored via the SCADA, but only the reservoir in the city of Resen has an implemented control, i.e. 2 electric motor valves are installed for redirecting the flow of water from the reservoir and to it, when certain peaks in the demand or surplus of pressure occurs.

B. SCADA architecture

The SCADA architecture consists of 19 points, as mentioned, with one point being the SCADA center that communicates with the other 18 points through wireless communication in a multi-point architecture in star topology. This architecture, as shown in Figure 7, in general assumes only one master device for several slave devices, where data is passed between the master and each one of the existing slaves. In the case of two of the slaves need to exchange data between each other, it must be sent to the master device first, which acts as a moderator on the communication. The physical application of the architecture includes 16 measurement points equipped with RTUs, and the other 3 equipped with 3G/4G routers. The SCADA center uses these routers to initiate communication with all 18 points in the system via the means of wireless network. The other 2 measuring points are the reservoir in the city and the wells or pump station at Carev Dvor. Their configuration consists of PLCs and HMI screens for local monitoring and control by the operators there.

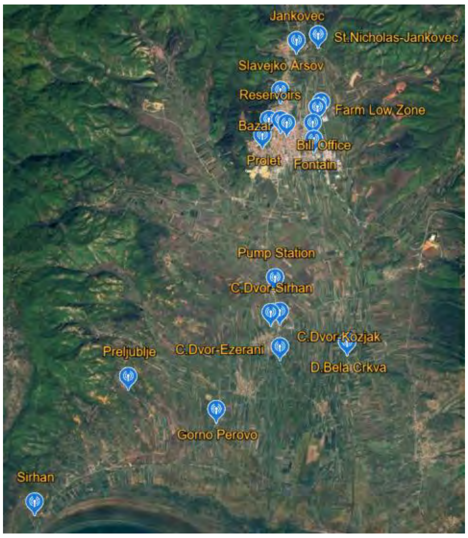

Figure 6 Placement of the 19 measurement points

The communication protocol of choice for this case is the MODBUS. Modbus is considered one of the main used and most popular protocols in the industrial field, using not just traditional serial protocols, but also Ethernet protocols, allowing different devices to use this protocol as their main communication method. When communications are placed between serial and Ethernet networks, there is a need to use a gateway in order to properly handle the connection [4]. More precisely the communication protocol used in the SCADA system is MODBUS RTU wrapped in a MODBUS TCP/IP header [5]. This means that the RTUs use the MODBUS RTU communication protocol, but since the communication is done via GPRS technology, they receive the messages from the master router via the MODBUS TCP/IP protocol. The RTUs will handle the conversion and read out the message. When configuring the RTUs, a slave address must be assigned for them to be reached by the SCADA. On the other hand, the 3G/4G routers use only MODBUS TCP/IP and need to be configured with proper tunneling between them to enable data transfer.

It is worth mentioning that all 19 points are in a private IP range or APN domain, and connection to the outside internet is nearly impossible. This increases the security against potential breaches in the system. Additionally, the SCADA interface consists of a map with all the measurement points, alarms and alarm history, historical trends, proper indicators for the measured values, detailed insights for each measuring point, and admin access to the parameters for each point.

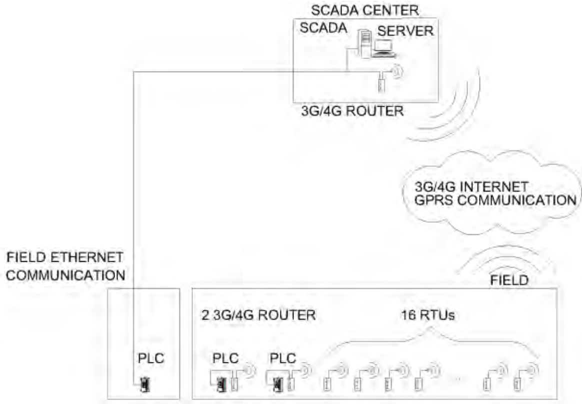

Figure 7 SCADA Architecture of the system

VI. Conclusion

From everything that has been developed and presented above in this paper, a conclusion can primarily be drawn based on the SCADA system and the hydraulic system of the water supply network. This means that progress in both areas should go hand in hand, as poor implementation in one field cannot be compensated by excessive investments in the other.

A. *Conclusion based on the hydraulic model*

If scenarios 2 and 3 are implemented properly and DMA and PMA are formed as prescribed, the following results can be expected: a 44.4% reduction in pressure, a 62.2% decrease in the number of network failures, an 8.9% reduction in water consumption by users, and a 44.4% decrease in water losses.

B. *Conclusion on overall SCADA system*

To achieve the desired effects from implementing these scenarios, cohesion among all segments of the system is necessary. The ability to detect network faults early allows the SCADA system to provide real-time information on abnormalities in measured values or errors in executive elements. The benefits of implementing a SCADA system and establishing DMAs and PMAs include a reduced number of faults due to lower pressure in the network, the ability to identify areas with water loss (such as illegal connections), increased financial efficiency by reducing the amount of non-revenue water, and greater financial benefits due to reduced water production and a decreased need to activate the wells, resulting in lower electricity consumption. Additionally, end users can benefit from lower water bills, there is an extended lifespan of the pipeline network, and there are greater environmental benefits.

C. *Recommendations for further work*

Further works can be done if the proposed 2 scenarios are realized and implemented properly. In terms of enhancing hydraulic characteristics, if the recommendation from [2] is considered an additional PMA can be introduced, pressure regulation and management could yield even greater benefits. This is particularly relevant given that the proposed area of interest falls within a high-pressure zone as shown in Figure 8.

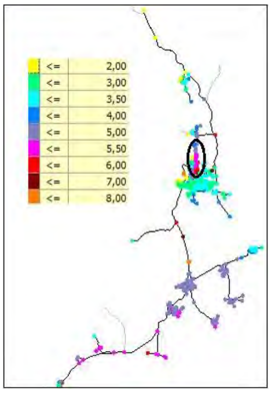

Figure 8 Proposed PMA after scenario 3 [2]

Implementing DMAs in water supply networks not only reduces water losses but also provides early indications of pipeline conditions. By comparing network pressures and detecting deviations under specific working conditions, early maintenance of pipelines and sensors is possible, thus requiring advanced SCADA system complexity. Different approaches to managing quality rely on statistical processes, including univariate and multivariate methods.

Univariate methods use control charts for monitoring a single variable, identifying potential defects through deviations from expected values based on simple mathematical models. Multivariate methods, such as Principal Component Analysis (PCA), analyze correlations among multiple variables to detect anomalies, thoroughly explained in [6].

Multivariate approaches can also validate measurement accuracy through crosschecks with feedback from valves and pumps. Significant deviations across multiple sensors or changes in valve/pump states indicate anomalies, often due to sudden water demand spikes or pipeline ruptures.

These methods lead to advanced machine learning algorithms, such as anomaly detection, crucial for timely and efficient equipment maintenance.

Furthermore implementing the PMA elements such as PRVs and the existing booster pump stations in the SCADA can enhance the control dimensionality of the systems by implementing and upgrading the system with proper control methods for real-time control and monitoring, such as reinforcement learning or neural network controllers.

Integrating such algorithms into SCADA systems creates intelligent systems, aligning with Industrial Internet of Things (IIoT) standards when connected to the internet or implemented to the cloud [7] [8].

Acknowledgment

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Model Predictive Control of a 2-DOF Robotic Arm and Comparative Analysis with Fuzzy Logic Control

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Dedicated to Prof. Mile J. Stankovski on his anniversary

***Abstract*—In this study we present a control design method of a Model Predictive Controller (MPC) for a 2-DOF planar robotic arm. This controller uses a system model to predict future behavior, allowing it to optimize control actions over a certain horizon, while satisfying a set of constraints. Building upon our previous work where we designed FLCs that rely on pre-defined rules, in this paper we propose a novel MPC approach and conduct a comparative analysis between the two control methodologies. To facilitate a comprehensive comparison, we calculated the Root Mean Square Error (RMSE) and Integral Absolute Control Signal (IACS) for the two controllers over the same input signal. The results demonstrate that the proposed MPC controller exhibits excellent response and robustness outperforming the FLCs in terms of control accuracy while also demanding less energy. A complete simulation environment is developed through the MATLAB/Simulink software.**

***Keywords*—Model Predictive Control; Fuzzy Logic Control; trajectory tracking control; robotic arm**

I. INTRODUCTION

Cardiovascular diseases have reigned as the leading cause of death, according to Centers for Disease Control and Prevention statistics [1]. Coronary artery disease, a condition where plaque buildup narrows coronary arteries and restricts blood flow, is most commonly treated with Coronary Artery Bypass Grafting (CABG) Surgery [3], [4], [5]. CABG is a procedure used to bypass the blocked coronary artery using healthy artery harvested from another part of the body [3], [4], [5], [7].

The traditional open-chest, on-pump CABG remains the most common procedure. Performed on a stopped heart using a cardiopulmonary bypass (CPB) machine, it carries inherent risks and complications for patients. On the other hand, the off-pump CABG offers an alternative, eliminating cardiopulmonary bypass risks and operating on a beating heart with stabilizers for targeted regions. However, both approaches involve a large chest incision, increasing post-surgical recovery challenges [3], [4], [5], [7]. Surgical procedures have revolutionized a lot, especially with the minimally invasive surgery, offering patients significant advantages over traditional open surgery. These advantages include reduced trauma, faster recovery times, and improved cosmetic outcomes [1]. However, complex minimally invasive surgery procedures like coronary artery bypass grafting (CABG) present unique challenges. The limited dexterity and visualization within the confined operative field make precise manipulation of delicate structures difficult [3], [4].

Robotic techniques have proven to be very successful for overcoming these difficulties by providing enhanced control, improved visualization through high-resolution 3D cameras, and tremor filtering, enabling surgeons to perform complex maneuvers with greater precision [5], [6]. Despite these advantages, the minimally invasive CABG procedures that are performed on the beating heart still use minimally invasive stabilizer. As reported in [8] there are concerns that the force applied by the stabilizers can cause damage to the heart tissue. The past two decades have witnessed a surge in the development of complex surgical robotic systems like Da Vinci [9], [10], Raven [11], and MiroSurge [12]. This is due to the fact that the trajectory of heart's movement is quasiperiodic (involving 3 translational and 3 rotational degrees of freedom), necessitating highly dynamic mechanical systems for precise manipulation during surgery [5], [6].

In our previous study [2] a Fuzzy Logic control (FLC) strategy for tracking the dynamic motion trajectory of a 2-DOF robotic arm was designed and analyzed. In the FLC controller discussed there, despite the commonly used position and velocity as inputs, the error second derivative was introduced as a third input, to achieve better accuracy tracking of the heart's motion.

Building upon our previous work that employed FLC for each joint of a 2-DOF planar robotic arm [2], this study delves into Model Predictive Control (MPC) as an alternative control strategy. After a detailed design of the control strategy of MPC for a 2-DOF robotic arm, we perform a comparative analysis to assess the influence of the two distinct control approaches on the overall performance of the robotic arm.

This paper is organized as follows. In Section II we give a brief introduction to the modeling of the 2-DOF planar robotic arm and a detailed strategy of the design of the control system. Section III provides a brief overview of the design of the FLC controllers in our previous study. The simulation results of the designed system and the comparative analysis are presented in Section IV. Here we analyze the RMSE and IACS values for both controllers. And lastly, in Section V we give the necessary conclusions.

II. Methodology for Model Predictive Controller Design of a 2-DOF Robotic Arm

This paper builds upon our prior work presented in [2], by exploring an alternative control method: Model Predictive Control. MPC provides several advantages over the standard FLC, including the ability to optimize control actions over a future time horizon and handle system constraints explicitly. We implement MPC controller for the same 2-DOF robotic arm and compare its behavior with the previously developed FLC system, with further details from [2] outlined in Section III. The objective is to assess whether MPC can achieve better tracking accuracy and robustness, potentially making it even more suitable for the delicate tasks involved in CABG surgery.

The Model predictive control (MPC) is an advanced control technique that is used to control a process while satisfying a set of constraints [14]. Model predictive control (MPC) is widely used in the robotics community. This is, on one hand, due to its ability to handle linear or nonlinear multiple-input multiple-output systems with state and input constraints. On the other hand, the formulation of the control task as optimization problem offers a high degree of flexibility. The drawback is the high computational demand for real-time solution of the optimization problem [13].

The main strategy of a model predictive controller is illustrated in Figure 1. In a typical MPC algorithm the system outputs are predicted for a certain interval of time (prediction horizon) by making use of accurate system model which is constructed based on the information (inputs and outputs) gathered from the system past as well as future control signals that have to be determined properly. As shown in Figure 1 the control signal is a sequence of step functions with variable amplitude. Amplitudes of these inputs are obtained by solving an optimization problem that is defined such that the difference between the system output and the reference is minimal. The objective function in the MPC optimization problem plays a central role, and it is usually a quadratic function of the difference between the predicted output signals and the control effort [15].

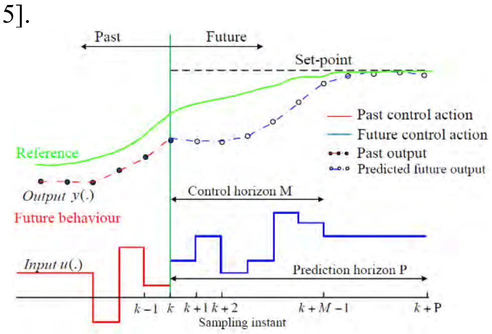

Figure 1. Visual illustration of the MPC control [18].

At each time step, MPC solves an optimization problem to minimize the quadratic cost function over the prediction horizon N_p. The system model is used to predict future outputs over N_p, based on the current state of the system and future control inputs. The optimization also provides a sequence of control inputs over the control horizon N_c, out of which only the first control input in the sequence is applied to the system. This process is repeated at the next time step with updated state information.

The control horizon N_c defines the length of time over which the MPC optimizes the control inputs. The balance between the prediction and control horizon is crucial for the performance of the MPC. Usually, N_c is less than N_p, and cannot be bigger than N_p, i.e., the following condition must be met $N_c \leq N_p$. In general, a longer prediction horizon can improve the prediction capabilities of the controller but increases the computational complexity. A shorter N_c reduces the number of control inputs to optimize, making the problem more tractable but potentially less flexible.

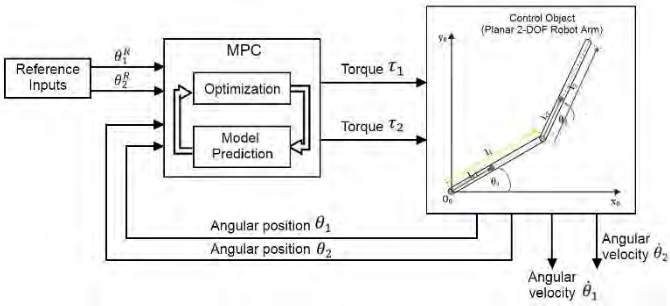

Figure 2. Detailed control scheme for trajectory tracking using MPC.

As in [2] we can split the design process of the control system for trajectory tracking of a 2-DOF robot arm using Model Predictive Controller in a few steps:

STEP 1. Designing the model of a 2-DOF robotic arm;
STEP 2. Defining the reference input signals;
STEP 3. Designing the MPC controller;
STEP 4. Applying the control approach to the real system/ model;

The detailed control scheme used to design the control system is presented on Figure 2.

A. Modeling of a 2-DOF Planar Robotic Arm

The same 2-DOF planar robotic arm from our previous paper was used and it is shown in Figure 3. [2]

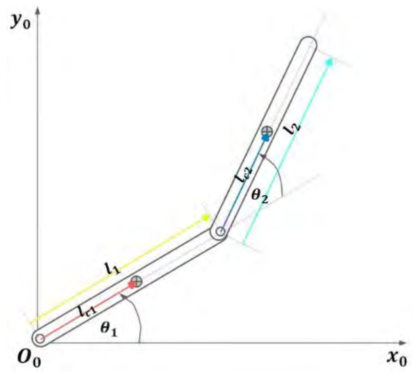

Figure 3. A 2-DOF robotic arm scheme [2].

The following notation was used to define the dynamic model of the robotic arm: τ - Generalized forces vector; M - Inertia matrix; C - Centrifuge and Coriolis force vectors; G - Gravitational force vector; θ - Components of the joint angular position vector; $\dot{\theta}$- Components of the joint angular velocity vector; $\ddot{\theta}$- Components of the joint angular acceleration vector [2].

The dynamic model of the robotic arm was developed using the Lagrangian formalism. The 2-DOF robot arm model had the dimension values given in Table I [2]:

TABLE I. MANIPULATOR ROBOT PARAMETERS

Joint 1	Joint 2
$m_1 = 0.392924$ [kg]	$m_2 = 0.094403$ [kg]
$l_1 = 0.2032$ [m]	$l_2 = 0.1524$ [m]
$l_{c1} = 0.104648$ [m]	$l_{c2} = 0.081788$ [m]
$I_1 = 0.0011411$ [kg·m^2]	$I_2 = 0.0020247$ [kg·m^2]

Using the kinetic and potential energy of the entire system and using the Lagrangian formalism we obtained the following model given in matrix form (further details on the process of modelling can be found in [2]):

$$\begin{bmatrix} m_1 l_{c_1}^2 + m_2 l_1^2 + j_1 & m_2 l_1 l_{c_2} \cos(\theta_1 - \theta_2) \\ m_2 l_1 l_{c_2} \cos(\theta_1 - \theta_2) & m_2 l_{c_2}^2 + j_2 \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} - \left(m_2 l_1 l_{c_2} g \sin(\theta_1 - \theta_2)\right) \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} + \begin{bmatrix} (m_1 l_{c_1} + m_2 l_1) g \cos\theta_1 \\ m_2 l_{c_2} g \cos\theta_2 \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \quad (1)$$

B. Designing the Model Predictive Controller for the Robot

A MPC control design approach mainly consists of the following components:

a) A discrete-time model
b) An objective function – cost function
c) Constraints on inputs (torque limits) and rarely on the outputs.

Here discussed MPC controller is fully designed and analyzed in MATLAB – Simulink. The first step in designing the MPC controller is obtaining a reliable model of the process. Since the MPC controller used here is linear, a discrete-linear model is obtained for (1) around the equilibrium points $\theta_1(0) = \pi/4$, and $\theta_2(0) = \pi/6$, with sampling period of 0.01s. The general linear discrete time, state space dynamic model of a system is defined as:

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k), \end{aligned} \quad (2)$$

where $x(k) = [\theta_1, \dot{\theta}_1, \theta_2, \dot{\theta}_2]^T$ is the state vector, $u(k) = [\tau_1, \tau_2]^T$ is the input vector and $y(k) = [\theta_1, \theta_2]^T$ is the output vector at the sampling instant k. The matrices A, B and C are the system matrix, input matrix, and output matrix, respectively. The numerical values of the matrices are omitted for brevity.

Next, the quadratic cost function, used in MATLAB–Simulink [17], incorporating terms that penalize deviations from desired state trajectories and control effort, is illustrated with:

$$J = \sum_{i=1}^{N_p} \left[\hat{x}_{k+i} - x_{ref,k+i}\right]^2 + R \sum_{j=0}^{N_c - 1} u_{k+j}^2 \quad (3)$$

where $\hat{x}_{k+i}$ is the output prediction at time $i = 1, \ldots, N_p$ based on measurement at current time k, $x_{ref,k+i}$ defines the reference trajectory, u_{k+j} is calculated control input where $j = 0, \ldots, N_c - 1$ and R is weighing factor that penalizes big control effort. The control input constraints are defined as: $u_{min} \le u_{k+j} \le u_{max}$.

After multiple tests, it was observed that the horizon length N_p had a strong influence on the volatility of the control signals amplitudes, which, in the analyzed robotic system, are the robot torques τ_1 and τ_2. The main conclusion drawn is that a short N_p implies a large variation in the amplitudes of the robot torques. Therefore, based on the RMSE and IACS value an acceptable control performance was attained by assuming the values of the parameters given in Table II:

TABLE II. MPC OPTIMIZATION PARAMETERS

Sample Time	T_s	0.01s
Prediction Horizon	N_p	22
Control Horizon	N_c	3
Weight factors	R	$r_{\tau_1,\tau_2} = 7.4$
Input constraints	u	$\lvert u_{1,2} \rvert \le 30$

III. USED FUZZY LOGIC CONTROLLER DESIGN OF A 2-DOF PLANAR ROBOTIC ARM MODEL

In this section we give a brief overview of the controller system design, presented in [2], in its basic form, in order to continue with a comparative analysis with the new MPC control strategy that was presented in Section II.

Two FLCs, one controller per joint were used to control the planar 2-DOF robotic arm. The design process of the control system for trajectory tracking of a 2-DOF planar robotic arm consisted of the following steps (Figure 3 [2]):

STEP 1. Designing the model of a 2-DOF robotic arm;
STEP 2. Defining the reference input signals;
STEP 3. Designing the FLCs;
STEP 4. Applying the control to the real system/model.

A. Designing the Fuzzy Logic Controllers for the Robot

In [2] the process of designing the FLCs consists of the following steps:

a) Defining inputs (angular position θ_1,θ_2; angular velocity $\dot{\theta}_1$, $\dot{\theta}_2$ and angular acceleration $\ddot{\theta}_1$, $\ddot{\theta}_2$) and outputs (torque τ1, τ2), respectively for FLC1 and FLC2;
b) Selection of fuzzy inference engine (Mamdani type);
c) Design of membership functions and rule bases;
d) Selection of the defuzzification method (Centroid).

The membership functions for the fuzzy logic controllers FLC 1 and FLC 2 are defined in [2] as follows:

The angular position θ_1,θ_2 for both fuzzy logic controllers is identical and is represented by five membership functions, with ranges from -2 to 2. These functions are: Negative Big (NB) and Positive Big (PB) which are trapezoidal, Negative Small (NS) and Positive Small (PS) are Gaussian functions and Zero (Z) is triangular.

The angular velocity $\dot{\theta}_1$, $\dot{\theta}_2$ is defined in a similar way, again with five membership functions with ranges from -5 to 5. The functions are: Left Very Fast (LVF), Left Fast (LF), Right Fast

(RF) and Right Very Fast (RVF) are Bell-shaped functions and Slow (S) is a Gaussian function.

The angular acceleration $\ddot{\theta}_1$, $\ddot{\theta}_2$ is defined with three membership functions with ranges from -2 to 2 for FLC1 and -1 to 1 for FLC2. The functions are two triangular functions - Negative (N) and Positive (P) and one Gaussian - Zero (Z).

The torque τ1, τ2 is defined with five membership functions with ranges from -20 to 20. FLC1 has two trapezoidal functions, two Gaussian and one triangular function. While FLC 2 has two trapezoidal and three triangular functions.

The rule bases in [2] are stored as a Fuzzy Associative Memory (FAM). Two FAMs were defined for the controllers, given in Table III. In FAM 1 the angular velocity $\dot{\theta}_1$, $\dot{\theta}_2$ was combined with the angular position θ_1,θ_2, while FAM 2 combined angular position θ_1,θ_2 and acceleration $\ddot{\theta}_1$, $\ddot{\theta}_2$. We suppressed some of the rules in FAM2, since they did not impact the results [2].

TABLE III. FAM 1 AND FAM 2 FOR THE FLCS

FAM1		**Angular velocity $\dot{\theta}_1$, $\dot{\theta}_2$**				
Ang. pos.θ_1,θ_2		LVF	LF	S	RF	RVF
	NB	LS	Z	LB	LB	LB
	NS	RB	LS	LB	LB	LB
	Z	RB	RS	Z	LS	LB
	PS	RB	RB	RB	RS	LB
	PB	RB	RB	RB	RS	Z

FAM2		**Ang. accelerat. $\ddot{\theta}_1$, $\ddot{\theta}_2$**		
Ang. pos.θ_1,θ_2		N	Z	P
	NB	x	x	x
	NS	x	x	LB
	Z	x	Z	x
	PS	RS	x	x
	PB	x	x	x

For the defuzzification method we used Centroid method, directly selected in MATLAB [2] and [16].

IV. SIMULATION RESULTS

In order to show the effectiveness of the proposed MPC controller, a comparison study with the FLCs was made. We implemented the designed control scheme to the simulated dynamical model of the planar robotic arm in MATLAB-Simulink. The proposed algorithm was evaluated by using three different refence input signals, more precisely sinusoidal signal, square and free waveform signal.

The physical and mechanical parameters of the robot used for simulation studies are given in Table I. The operating point around which the system (1) was linearized to obtain the linear model for prediction is $\theta_1(0) = \pi/4$, and $\theta_2(0) = \pi/6$. For a rigorous comparative analysis with our previous work [2], the input signals used here are those defined in [2], characterized by amplitude ranges that do not encompass the linearization operating point. As a result, one can conclude that the control performance obtained by the MPC controller will be worse than the performance that could potentially be achieved if the input signals were defined closer to the operating point.

Figure 4 illustrates the comparison results of tracking a sinusoidal trajectory. The comparison is between the convergence of the joint angles θ_1 and θ_2, respectively, to their reference values, using the FLC and the MPC control. By close visual inspection it can be observed that the MPC and the FLC achieve the set objective, which is both controllers successfully steer the joints close to the reference trajectory.

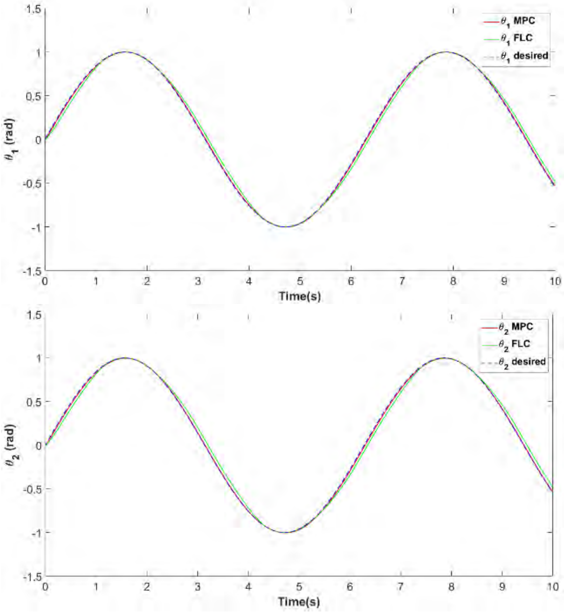

Figure 4. Tracking a sinusoidal trajectory with MPC and FLC.

Figure 5 shows the tracking results of a square waveform signal. This signal is harder to follow, due to the 90° abrupt change of direction, i.e. the real angular position needs more time to follow the referenced one. It can be noticed that the FLC shows a smoother response to these abrupt changes, while the MPC demonstrates a quicker reaction to changes in the system.

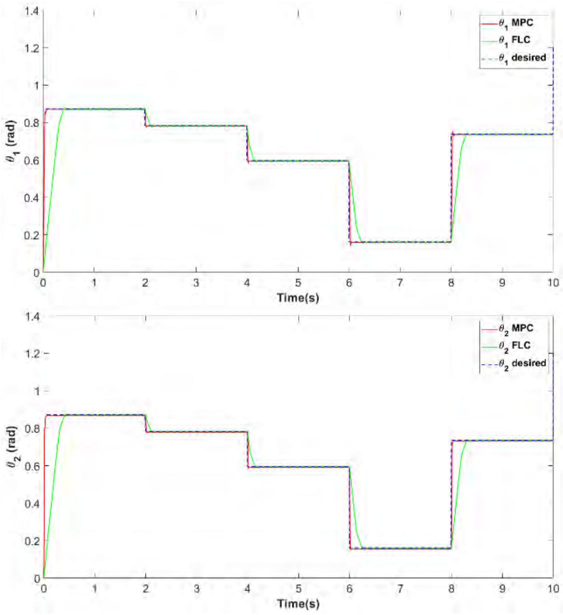

Figure 5. Tracking a square waveform trajectory with MPC and FLC.

The last reference signal is the free waveform trajectory, chosen for its closeness to the real heart motion trajectory in one dimension [5]. Figure 6 illustrates that the output generated by the FLC cannot closely follow the reference trajectory during the initial phase. In the latter phase, the tracking performance of the FLC and MPC seem to even out.

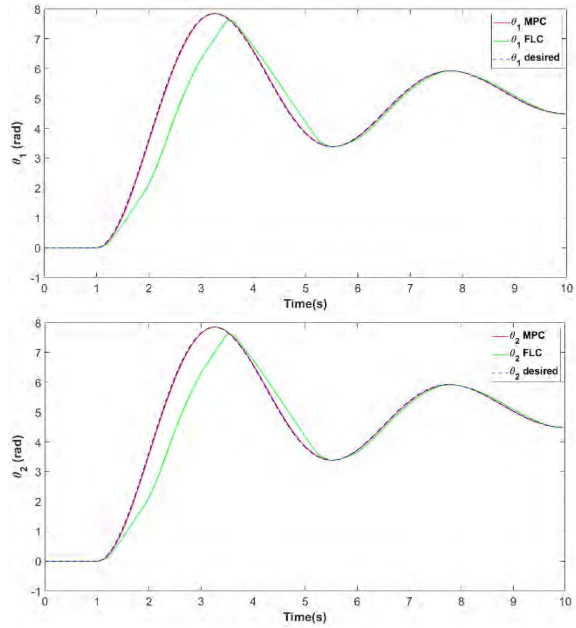

Figure 6. Tracking a free waveform trajectory with MPC and FLC.

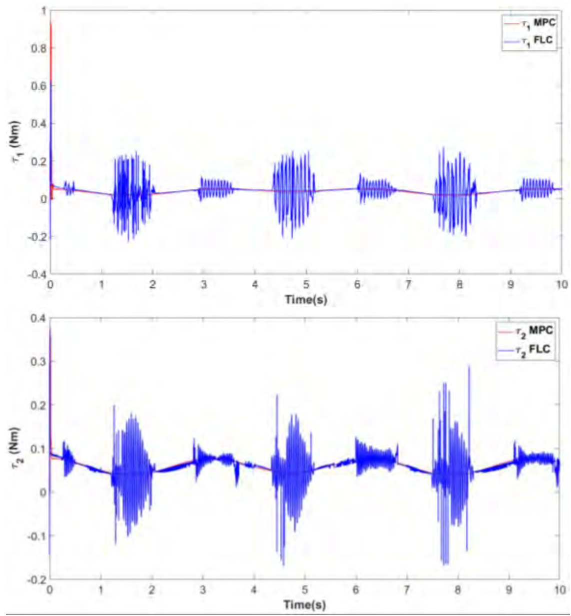

Figure 7. FLC vs MPC robot torque control during sinusoidal tracking.

Figure 7, Figure 8 and Figure 9 show the comparison between the robot torques τ_1 and τ_2, respectively, that have been obtained during different trajectory tracking, using the FLC and the MPC control. From the figures it is visible that the MPC control approach under all three input trajectories has smoot control effort without visible fluctuations, except in the case of square input trajectory, where abrupt changes in control signal amplitudes are observed. On the other hand, the control signal of the FLC is affected by temporal fluctuations in the control signal which have negative impact in both: control effort energy and output tracking performance. In the case of following the smooth input trajectory like the sinusoidal and the free waveform signals the MPC control approach exhibited lower and more consistent energy consumption. However, for trajectories with abrupt changes, such as the square waveform given in Figure 8, the computational demands of efficiently predicting control actions for rapid transitions lead to much higher energy consumption when using the MPC control approach compared to FLC.

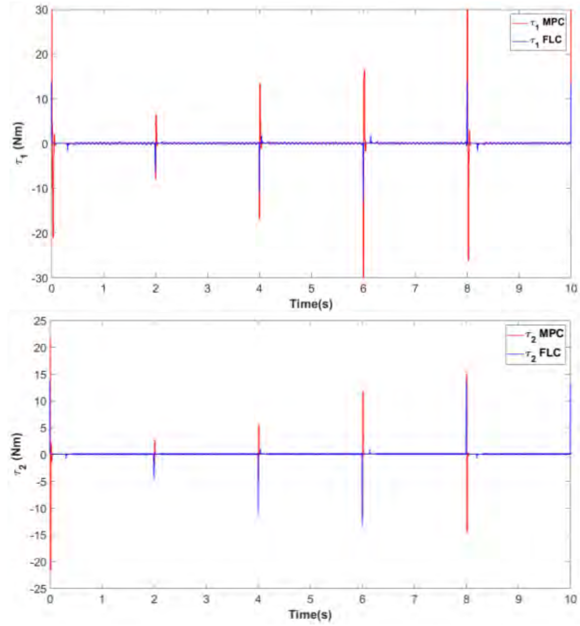

Figure 8. FLC vs MPC robot torque during square waveform tracking.

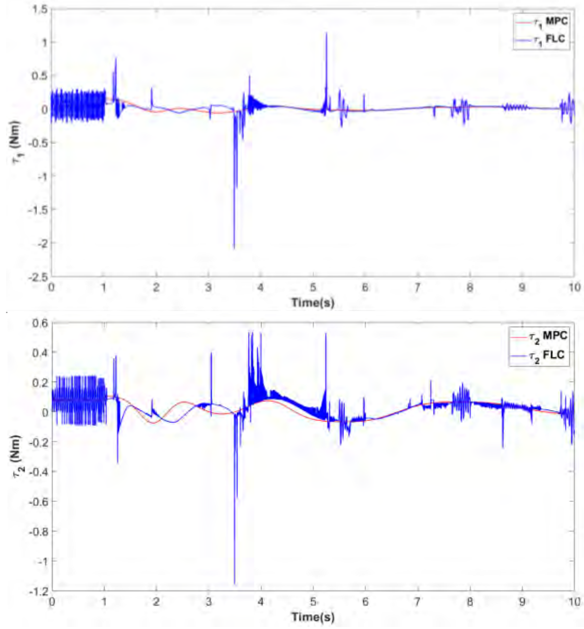

Figure 9. FLC vs MPC robot torque during free waveform tracking.

To quantify the tracking performance of the designed controllers for the different types of input trajectories, we calculate the angular position RMSE, which measures the dispersion of the tracking error, given by (4):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2} \tag{4}$$

where $\hat{y}_i$ and y_i are the desired and the real values of the tracking signal, respectively. To assess the effectiveness of different control strategies for the 2-DOF robotic arm, we utilized the

Integral Absolute Control Signal (IACS) of the control signal. IACS measure the system's ability to execute commands smoothly, while striving to minimize deviations from the desired trajectory. A lower IACS value indicates more efficient energy usage and smoother control performance. We calculated the IACS with the following equation (5):

$$IACS = \frac{1}{n}\int_0^t |u(t)|dt \qquad (5)$$

where $u(t)$ is the torque that is required to move the corresponding joint to the desired angular position.

The results in Table IV show that for all the three different trajectories, the MPC consistently shows lower RMSE values compared to FLC. However, the IACS values indicate that the MPC strategy for smoother trajectories achieves a significantly lower IACS compared to FLC. From this it can be concluded that the MPC controller achieves superior tracking accuracy for the robotic arm, ensuring it follows the desired trajectories more closely.

TABLE IV. RMSE AND IACS FOR FLC AND MPC

Signal	Type of Error	FLC		MPC	
		Joint 1	Joint 2	Joint 1	Joint2
Sinusoidal	RMSE	0.0349	0.0376	0.0102	0.0104
	IACS	$6.89*10^{-5}$	$8.09*10^{-5}$	$3.88*10^{-5}$	$5.98*10^{-5}$
Square waveform	RMSE	0.2389	0.2383	0.0438	0.0338
	IACS	$4.8*10^{-4}$	$3.36*10^{-4}$	$2.98*10^{-4}$	$1.78*10^{-4}$
Free waveform	RMSE	0.3557	0.3553	0.0325	0.0316
	IACS	$2.65*10^{-5}$	$3.12*10^{-5}$	$3.07*10^{-5}$	$4.67*10^{-5}$

V. CONCLUSION

Model predictive control (MPC) is a powerful tool for controlling constrained linear and nonlinear systems. While both FLC and MPC controllers achieved their control objectives, the simulation results in MATLAB-Simulink demonstrate the superiority of MPC for both joints. Under the defined scenarios, the MPC controller outperforms the FLC in terms of output accuracy and energy efficiency, as evidenced by lower RMSE and IACS values. However, compared to FLC, MPC can be computationally expensive, especially for real-time applications, and tuning the parameters requires significant effort. Despite this, MPC's capability for multi-objective optimization allows for strategies that minimize energy consumption while maintaining a good performance. Furthermore, its ability to adapt to changing dynamics and handle constraints inherently enhances the controller's robustness to disturbances and uncertainties.

It is important to note that the FLCs used in [2] are not optimized but rather experimentally tuned, which potentially can explain their lower performance. This contrasts with the MPC, where optimization efforts were applied. Future work could focus on optimizing FLCs by refining membership functions, incorporating neural networks, or implementing Adaptive Neural Fuzzy Inference Systems, potentially leading to more optimal control strategies. Such advancements would enable a more equitable comparison between MPC and FLC, ensuring that both controllers are optimized and evaluated under similar conditions.

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Optimal Control Algorithm for Electrical Load Management in Touring Buses and Comparative Analysis with Fuzzy Logic Control

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Dedicated to Prof. Mile J. Stankovski on his anniversary

***Abstract*—This paper discusses the use of Pontryagin's Minimum Principle (PMP) approach for electrical load management in touring busses. The backwards simulation modeling technique is utilized, based on the VECTO drive cycle to obtain the powertrain model. The PMP algorithm determines the power split between the battery, load, and the alternator, choosing the optimal battery power output, which minimizes the given cost function. The outcome of this strategy, in terms of fuel consumption, is compared to the conventional battery charging approach, as well as to a fuzzy-logic control approach. Based on the simulation results, we can conclude that the proposed algorithm achieves superior fuel economy in comparison with both strategies.**

***Keywords*—energy management, optimal control, fuzzy logic control, touring bus, electrical load management**

I. Introduction

Conventional internal combustion engines (ICEs) have existed for over a century. As a result of the fast economic growth and the expansion of the world population, the demand for vehicles has drastically increased in the past decades. The usage of fossil fuels, being a major contributor in global warming and one of the biggest pollution sources, led the countries to implement strict standards of automotive exhaust emissions and energy consumption. Therefore, the automotive industry is striving to develop control solutions to improve the fuel economy for ICE vehicles by investing in more efficient energy management (EM) technologies.

There are different approaches for efficient vehicle electrical load management, found in literature, starting from various optimization techniques [1], [2], [3], [4], [5], [6], [7], [8], [9], to more intelligent approaches, incorporating artificial intelligence, machine learning, or other techniques [7], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19]. Part of these methods are applied in conventional (alternator-based) vehicles, while part in hybrid vehicles (HVs).

There are numerous optimization techniques that can be found in the recent research literature, used for electrical load management systems. For example, in [1] a real-time vehicle EM system is proposed, based on Pontryagin's Minimum Principle (PMP), used to determine the optimal power distribution between the alternator and the battery. In the same context, paper [2] analyses and compares different optimization approaches: PMP, Optimal Power Distribution – OPD, Equivalent Consumption Minimization Strategy – ECMS, Model Predictive Controller – MPC, Modified Dynamic Programming – DP etc. Paper [3], on the other hand, presents a dynamic optimal regulation strategy for controlling the output power of the alternator and battery, whereas paper [4] presents an ECMS for controlling the alternator's duty cycle to optimize the fuel economy. Differently from the above approaches, authors in [5] propose optimal control algorithms for EM of automotive systems, introducing battery and supercapacitor storage devices, whereas in [6] a simultaneous optimization technique based on Multi Objective genetic algorithms is given. While authors in [7] give a comparison between a PMP optimized PI-controller and a fuzzy logic controller, applied in HVs, paper [8] presents an adaptive MPC for power management in hybrid electric vehicles, whereas in [26], [27], [28], [29], [30] a PMP algorithm is applied for electrical load management for various hybrid powertrains. While papers [1], [2], [3] and [4] are optimal strategies applied in conventional alternator-based vehicles, papers [5], [6], [7], [8], [26], [27], [28], [29] and [30] present optimal solutions, applied in unconventional powertrains, such as fuel cell vehicles, HVs, configurations using a supercapacitor, etc. Nevertheless, many of the strategies are adequate and can be applied to both powertrains.

Regarding intelligent control strategies, there are also numerous approaches for smart automotive power management. As an illustration, authors in [10] adjust the operating mode of the alternator, using an intelligent control strategy, whereas paper [11] presents a type of intelligent alternator control strategy, which reduces fuel consumption, as well as exhaust gas pollution. Research conducted for AI based power management optimization strategies are mainly applied in HVs ([12], [13], [14], [15], [16], and [17]), using different smart algorithms and techniques. Also, the numerous cases where intelligent Fuzzy Logic (FL) approaches are applied consider HVs, as in [17], [18] and [19], which was motivation for our work, given in [25], where FL approach for intelligent alternator-based power management in touring buses was proposed.

To the best of our knowledge, the numerous optimization techniques for electrical load management are applied in cars, both for conventional and hybrid car powertrains (as in [1], [2], [3], [4], [5], [6], [7], [8], [26], [27], [28], [29], [30], and others). This was motivation for the research in this paper, where a new approach for optimal control of conventional powertrains in touring buses was investigated, using a Pontryagin's Minimum Principle. The PMP algorithm determines the power split between the battery, load, and the alternator, choosing the optimal battery power output, which minimizes the given cost function.

As in [25] we have investigated a fuzzy logic algorithm that determines the applied voltage on the battery, based on the Brake Specific Fuel Consumption (BSFC) map and the battery state of charge, in this paper we also give a comparison of the results between the PMP algorithm, conventional baseline strategy and the fuzzy-logic control strategy. The simulation results reveal that the optimal control, in this case, is a better alternative in achieving improved fuel economy.

The paper is structured as follows. Section 2 presents the powertrain modeling steps, which was also presented in [25]. Section 3 presents the EM problem description, while Section 4 gives the design of the PMP controller for choosing the optimal battery output power, for the given powertrain. The comparative simulation analysis is given in Section 5. We conclude the paper, giving the necessary conclusions in Section 6.

II. Powertrain Modeling

A. Backwards Simulation of a Powertrain

Here we present the powertrain modeling steps (as it was presented in our work [25]). The backwards approach of modeling a powertrain consists of using static equations and efficiency maps [21]. The model assumes that a predefined speed trace is met by the vehicle. Therefore, there is no driver model in the simulation [22]. The model starts from the longitudinal speed/acceleration profiles in the drive cycle, which are used to calculate the required torque and speed at the wheels. Then the chain continues to the transmission and engine module, where the required engine speed and torque are calculated (used to estimate the amount of the necessary primary energy for the drive cycle) [21]. Fig. 1 shows the typical computational scheme of a backwards model. This model is executed faster than the forward-looking models [21], but it poses a major weakness, resulting from using the steady state maps and the assumption that the vehicle speed trace is already met. Below we give the modeling steps for all the building blocks of the model.

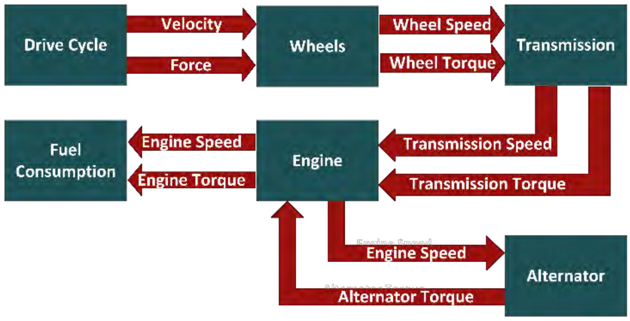

Fig. 1. Signal flow in a backwards-looking powertrain

B. Vehicle Longitudinal Dynamics

The vehicle modeling starts by considering the total traction force ($F_{Traction}$), which is a sum of the following forces: aerodynamic resistance (F_{Drag}); the rolling resistance force ($F_{Rolling}$); the Newtonian acceleration force (F_{Newton}); and the gravitational force ($F_{Gravity}$); as given below [23]:

$$F_{Drag} = \frac{1}{2}\rho * A_f * C_d * v^2 \tag{1}$$

$$F_{Rolling} = m * g * C_r * \cos\theta \tag{2}$$

$$F_{Newton} = m * a \tag{3}$$

$$F_{Gravity} = m * g * \sin\theta \tag{4}$$

$$F_{Traction} = F_{Drag} + F_{Rolling} + F_{Newton} + F_{Gravity}, \tag{5}$$

where A_f, – frontal area of the vehicle; ρ – density of the air, C_d– drag coefficient; v – velocity; m – mass of the vehicle; g – gravitational acceleration; C_r – rolling resistance coefficient; θ – road inclination; and a – vehicle acceleration.

Given the wheel radius r, the wheels angular speed (ω_w) and the wheel torque (T_w) can be calculated as follows:

$$\omega_w = \frac{60 * v}{2 * \pi * r} \tag{6}$$

$$T_w = F_{Traction} * r \tag{7}$$

C. Transmission

The engine torque (T_e) and engine speed (ω_e) are given with:

$$T_e = \frac{T_w}{i_g * \eta} + T_a \tag{8}$$

$$\omega_e = \omega_w * i_g \tag{9}$$

The first term in (8) is the traction torque, defining the engine power transmission to the wheels through the gearbox, and the second term being the alternator torque; i_g is the appropriate gear ratio and η is a static efficiency, which we assumed to be 0.95 (95%).

D. Internal Combustion Engine – ICE

The modeling of the ICE is based on a fuel consumption map (Fig. 2). The map shows the brake specific fuel consumption (BSFC) curves, resulting from the engine RPM (revolutions per minute [min^{-1}]) and the brake mean effective pressure (BMEP). BMEP is given with:

$$p_e = \frac{2*\pi*n_c*T_e}{V_d*100000} \quad (10)$$

where n_c is the number of revolutions per stroke (for a 4-stroke engine, n_c = 2), and V_d is displacement volume. The BSFC, given in g/kwh, measures the fuel efficiency of a combustion engine. The vehicle is thus assumed to always be in the most efficient gear.

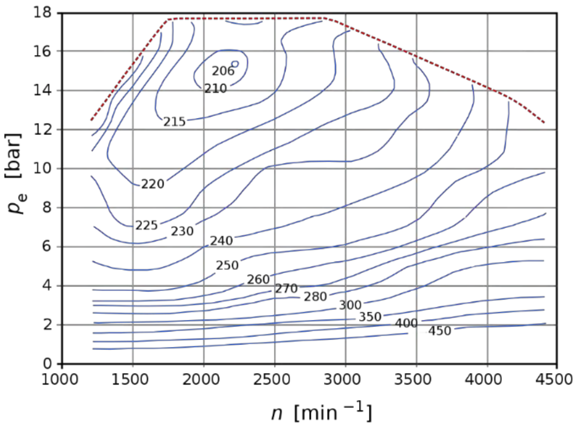

Fig. 2. Fuel consumption map

E. Vehicle Electrical System

The electrical system of a conventional (non-hybrid) vehicle typically consists of three main components: the battery, the alternator, and the electrical loads, as shown on Fig. 3. Smart alternators are essentially those that have their output voltage controlled externally via the Engine Control Unit (ECU) rather than an internal voltage regulator as found in traditional alternators. The ECU commands the alternator's duty cycle, which generates a field current, in relation to the engine speed. The alternator power is split between the electrical load demand and the battery power charge (Fig. 3) [2]. Depending on this power balance, the battery accepts or supplies current. Studying this ability is discussed in more detail in the next sections. The work in this paper was developed for the electrical system of a conventional diesel bus which uses four alternators in parallel, in order to supply the load demand.

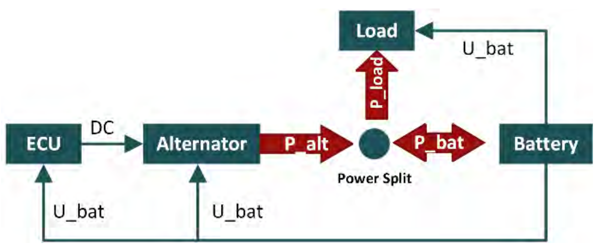

Fig. 3. Vehicle electrical system

1) Alternator

The alternator model consists of two lookup-tables, which specify the maximal output power (P_{a_max}) and the torque (T_a) for a single alternator, based on the alternator speed (ω_a), output current (I_a) and a fixed battery voltage of $28V$. The plots are shown on Fig. 4 and Fig. 5 respectively, while their implicit forms are given in (11) and (12), where $\omega_a = 4 * \omega_e$.

$$P_{a\_max} = P_{a\_max}(\omega_a) \quad (11)$$

$$T_a = T_a(\omega_a, I_a) \quad (12)$$

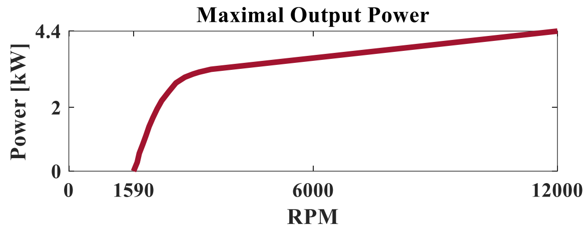

Fig. 4. Maximal output power of the alternator

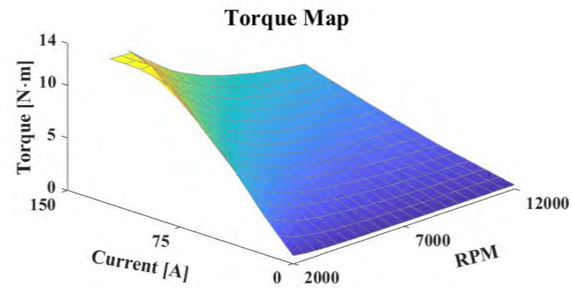

Fig. 5. Alternator torque map

2) Battery

The modeling of the 24V lead-acid battery is made using the "Schiffer" battery model [24]. The cell voltage (U_0) is calculated using a modified Shepherd equation:

$$U(t) = U_0 - gDoD + \rho_c \frac{I}{C_N} + \rho_c m_c \frac{I}{C_N} \frac{SoC}{C_c - SoC} \;, \forall I > 0 \quad (13)$$

$$U(t) = U_0 - gDoD + \rho_d \frac{I}{C_N} + \rho_d m_d \frac{I}{C_N} \frac{DoD}{C_d - DoD}, \forall I < 0 \quad (14)$$

Equation (13), and (14) consists of four terms. The first is the open circuit voltage (OCV), i.e. U_0, under fully charged conditions. The second term is associated with the change of OCV with the state of charge (SOC), where g is an electrolyte proportionality constant, while $DOD = 1 - SOC$ is the depth of discharge. SOC is the state of charge ($SOC = 1$ - fully charged battery; SOC = 0 - after discharge of the nominal capacity). The third term describes the ohmic losses, represented by an ohmic resistance, where ρ_c (ρ_d) is the aggregated internal resistance during charge (discharge), I is the applied current (charge: $I >$ 0, discharge: $I \leq 0$), and C_N is the nominal capacity. The fourth term models the overvoltage as a function of current and state of charge, where m_c (m_d) is the charge transfer overvoltage coefficient and c_c (C_d) is the normalized capacity, during charge (discharge), respectively. SOC of the battery is calculated through integration of the difference between the current (I) and the gassing current (I_{gas}), divided by the nominal capacity $C_N = 220\,Ah$, where $SOC(0)$ is the SOC at time t_0.

$$SoC(t) = \int_0^t \frac{I(t) - I_{gas}(t)}{C_N} \, d\tau \quad (15)$$

3) *Electrical load*

The electrical load profile has two major consumers: the air conditioning (7.5kW with a 50% duty cycle) and the ventilation (3kW with a 35% duty cycle). Additionally, there are 45 smaller consumers taken into consideration such as: interior/exterior lights, windscreen wipers, radio etc., with a total power of 4.1kW and an arbitrary duty cycle. The profile of the electrical load over the VECTO drive cycle is given on Fig. 6.

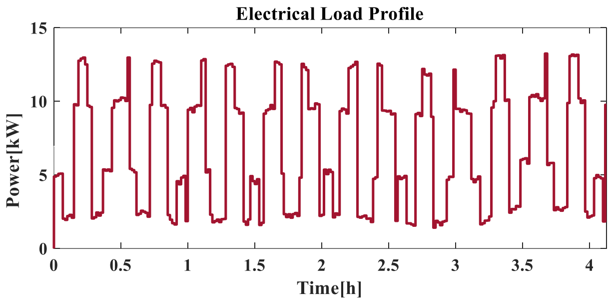

Fig. 6. Electrical load profile

III. Problem Description

In [25], we have studied an electrical load management using a fuzzy logic control in touring buses. For the purpose of a comparison analysis, given later, the problem description given here is presented in a similar fashion. When the alternator is running and producing a charging voltage, a mechanical load on the engine is produced through the alternator belt. As the output voltage rises, the mechanical load increases, making it harder for the engine to turn the alternator, thus consuming more fuel in the process (Fig. 7). In the conventional control strategy, the alternator maintains the battery voltage at a predetermined value, to ensure a full charge, and only utilizes the battery when the alternator power is incapable of supplying the electrical load demand. Therefore, using the battery's ability to work as a reversible energy storage device could be controlled and may in fact be beneficial for the fuel economy [1], [2], [3], [4], [5], [10], [11]. To decrease the fuel consumption, one possible strategy is to control the power split between the battery and the alternator, while maintaining the SOC, within the working range.

The numerous optimization techniques for electrical load management are applied in cars, both for conventional and hybrid car powertrains (as in [1], [2], [3], [4], [5], [6], [7], [8], [26], [27], [28], [29], [30], and others). Here, differently from the above works, an optimal electrical power management in a conventional powertrain, applied in touring buses, was investigated. Our proposed EM strategy consists of the following. It forces the alternator to decrease its output during periods of overall inefficiency, so the charge rate becomes negative, unloading the engine and supporting the vehicle electrical load with the energy stored in the battery. Oppositely, during moments of overall efficiency of the system, the alternator is forced to increase its output beyond what is needed, powering the vehicle electrical system, i.e., the extra power is absorbed by the battery. A PMP control is implemented, as a tool for solving this optimization problem. The PMP algorithm will be further explained in the following chapters.

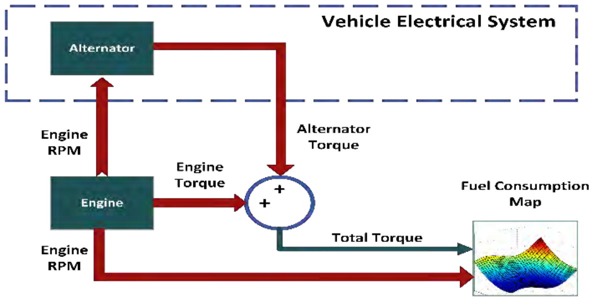

Fig. 7. Connection between vehicle's electrical system and the engine

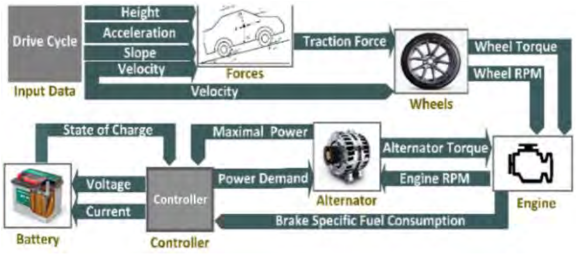

Fig. 8. Simulink model of a powertrain

IV. Application of Pontryagin's Minimum Principle for Optimal Control in the Given Powertrain

Pontryagin's minimum principle [31] is an analytic optimization method that serves as a tool for solving problems from the optimal control field. This algorithm transforms a given optimization problem into a momentary Hamiltonian optimization problem.

The quantity that needs to be minimized is the mass fuel flow rate $\dot{m}_f$ measured in g/s, whereas the state variable $x(t)$ is the state of charge of the battery. Additionally, the momentary output power of the battery $P_B(t)$ is the control variable $u(t)$. Finally, we can define $L\big(x(t), u(t)\big)$ as:

$$L\big(u(t)\big) = \dot{m}_f(\omega_e(t), T_e(t)) \tag{16}$$

The goal of the optimal control EM strategy is to minimize the fuel consumption rate over a certain drive cycle defined with $[t_0, t_f]$. Thus, we can define the cost function as follows:

$$J = min\left(\int_{t_0}^{t_f} m_f(x(t), u(t), t)dt\right) \tag{17}$$

Meanwhile, the state equation is given with (18), and the equation for the battery current is given with equation (19), both derived from the modified Shepherd equation given with equations (13) and (14).

$$\dot{x}(t) = \frac{-I_B\big(x(t), u(t)\big)}{3600Ah_{nom}} \tag{18}$$

$$I_B(t) = \frac{U_0 - gDoD - \sqrt{(U_0 - gDoD)^2 - 4P_B R_i}}{2R_i}\ , \tag{19}$$

where the output power of the battery is given with $P_B = U_B * I_B$, and $x = SoC = 1 - DoD$ where DoD - depth of discharge. On the other hand, there are two cases for the internal resistance of the battery: the equation (20) gives the value of the battery resistance during the charging process, whereas the equation

(21) calculates the resistance during the discharging process such as:

$$R_i(t) = \begin{cases} \frac{\rho_c}{C_N} + \frac{\rho_{cM_c}}{C_N}\frac{SoC}{C_c - SoC}, \ I_B < 0 & (20) \\ \frac{\rho_d}{C_N} + \frac{\rho_{dM_d}}{C_N}\frac{DoD}{C_D - DoD}, \ I_B > 0 & (21) \end{cases}$$

The positive sign of the current indicates discharge, while the negative current indicates charging of the battery. There are several physical boundaries of the system that must be taken into consideration, which relate to the state variable and the minimum and maximum values of all the electrical units in the system (alternator, battery, and load). The system boundaries are given with equation (22). x_0 and x_f are the initial and final value of the state variable; x_{min} and x_{max} are the minimal and maximal allowed value of the state of charge; $P_{B,max}$ and $P_{B,min}$ are the maximum and minimum output power of the battery; $P_L(t)$ is the power of the load, while the maximal output power of the alternator is regulated according to Fig. 4.

$$\begin{cases} x(0) = x_0 \\ x(f) = x_f \\ x(t) \in [x_{min}, x_{max}] \\ P_{alt}(t) \in [0, P_{alt,max}] \\ P_B(t) \ \in [P_{B,min}, P_{B,max}] \\ P_L(t) = P_{alt}(t) + P_B(t) \end{cases} \tag{22}$$

Finally, the Hamiltonian function is constructed as follows:

$$\mathrm{H}(x, u, \lambda, t) = \dot{m}_f(t) - (\gamma(t) - \varphi(t)) * \dot{x}(t)\,. \tag{23}$$

$\gamma(t)$ is known as a costate variable, which is a parameter that decides the tendency of the algorithm; thus, its initial value must be tuned. A smaller value of $\gamma_0 = \gamma(0)$ will prioritize charging, while a larger value will prioritize discharging of the battery. For the goals of our research, we want the battery SOC (state variable x) to be in a charge sustaining mode, limited inside predefined boundaries $[77\% - 83\%]$. For such a goal to be achieved, the initial value of the costate variable (γ_0) needs to be an optimal, perfectly balanced value. Additionally, the final value of the state variable $x(f) = x_f$ has to be almost equal to its initial value.

$$x(0) \cong x(f) \tag{24}$$

The other parameter in equation (23) is $\varphi(t)$ which represents the working coefficient of the battery. It serves to keep the SOC within the predefined boundaries and is defined with:

$$\varphi(t) = \begin{cases} \varphi_B: & SoC > SoC_H \\ 0: & else \\ -\varphi_B: & SoC < SoC_L \end{cases} \tag{25}$$

where φ_B is a larger value which serves to combat the $\gamma(t)$, when the SOC reaches the maximal or minimal value.

1) Shooting method

A very good approximation of the optimal solution of the PMP is obtained if a value for the initial condition $\gamma_0 = \gamma(0)$ that satisfies the above conditions is found [32]. This can be done offline, using a single shooting method. In the shooting method, the initial condition γ_0 that satisfies the necessary conditions of the PMP is obtained simply by "sweeping" across a range of values of γ to identify the value for which $x(0) \cong x(tf)$. The algorithm that we use here can be found in [1] (or similar variants in [2], [5], [26], [32], and others).

V. Simulation Results

Fig. 8 presents the simulation model, used to compute the fuel consumption of a conventional diesel bus. The proposed control strategy was implemented and simulated (using Simulink, MATLAB) over the VECTO drive cycle [20], which is shown on Fig. 9.

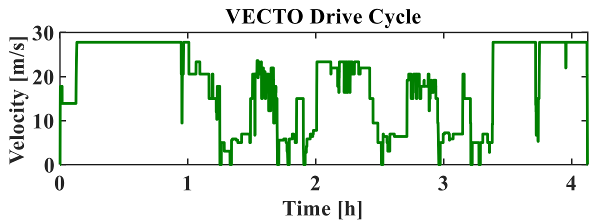

Fig. 9. VECTO drive cycle

We first evaluate the proposed PMP strategy. The change of the battery SOC over the VECTO drive cycle, when the PMP strategy is used, is shown on Fig. 10, whereas the power split between the alternator, the battery and the load is given on Fig. 11. The SOC (state variable x) is inside the predefined boundaries, mentioned above, with almost equal initial and final value, as defined with (24). On the other side, it is evident from Fig. 11 that the battery is being utilized in an optimal way, thus unloading the engine during inefficient periods, directly leading to an improved overall fuel economy.

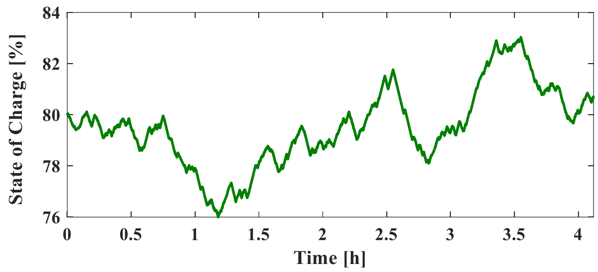

Fig. 10. Change of SoC during the PMP strategy

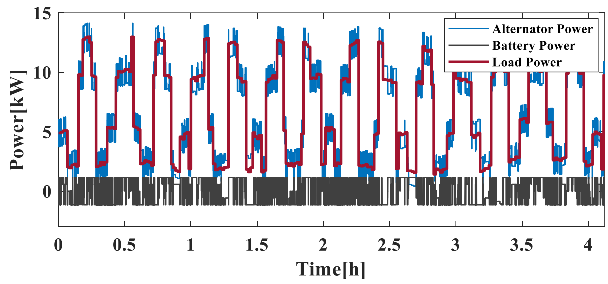

Fig. 11. Power split with the PMP strategy

Furthermore, the proposed PMP power split strategy was compared with the conventional and fuzzy logic strategy (given in our previous study [25]). The numerical results are shown in Table I, where the percentual savings and fuel consumptions are given. The PMP algorithm achieves a fuel economy of 30.08 L/100km over the VECTO drive cycle, which is an improvement of 0.89% compared to the conventional algorithm, whereas surpassing the fuzzy logic control strategy by 0.13%.

TABLE I. FUEL SAVINGS COMPARISON

Control Strategy	Fuel Consumption L/100km	Fuel Economy Improvement
Baseline	**30.35**	**/**
Fuzzy Logic	**30.12**	**0.76%**
PMP	**30.08**	**0.89%**

VI. CONCLUSIONS

From the numerical results given in Table I, the optimal control algorithm comes out as a more efficient EM strategy, achieving better overall fuel efficiency than the fuzzy logic algorithm and the conventional approach. However, even though the PMP strategy surpasses both algorithms in terms of efficiency, the improvement in the fuel economy will come at a higher implementation cost, because the optimal control algorithm requires larger computational power, compared to the other two strategies. It is also good to note that the percentual results are inside the expected range, obtained in other works ([1], [2], [3], [4], [5], [10], [11]).

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Segment Routing IPv6 for Future Networks

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***Abstract* — With the overload and complexity of IP connectivity and the variety of protocols that each technology and application has been introducing in order to keep human beings connected to the modern Internet, it is a priority for Service Providers to seek a simplification of their infrastructures to make them more efficient, scalable, simpler and profitable. Segment Routing IPv6 (SRv6) is a networking technology designed to simplify and enhance network traffic engineering, forwarding, and service delivery in IPv6 networks. It leverages the capabilities of IPv6 data plane and header extension to encode forwarding instructions, enabling efficient and flexible routing without the need for additional signaling protocols. Allows for the creation of explicit paths through the network by defining segments, each representing a specific instruction or network function, such as service chaining, traffic engineering, and network slicing. SRv6 is a promising solution to support advanced services such as services in future 6G mobile networks.**

***Keywords* — IPv6, MPLS, Segment Routing, SRv6, 6G.**

I. Introduction

DUE to the appearance of new communication protocols and technologies such as 6G, IoT, telepresence, Artificial Intelligence, microservices, Big Data requirements, cybersecurity concerns and Software-Defined Networking, the processing carried out by All-IP dual-stack WAN Infrastructures is becoming overloaded, thus not allowing to scale and being resilient in the near future, [1]. Given the era of digital transformation, automation and programmability, an ISP architecture is needed that will be easier to manage and operate. The newest version of internet protocol is IPv6 formulated by the Internet Engineering Task Force (IETF), which helps identify and local endpoint systems on a computer network and route online traffic while addressing the problem of IPv4 address. Until now, the use of MPLS on the ISP side has covered the current market needs, [2], but with the exponential growth of information handling and processing, this technological and business model may be threatened as it cannot meet the new information transmission requirements which that lead to non-profitable Service Providers (SP).

SRv6 emerges as a pivotal technology, leveraging the inherent capabilities of IPv6 to streamline packet forwarding and service delivery. Network routing relied on complex protocols and overlays to guide traffic along predetermined paths. SRv6 introduces a fundamental departure from this approach by embedding routing instructions directly into the IPv6 packet header. This innovative and smart technique empowers network operators with granular control over packet forwarding without the need for additional signaling protocols or overhead. SRv6 at its core, enables the creation of explicit paths, or segments, within the network. These segments serve as waypoints, each representing a specific network function, such as service chaining, traffic engineering or network slicing. By encapsulating these instructions within the IPv6 header, SRv6 enables a more deterministic and efficient routing mechanism, enhancing overall network performance and facilitating seamless network operations.

The IPv6 protocol has many features including the expanded addressing capability, simplification of the header format, auto-configuration mechanism, improved support for extensions and options, extensions for authentication and privacy, flow labeling capability and so on. For these reasons SR can be instantiated over the IPv6 data plane, in what is Segment Routing v6 (SRv6), using a new type of Routing Extension Header called the Segment Routing Header (SRH). SRv6 is designed to coexist with existing network architectures, including MPLS networks and IPv4. It provides backward compatibility mechanisms to ensure seamless integration with legacy networks, enabling operators to transition to SRv6 gradually. This interoperability allows operators to leverage existing investments in network infrastructure while benefiting from the scalability, flexibility, and programmability of SRv6.

In this direction, this paper uniquely examines the functioning of Segment Routing for IPv6 (SRv6), emphasizing its deployment in future 6G mobile networks. Its focused analysis on SRv6's operational benefits and future applications sets it apart from more general networking surveys. The rest of the paper is organized as follows. Section II explains them IP6 characteristics important for routing in the mobile network. Section III provides details about functioning of segment routing for IPv6. The comparison of SR-MPLS and SRv6 is elaborated in Section IV. Section V describes SRv6 deployment for the future 6G mobile networks. Finally, Section VI concludes the paper, addresses the challenges in 6G network and provides directions for future work.

II. IP6 Characteristics Important for Routing in the Mobile Network

Mobile Internet access from smartphones and other mobile devices is accelerating the exhaustion of IPv4 addresses. IPv6 crucial for the continued operation and growth of the Internet, and in particular plays a critical role in modern networks. IPv6 offers several characteristics that make it particularly well-suited for routing in mobile networks:

A. IPv6 Header format

IP version 6 (IPv6) is the latest. It is also said to be the next-generation IP protocol. IPv6 provides several advantages over IPv4.

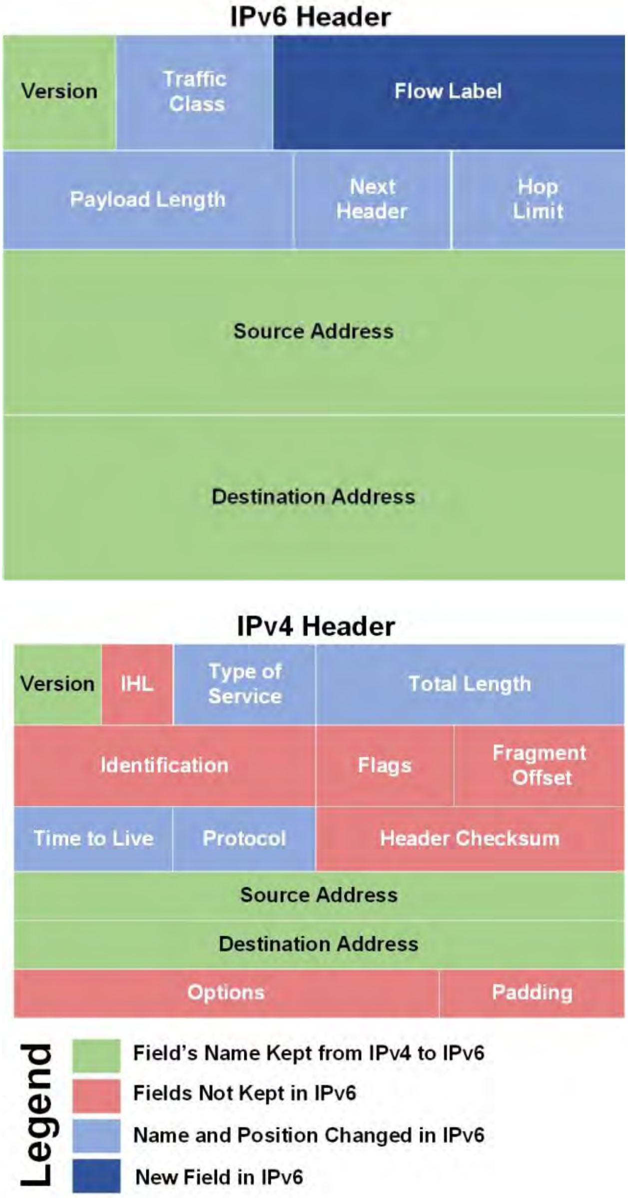

Fig. 1. IP header comparison

Key changes from IPv4 header to IPv6 header include the following (Fig.1):

- *Unchanged Fields*: Three fields are used the same way and *retain* the same name (though they have different content and/or size): Version, Source Address and Destination Address.
- *Renamed Fields*: Two fields are used the same way but *renamed*: Traffic Class and Hop Limit
- *Modified Fields*: Two fields are used in a way similar way in IPv4 but are slightly different in meaning and also renamed: Payload Length and Next Header.
- *Added Fields*: There is one new field: Flow Label.
- *Removed Fields*: To cut down on header length and unnecessary work, five IPv4 header fields are removed from the IPv6 header

B. Address Space

Compared to IPv4's 32 bits, IPv6 offers a vastly expanded address space with address lemgth of 128 bits, which gives 340 trillion trillion trillion addresses i.e. 2^{128}=340,282,366,920,938,463,463,374,607,431,768,211,456 = 67 billion billion addresses per cm^2 of the planet surface.

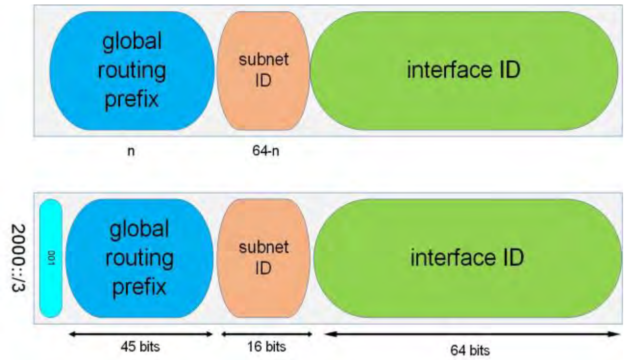

Fig. 2. IPv6 address format

The sheer size of IPv6's address space (2^{128}) means that it can accommodate an almost infinite number of devices, crucial in mobile networks where the number of connected devices is rapidly increasing. With IPv6, each device can have a unique globally routable address (address format is given in Fig. 2), eliminating the need for techniques like Network Address Translation (NAT), simplifying routing and improving end-to-end connectivity [3], [4].

Routing solutions need to efficiently handle this scalability requirement to support the proliferation of smartphones, IoT devices, and other connected gadgets.

C. Autoconfiguration

IPv6 incorporates two main mechanisms for address assignment: Stateless Address Autoconfiguration (SLAAC) as shown in Fig. 3, and Dynamic Host Configuration Protocol version 6 (DHCPv6).

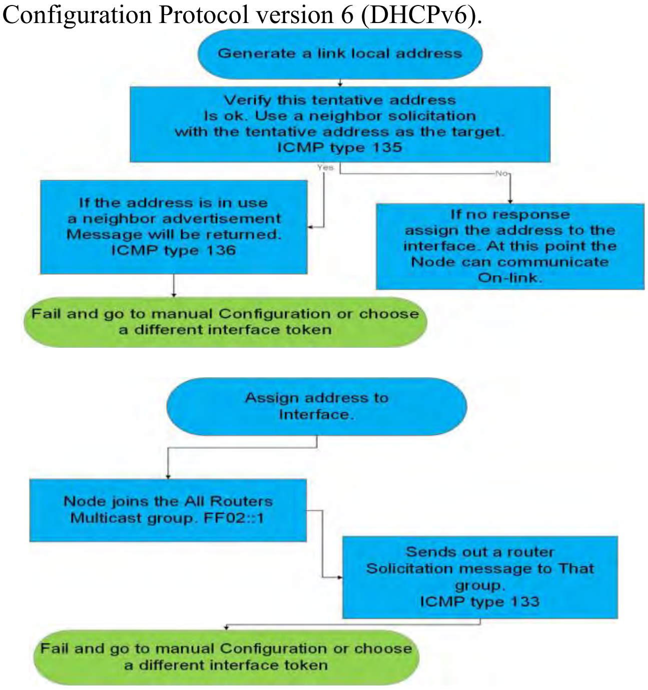

Fig. 3. Stateless Autoconfiguration

DHCPv6 can also be used for more advanced configuration options, providing flexibility in assigning addresses and additional parameters to devices.

SLAAC allows devices to generate their IPv6 addresses based on the network prefix advertised by routers, reducing the need for manual configuration [5].

In mobile networks, where devices frequently connect and disconnect, autoconfiguration mechanisms like SLAAC reduce administrative overhead and simplify network management [6].

D. Mobility Support

MIPv6 enables devices to maintain continuous connectivity and retain their IP addresses as they move between different network attachment points.

IPv6 mobility protocols, such as Mobile IPv6 (MIPv6), Proxy Mobile IPv6 (PMIPv6), and Hierarchical Mobile IPv6 (HMIPv6), facilitate seamless mobility for devices. PMIPv6 and HMIPv6 provide localized mobility management, reducing signaling overhead and improving scalability in large-scale mobile deployments. Routing in IPv6 mobile networks must support these mobility protocols to efficiently route traffic to the current location of mobile devices, ensuring uninterrupted communication sessions during handovers, [2]. Routing solutions are to optimize routing table management and signaling overhead to accommodate the dynamic nature of mobile environments and facilitate efficient routing handovers.

E. Security Features

IPv6 incorporates IPsec (Internet Protocol Security) as an integral part of the protocol suite, providing integrity, authentication, and confidentiality services for IPv6 traffic [2].

Through its implementation of encrypting and authenticating its network communications IPv6 contains an additional layer of network security. Native security is a good example showing how IPv6 takes security preventative measures more seriously by making support for IPsec a requirement in its implementation. IPSec is also available for IPv4 implementations and is optional. In contrast, support for IPSec in IPv6 implementations is not an option, but a requirement The term IPsec refers to a suite of protocols from the IETF providing network layer encryption and authentication for IP-based networks. The objective of IPsec is to authenticate, and/or encrypt, all traffic at the IP level.

III. FUNCTIONING OF SEGMENT ROUTING FOR IPV6

SRv6 can be simply understood as a combination of SR and IPv6. SR appeared as a result of competition presssure SDN (Software-defined networking). Its core idea is to divide a packet forwarding path into different segments and insert segment information into a packet at the ingress of the path. A transit node only needs to forward the packet according to the segment information carried in the packet. Such a path segment is referred to as a segment, which is identified by a segment identifier (SID). Both IPv6 and MPLS can be used as the forwarding planes of SR [7]. IPv6-based SR is referred to as SRv6, and its SIDs are represented by IPv6 addresses. MPLS-based SR is referred to as Segment Routing MPLS (SR-MPLS), and its SIDs are represented by MPLS labels.

A. Segment Routing Header (SRH)

To implement SR based on the IPv6 forwarding plane, a Segment Routing header (SRH) is added as an IPv6 routing extension header (Fig. 4). The SRH specifies an IPv6 explicit path and stores the IPv6 segment list information. When a packet is forwarded, the Segments Left (SL) and Segment List fields are both used to determine the IPv6 destination address (IPv6 DA) and how the packet should be forwarded.

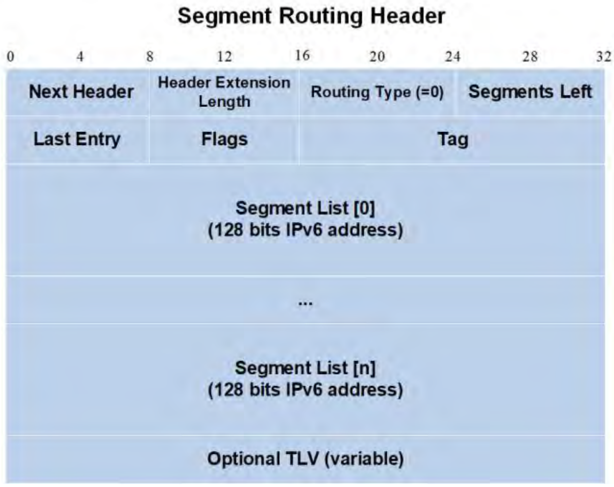

Fig. 4. Segment Routing Header format

A segment list is a forwarding path that is formed by arranging segments and network nodes in sequence.

Figure 5 shows the scenario of forwarding a packet from host 1 to host 2 through several nodes. The nodes in the path, namely A, B, D, and E, support SRv6, while node C only supports IPv6. Network programming is required on source node A, so that the packet is sent to host 2 through node E after passing through links B-C and C-D.

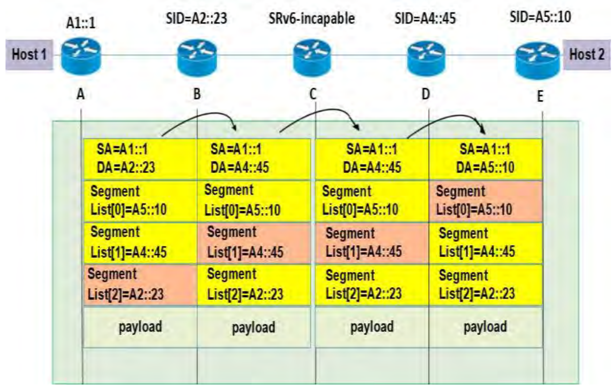

Fig. 5. SRv6 packet forwarding process

The packet forwarding process goes as follows:

- To forward the packet from node A to host 2 through nodes B, C, D, and E using SRv6, node A needs to encapsulate the SRv6 path information into an SRH. This information includes the SIDs of the B-C and C-D links, as well as SID A5::100 advertised by node E, and is encapsulated in reverse order. The packet's encapsulated header also includes an SL value of 2, indicating that there are three SIDs in total, and the segment list to be processed is "Segment List". Consequently, node A copies the value of Segment List [2] to the DA field in the outer IPv6 header, searches the corresponding IPv6 routing table according to the longest match rule, and then forwards the packet to node B.

- After receiving the packet, node B searches its local SID table (which stores the SRv6 SID information it generates) based on the destination address in the outer IPv6 header and finds a matching End.X SID. According to the instructions defined by the End.X SID, node B decrements the SL value by 1, updates the DA field in the outer IPv6 header with the Segment List [1] value, and then sends the packet over the link (B-C) bound to the SID.
- When the packet arrives at node C, it cannot recognize the SRH because it lacks any SRv6 capabilities. As such, it treats the packet as a common IPv6 packet. Specifically, it searches the corresponding IPv6 routing table according to the longest match rule and then forwards the packet to node D, which is represented by the current destination address.
- Upon receiving the packet forwarded by node C, node D searches its local SID table using the destination address A4::45 and finds a matching End.X SID. Similar to node B, node D decrements the SL value by 1, updates the DA field in the outer IPv6 header with A5::100, and then sends the packet over the link bound to the End.X SID.
- When the packet arrives at node E, it searches its local SID table based on A5::100 and finds a matching End.DT4 SID. According to the instructions defined by the SID, node E decapsulates the packet by removing the IPv6 header, searches the IPv4 routing table of the VPN instance bound to the End.DT4 SID, and ends the process by sending the inner IPv4 packet to host 2.

B. SRv6 Working Mode

SRv6 can work in either SRv6 Traffic Engineering (TE) Policy or SRv6 Best Effort (BE) mode. Both modes can be used to carry traditional services, such as L3VPN, EVPN L3VPN, EVPN VPLS, EVPN VPWS, and public IP services.

Figure 6 shows SRv6 TE Policy that leverages SR's source routing mechanism to instruct packet forwarding across a network based on an ordered list of segments (path information) encapsulated by the source node. As a result, SRv6 TE Policy can be used to implement traffic engineering, which improves network quality and meets E2E service requirements, [8]. When combined with SDN, SRv6 TE Policy is ideal for service-driven networks and is the recommended SRv6 working mode.

1. The forwarder (PE3) reports network topology information to the controller through BGP-LS. The topology information includes node and link information and TE attributes, such as the link cost, bandwidth, and delay.
2. After gathering the topology information, the controller examines it and calculates routes that meet the service level agreement (SLA) requirements based on the service's specifications.
3. The controller delivers path information to the ingress (PE1) of the network. The ingress then generates SRv6 TE Policies, which include the headend addresses, destination addresses, and colors (extended community attribute).
4. The ingress node (PE1) chooses a suitable SRv6 TE Policy to direct service forwarding. As the service is forwarded, each forwarder in the network performs the instructions contained within their advertised Segment IDs (SIDs) based on the data carried by the SRv6 packets [9].

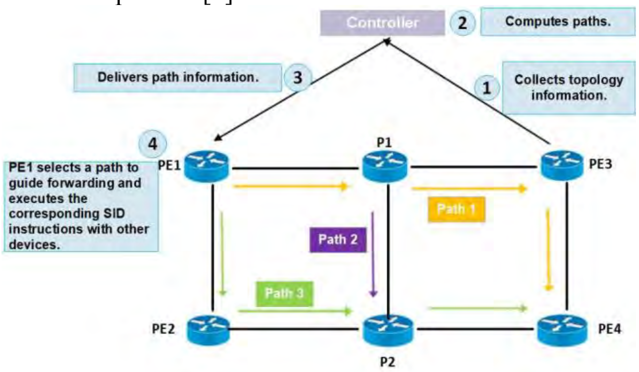

Fig. 6. SRv6 packet forwarding process

SRv6 BE functions similarly to LDP in an MPLS network, whereby it utilizes the IGP's SPF algorithm to calculate the most efficient SRv6 path, employing only one Service SID for directing packet forwarding over links. As a best-effort working mode, SRv6 BE does not have TE capabilities and is generally used to carry common VPN services for quick service provisioning [10].

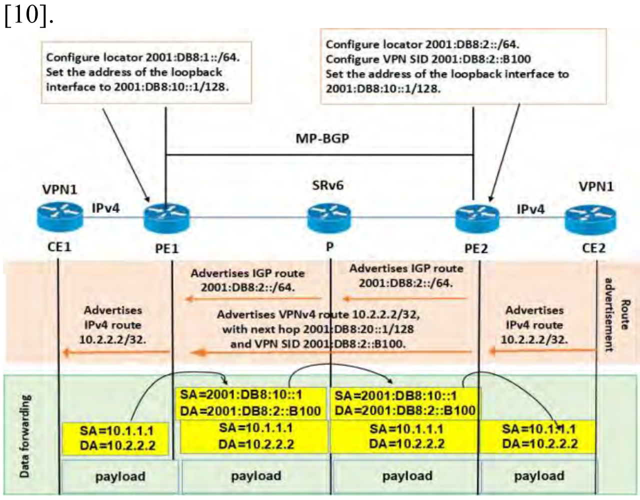

Fig. 7. SRv6 BE working process

To illustrate how SRv6 BE services are implemented, let's take the example of L3VPNv4 over SRv6 BE show in Figure 7. In this network setup, VPN instances are distributed across the network, with SRv6 deployed on both PE1 and PE2, while IPv6 is implemented on the P node. Route advertisement phase:

1. A locator is configured on PE2.
2. To inform PE1 about the SRv6 SID, PE2 employs an IGP to advertise the locator route 2001:DB8:2::/64.

This route is then added to the IPv6 routing table of PE1.

3. After a VPN SID (2001:DB8:2::B100) within the locator range is configured on PE2, PE2 generates a local SID entry.
4. Once CE2 advertises an IPv4 route, PE2 transforms the route into a BGP VPNv4 route and propagates it to its MP-BGP peer, PE1. This route includes the SRv6 VPN SID, specifically the SID 2001:DB8:2::B100 assigned to the VPN instance.
5. After receiving the VPNv4 route, PE1 leaks the route to the routing table of the corresponding VPN instance, converts it into a common IPv4 route, and advertises it to CE1, [11].

IV. COMPARISON OF SR-MPLS AND SRV6

Segment Routing (SR) can be implemented using two main approaches: Segment Routing for IPv6 (SRv6) and Segment Routing with MPLS (SR-MPLS). Their comparison is given in Table 1 and also discussed here below. Both approaches aim to simplify and enhance network routing by encoding paths directly within packet headers, but they differ in their underlying technologies and specific implementations.

A. Header Encoding

SR-MPLS uses a stack of MPLS labels to encode the path. Each label represents a segment, and the stack order defines the sequence of segments.

Each MPLS label is 20 bits long and includes fields for the label value, Traffic Class (TC), Bottom of Stack (BoS) flag, and Time-to-Live (TTL).

Regarding the SRH (Segment Routing Header) structure the SRH includes fields for the Next Header, Hdr Ext Len, Routing Type, Segments Left, Last Entry, Flags, and a list of SIDs [12], [13].

SRv6 uses the IPv6 SRH to encode the path. The SRH contains a list of Segment Identifiers (SIDs), each represented as a 128-bit IPv6 address.

B. Network Compatibility

SR-MPLS is Compatible with existing MPLS networks, making it easier to integrate into environments that already use MPLS for traffic engineering and VPNs.

-MPLS Tools and Practices: Benefits from mature MPLS operational practices and tools.

Regarding the IPv6 requirement SRv6 requires IPv6 support throughout the network. It aligns with the industry shift towards IPv6, offering a future-proof solution for new deployments [14].

C. Flexibility and Scalability

SR-MPLS (Segment Representation MPLS) labels are less flexible and typically represent basic forwarding actions or adjacencies. Label Stack Depth: Limited by the practical depth of the MPLS label stack. Deep label stacks can become cumbersome and may impact performance due to hardware limitations.

SRv6 leverages the vast IPv6 address space, allowing for more complex and scalable segment definitions.Function Encoding: SIDs in SRv6 can represent a wide range of functions and actions beyond simple forwarding, such as service chaining and advanced network programming [15].

Table 1. Comparison between SR-MPLS and SRv6

FEATURE	SR-MPLS	SRv6
Header Encoding	MPLS label stack: 20-bit labels	IPv6 Segment Routing Header (SRH): 128-bit SIDs
Label/Segment Structure	20-bit labels including label value, Traffic Class, BoS flag, TTL	128-bit IPv6 addresses encoded in the SRH
Scalability	Limited by the depth of the MPLS label stack	Utilizes vast IPv6 address space for high scalability
Flexibility	Limited flexibility, especially for complex paths	High flexibility with programmable SIDs
Network Compatibility	Compatible with existing MPLS infrastructure	Requires IPv6 support throughout the network
Path Encoding Complexity	Efficient for simple paths, complex for deep stacks	Handles complex paths within SRH, larger headers
Traffic Engineering	Optimizes path selection, traffic engineering	Similar capabilities with added flexibility
Network Slicing	Implemented using MPLS L3VPN and L2VPN technologies	Virtual network slices with distinct policies
Fast Reroute	Provides quick rerouting around network failures	Precomputed backup paths encoded in SIDs for instant failover
Use Cases	Existing MPLS networks, traffic engineering, VPNs	Modern data centers, cloud, IPv6 networks
Monitoring and OAM	Relies on MPLS OAM tools	Enhanced OAM with information embedded in SRH

V. SRV6 DEPLOYMENT FOR FUTURE 6G MOBILE NETWORKS

Deploying SRv6 for future 6G mobile networks involves leveraging its capabilities to support the advanced requirements and use cases anticipated for 6G. SRv6, with its flexible and scalable nature, is well-suited to meet the demands of 6G, including enhanced mobile broadband, ultra-reliable low-latency communications, and massive machine-type communications [16]. Here's a detailed look at how SRv6 can be deployed in 6G mobile networks and the benefits it offers:

Key Benefits of SRv6 for 6G networks are given below.

A. Flexibility and Scalability

SRv6 enables the encoding of complex paths and service chains directly within the packet header using the Segment Routing Header (SRH). This flexibility supports dynamic and programmable network behaviors, essential for the diverse and dynamic nature of 6G use cases [17].

This scalability is crucial for 6G networks, which will need to handle a massive increase in connected devices and data traffic.

B. Service Function Chaining

SRv6 allows for efficient service function chaining, where packets can be directed through a sequence of network services (e.g., firewalls, load balancers) as specified by the SIDs. This is vital for 6G networks, which will require sophisticated network services and security measures to handle advanced applications.

C. Network Slicing and Operational Efficiency

SRv6 supports the creation of virtual network slices, each with its own set of routing and service policies. Network slicing is a key feature of 6G, enabling the allocation of dedicated resources for different types of services and applications, such as IoT, critical communications, and high-speed mobile broadband.

The use of a single protocol for both routing and service chaining improves overall network efficiency.

D. Core, Edge and Access Networks

SRv6 Nodes: Deploy SRv6-capable routers and switches in the core network to handle high-speed, long-distance traffic. Segment Routing Header (SRH): Use SRH to encode paths and service chains, allowing for efficient routing and traffic engineering.Edge Nodes: Deploy SRv6 at the edge of the network, closer to the users and devices, to provide low-latency and localized services[18]. Base Stations and Access Points: Integrate SRv6 capabilities into 6G base stations and access points to support end-to-end SRv6 paths from the device to the core network.

VI. Conclusion

Segment Routing over IPv6 (SRv6) represents a transformative advancement in networking technology, uniquely positioned to meet the sophisticated demands of future 6G mobile networks. By leveraging the vast IPv6 address space, SRv6 offers unparalleled scalability, crucial for managing the exponential growth in connected devices and data traffic. The adoption of 128-bit Segment Identifiers (SIDs) enables SRv6 to encode complex network paths and functions directly into packet headers, providing exceptional flexibility and programmability. This allows for dynamic network behaviors and advanced service chaining, essential for the diverse 6G use cases such as enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC).

One of the key advantages of SRv6 is its support for efficient network slicing. By creating virtual network slices with distinct routing and service policies, SRv6 ensures isolated and optimized performance for different applications. This enhances resource utilization and enables tailored network services, essential for meeting the diverse requirements of 6G applications.

The future of Segment Routing over IPv6 (SRv6) in advanced networks, including 6G, is set to revolutionize network design and operation. SRv6 enhances network efficiency by embedding routing information directly into IPv6 addresses, streamlining path management and simplifying network operations. This streamlined approach is crucial for the high-performance demands of 6G, which requires ultra-low latency, exceptional reliability, and extensive device connectivity. In the context of 6G, SRv6 will facilitate dynamic network slicing, enabling the creation of virtual networks tailored to specific applications and services. This capability supports a wide range of use cases, from real-time data analytics and immersive experiences to autonomous systems and massive IoT deployments. SRv6's flexibility and programmability will allow for precise traffic management and optimized resource allocation, ensuring that the network can adapt efficiently to varying demands and conditions.

Furthermore, SRv6"s integration with 6G will enhance the network's ability to support advanced technologies, such as AI-driven applications and smart cities, by providing a robust and adaptable infrastructure. As future networks evolve, SRv6 will be instrumental in delivering the scalability, performance, and intelligence needed to meet the growing complexities of next-generation connectivity.

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Technical Aspects of using SRv6 compared to MPLS for a Telecom Operator

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***Abstract*— MPLS as a networking technology is present on the market for more than 25 years. It is still widely used in the telecom operators' networks, mostly due to the popular MPLS layer 2 and layer 3 VPN applications. Seamless MPLS comes as an extension to the MPLS, providing a greater degree of network scalability and flexibility, thereby providing better support for mobile 4G technology at the time. In this era of new services and emerging technologies, there are new demands for the transport networks infrastructures in terms of simplicity, scalability, flexibility, and network programmability. The IETF SPRING working group defined the "Problem Statement and Requirements", and has identified a source-based routing mechanism as a "Problem Solution". Segment Routing is promoted as MPLS successor in IP/MPLS and IPv6 networks. This paper analyzes the crucial technical aspects of Segment Routing over IPv6 (SRv6) for its future use by telecom operators in their transport networks.**

Keywords— BGP; IGP; IPv6 Segment Routing Header (SRH); Multiprotocol Label Switching (MPLS); Network Programmability; Seamless MPLS; Segment Routing; SPRING; SR-MPLS; SRv6; WAN technologies.

I. INTRODUCTION

WAN technologies may be classified as a pre-MPLS: Frame Relay and Asynchronous Transfer Mode (ATM), followed by MPLS and Seamless MPLS, and then Segment Routing envisioned as MPLS successor by technical community and network equipment vendors, with the accent to Segment Routing for IPv6 (SRv6).

MPLS technology and widely adopted MPLS applications, were a revolutionary concept at a time of appearing on the market. MPLS is about one unified and convergent network infrastructure for all kinds of services, including transport of the legacy layer 2 technologies.

Modern trends in this new technological era are continuing to reshape our world in many ways. In a separate section in this paper are outlined the IETF SPRING Working Group "Problem Statement and Requirements" for the transport network domain, in which source packet routing is promoted as a protocol of choice for a set of predefined use cases. Source packet routing is not something new and unknown in the networking, but reengineering this concept into Segment Routing (SR) brings serious advantages. An example of packet steering in SR-enabled network is given for better understanding of how Segment Routing operates and contributes in supporting new requirements for transport networks. Segment Routing for IPv6 (SRv6) is highlighted due to the great potential in network programmability, and other specific uses cases like 5G, stateless service chaining, etc. The "Principle of Simplicity" is elaborated in terms of architectural and philosophical guidelines, which correlates with significant contribution of the Segment Routing in simplifying transport networks.

II. MPLS TECHNOLOGY

A. MPLS overview

Multiprotocol Label Switching (MPLS) networking technology and its applications are present on the market for more than 25 years. MPLS is still very popular WAN technology among telecom operators.

Earliest WAN networks were circuit switched networks, owned and operated by telephone operators as a part of their own infrastructure for providing telephone services, as well as for providing WAN connectivity services for customers' remote sites. Among popular WAN services from that time were dedicated circuit switched leased lines, and later, with the invention of packet switched networks emerged Frame Relay and ATM. Wide adoption of the Internet Protocol (IP), popularization of the Internet services, and mass deployment of the Ethernet standard in the Local Area Networks (LANs), brings on the market Metro Ethernet (ME) and MPLS as a dominant WAN technologies.

One of the greatest benefits of MPLS today is the use of unified network infrastructure to carry all traffic types. MPLS-enabled layer 3 IP backbone can transport IPv4 and IPv6 layer 3 protocols, and different layer 2 protocols as well: Ethernet, Frame Relay, ATM, High-Level Data Link Control (HDLC), Point-to-Point Protocol (PPP), etc. Transporting IPv4 and IPv6 protocols over MPLS is known as layer 3 MPLS VPN application. Transporting any layer 2 protocol over MPLS is known as Any Transport over MPLS (AToM) application. Virtual Private LAN Service (VPLS) is another popular layer 2 MPLS VPN application that emulates a LAN across MPLS-enabled network, by forwarding the Ethernet frames in a point-to-multipoint and multipoint-to-multipoint fashion. Ethernet

VPN (EVPN) is another implementation of the layer 2 MPLS VPN application, which differs from VPLS in transferring control plane functionalities to Multi-Protocol Border Gateway Protocol (MP-BGP). Routers that are forwarding MPLS layer 2 or layer 3 VPN traffic, are not aware of the MPLS payload; they are just switching labeled traffic by looking at the top label.

B. *MPLS Label Stack*

MPLS is a networking technology for moving data packets over IP networks by using labels instead of destination IP addresses. Traffic is switched across the MPLS over Label Switched Path (LSP) by label push, swap, or pop operations. Set of labeled packets with identical characteristics which may be forwarded the same way is known as Forwarding Equivalence Class (FEC).

MPLS technology represents a set of procedures for enriching packets at the network layer with the so-called "label stack", thus transforming them into "labeled packets". LSRs (Label Switching Routers) are routers that support MPLS. LSRs must support appropriate encoding techniques to transmit a labeled packet at the corresponding data link, i.e. to create a labeled packet for a given label stack and network layer packet. The most commonly used LSRs' encoding techniques are for the transmission of labeled packets on a PPP data link, on a LAN data link, and other types of data links. Other switching devices, like ATM switches with MPLS support, are using different encoding techniques for generating the top entries of the label stack. MPLS Label Stack Encoding is described in RFC3032 “MPLS Label Stack Encoding” [1].

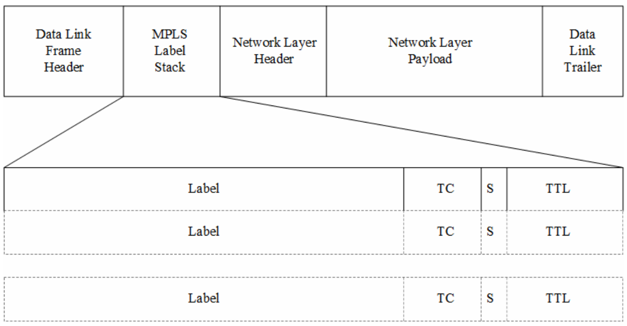

Fig. 1 MPLS Label Stack

On the Fig.1 is depicted MPLS header format, i.e. a label stack entry, and the position of the label stack in the layer 2 frame. The label stack entries appears after the data link layer headers, but before any network layer headers, and therefore MPLS is known as a layer 2.5 protocol in the TCP/IP protocol stack. The top of the label stack appears first, and the bottom of the label stack appears last. The network layer packet follows the label stack entry with the “S” bit set [1].

Following is a list of field names in the MPLS header: *Label*: Label Value, 20 bits; *TC*: Traffic Class field, 3 bits, EXP field prior 2008; *S*: Bottom of Stack, 1 bit; *TTL*: Time to Live, 8 bits

C. *MPLS fast convergence techniques*

As telecom providers move more applications to their IP/MPLS backbone networks, rapid network recovery after network failure becomes increasingly critical. Real-time applications like Voice over IP (VoIP), then different signalization and control protocols sensitive to networks’ disturbance, emerge developing mechanisms for fast convergence upon network failure in the IP/MPLS networks.

Loop-Free Alternate (LFA) Fast Reroute (FRR), and Remote LFA FRR (RLFA FRR), are two fast convergence mechanisms and they are closely tied to Topology Independent LFA (TI-LFA) used in Segment Routing (SR). In case of network failure, LFA preserves connectivity by installing a backup route to a pre-computed Repair Node (RN), which is directly connected to a Point of Local Repair (PLR) node. RLFA addresses LFA limitations in allowing other nodes that are not directly connected to PLR, to be elected as a Repair Node. In RLFA operation, repair tunnel is established between PLR and Repair Node, and in practice this is an MPLS tunnel. LFA and Remote LFA are protecting from node and link failure in the network. Both techniques are not providing 100% coverage in case of failure. TI-LFA is addressing limitations of the LFA and RLFA, and is characterized by the least restrictions on repair node selection, the best 100% coverage, and SR is mandatory as alternate routes are provided by deploying SR tunnels.

D. *Seamless MPLS Architecture*

Traditional MPLS has many challenges in the network management, operation and maintenance, in terms of very complex configuration for end-to-end network convergence and resilience mechanisms, then large network divided into multiple domains while services have to be delivered end-to-end, etc.

Seamless MPLS design is about a single IP/MPLS domain in the segmented telecom operators’ network infrastructures, using existing, well-known and standardized IP/MPLS protocols. Seamless MPLS scales over the core, aggregation and access network segments and thus provides scalability, flexibility, and simple and rapid service provisioning. Seamless MPLS network is characterized by: end-to-end MPLS transport and end-to-end service provisioning, better resiliency due to the separated IGP/LDP areas, better convergence, seamless integration with any access technology, IPv6 readiness.

One of the popular definitions about Seamless MPLS by Cisco is that Seamless or Unified MPLS is a traditional MPLS with the following additional features: IGP/LDP isolation; RFC3107 for labeled BGP; BGP filtering; flexibility in connecting access technologies; LFA, RLFA and BGP PIC for fast convergence; and end-to-end operations and maintenance [2].

Seamless MPLS separates transport plane and services. In the transport plane there is label distribution among different network segments: intra-area label distribution via LDP/RSVP; then inter-area label distribution via labeled BGP as specified in the RFC3107 “Carrying Label Information in BGP-4”, and via LDP Downstream-on-Demand (DoD) label advertisement, RFC7032. Seamless MPLS is not limited and may span over multiple Autonomous System (AS) domains as well, as described in RFC4364 “BGP/MPLS IP Virtual Private Networks (VPNs)” (RFC4364’s sections: “Carriers' Carriers” and “Multi-AS Backbones”). Seamless MPLS service plane is about end-to-end service’s label distribution for MPLS applications via LDP and MP-BGP.

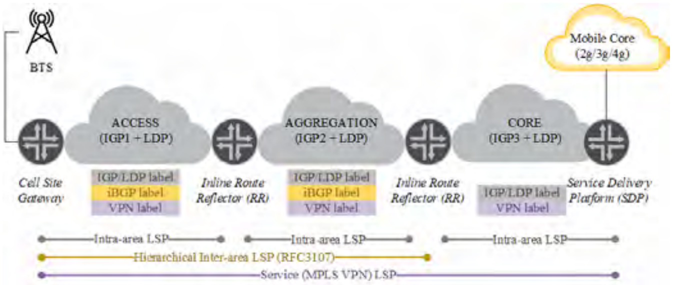

Fig. 2 Seamless MPLS

On Fig.2 is depicted Seamless IP/MPLS network design, consisted of access, aggregation and core network segments; every segment in different IGP and LDP domain; whole network under one AS domain. MPLS enabled Area Border Routers (ABRs) are positioned on the segments’ boundaries, and are representing inline MP-iBGP Route Reflectors (RR). In the access domain are Cell Site Gateways (CSGs), and in the core domain are Service Delivery Platforms (SDPs). On the left side of the picture is mobile Base Station (BTS) connected to a small MPLS CSG; on the right side is Mobile Voice and Packet Core for 2G/3G/4G, connected to MPLS SDP for mobile services. MPLS layer 3 VPN service configuration should be applied on the edge nodes only: CSG and SDP. Traffic between BTS and Mobile Core Platform is forwarded over multiple segments as presented on the picture. Inside the network segment traffic is forwarded by intra-area Label Switched Paths (LSPs) (formed by label exchange via LDP). Then traffic between network segments is forwarded by inter-area hierarchical LSP (formed by labeled iBGP described in RFC3107). End-to-end traffic forwarding is supported by the service MPLS VPN LSPs formed by bottom of the stack MPLS service labels exchanged via MP-iBGP.

MPLS is still dominant networking technology in telecom operators’ networks, but Segment Routing is something what is actually happening in the networks of the biggest telecom operators, and which are further expanding their transport networks capabilities.

III. Segment Routing Motivations and General Overview

A. *Era of emerging new services and new technologies*

Top emerging technical use cases listed in the CompTIA infographic [3] are: Artificial Intelligence (AI), Internet of Things (IoT), Machine Learning, 5G Networks, Edge Computing, Blockchain, Spatial Computing, Smart Spaces, Smart Cities and Homes, Homomorphic Encryption, Metaverses, 3D printing, and Robotics and Automation.

In the CompTIA blog “Top 10 Challenges Facing Technology in 2024” [4], are noted many new challenges that technology is facing and will face in the years to come: Generative AI trust, risk and security; Sustainable green technology as a must; Platform engineering as an emerging discipline for reducing the complexity of software development while raising code quality by providing reusable functionalities; Quantum Computing, Quantum Internet use cases described in the IETF Internet-Draft “Application Scenarios for the Quantum Internet”; Spatial Computing for enabling a new users’ experiences in the Metaverse; Multi-cloud and hybrid network environments; Cyber resilience instead of cyber avoidance, and building a security-first culture as cyber incidents are becoming inevitable.

In this era of new technologies and new services, the infrastructure of the transport networks does not follow the pace of new trends. IP/MPLS networks become operation intensive because of their complex implementations. There are no widely available tools for planning, provisioning and management of the IP/MPLS networks, due to the complexity of correlation with the distributed nature of the control plane, and collecting and analyzing high volume data in the forwarding plane. Most of the tools on the market are not easy to integrate and operate in a cost effective manner, and require high skilled network engineers with additional qualifications in software programming and scripting.

According to the “SEGMENT ROUTING, ACG Research Paper” [5], telecom operators are facing revenues falling and competition by the over-the-top providers. Conventional television service and many other cloud and streaming services are moving towards over-the-top (OTT), thus posing high internet capacity demands for telecom operators, potentially turning them into a dumb Internet pipes. These drivers are forcing network owners to consider transport technology that can provide a reduction in the complexity of today's networks through convergence across layers. Network owners are thinking about moving to Software Defined Networks (SDNs) in all networking segments: data centers and virtual cloud environments, but also in transport access, aggregation and core segments. SDN technology, coupled with Network Functions Virtualization (NFV), containers and other cloud technologies, will bring better utilization of the network resources by providing on demand services with required network capacities upon request and in real time.

B. *The Simplicity Principle*

New demands for transport network infrastructures are: simple design, sustainable green networks, uniform hardware, high traffic throughput, automatic and on-demand real-time network and services provisioning, smaller operational costs.

In the RFC3439 “Some Internet Architectural Guidelines and Philosophy” [6] are listed recommendations in the form of philosophical aspects, for network architects and designers of the Internet backbone networks. Those architectural guidelines are applicable not only to the Internet backbone networks, but to all networks and network services in general, because most of the services are moving to the over-the-internet. One of the fundamental concept identified and described in RFC3439 is the "Simplicity Principles", which state that complexity can greatly hinder efficient scaling, and controlling complexity is a mechanism to control network reliability and costs (capital expenditures (CAPEX) and operational expenditures (OPEX)). On the other side adding complexity to the system is somehow connected to the increasing the systems' robustness.

In the RFC3439 [6] are elaborated other principles as well, that can be easily identified as main principles applied to the Segment Routing protocol. In companion with "Simplicity Principles" is so called "end-to-end Argument", which promotes that end-to-end protocol design should not rely on maintaining path states on all nodes in the network, such states should be maintained in the edge points only. Next, the "Coupling Principle" is about increasing the interdependence between modules as things get larger, which in the same time increase complexity. Then, the industry experience proves the "Convergence Layering" principle, which states that 'Everything over Some Layer' (EoSL) concept may induce complexity and increase OPEX. "Avoid the Universal Interworking Function" and particularly "Avoid Control Plane Interworking" are principles which are declaring that interworking solutions have low performances, and bad impact on CAPEX and OPEX; there are various control plane protocols' interworking issues that are increasing probability for failures.

IP/MPLS networks fulfill their mission of providing a unified network infrastructure, and now are reaching a point where due to the degree of complexity cannot support future trends that require dynamic and real-time changes in the network infrastructure. This is where Segment Routing for IPv6 (SRv6) with programmability features comes into play.

C. Source Packet Routing in Networking (SPRING) initiative

Segment Routing is being standardized by IETF; the architecture and use-cases are handled in the Source Packet Routing in Networking (SPRING) working group. All statements in this subsection are taken over from RFC7855 "Source Packet Routing in Networking (SPRING) Problem Statement and Requirements" [7]. In the RFC7855 are outlined various use cases, with their requirements, that need to be taken into account by the Source Packet Routing in SPRING architecture for unicast traffic. Source Packet routing mechanism is in use in MPLS Traffic Engineering, there are also other network protocols with Source Packet routing in their implementations, but are not widely deployed.

Source Routing mechanism in Segment Routing is about the ability for a node to define a forwarding path through a network, which is not necessarily the best path that a particular packet will follow. The node at which explicit route is imposed is known as a source node, this may be any ingress node of an operator's network, and therefore is not limited to the originator of the packet. A number of network functions take advantage of the use of Segment Routing as described in RFC7855 [7]: network virtualization; network isolation and partitioning; network protection mechanisms on a link, node and path levels; network programmability; OAM mechanisms; simplification and reduction of network signalization and control protocols; load balancing; traffic engineering.

In the SPRING architecture are defined a set of requirements that must be met by Source Packet Routing implementations, all of them listed in the RFC7855 [7] and presented in the next few sentences. The SPRING architecture must be deployable partially on selected nodes, and incrementally - there shall be no requirement to mass deploy all nodes at once. The SPRING architecture must offload intermediate and end nodes in the network, from keeping policy states for traffic forwarding - policy states must be putted and instantiated in the packet header by the source node. The purpose of the SPRING architecture is to address use cases requiring removal of path state control and signaling in core network segments, not to replace existing source routing and traffic engineering mechanisms. The SPRING architecture should be universal, and its applicability should not depend on the types of data planes. The SPRING architecture should be applicable to MPLS data plane without any additional requirements, and to IPv6 data plane with the introduction of a new IPv6 Routing Header Type. The SPRING architecture must provide interoperability between network nodes with and without SPRING capability, for both the MPLS and IPv6 data planes.

All those requirements described above for the SPRING architecture, and implemented in the Segment Routing, characterized Segment Routing as a simple and scalable protocol, which enables seamless deployment. Those characteristics are defined on the website segment-routing.net [8] in terms of Simplicity, Scalability and Seamless deployment. *Simplicity* is in providing full control over the forwarding paths by following instructions encoded in packet headers, without requiring any additional control or signaling protocol, and even removing unnecessary protocols. *Scalability* in terms that Segment Routing does not require any additional path signaling control protocol; path state is keeping at the source node of the SR domain. *Seamless* deployment in terms that Segment Routing may be enabled on an MPLS or IPv6 data plane with a simple software upgrade of the network elements. SR can coexist with LDP network. There is no strict requirement for all nodes in the network to be SR-enabled.

Segment Routing technical characteristics when translated to describe business benefits are following: simplified network make network operations easier, resilient network provide fast recovery after node or link failure under 50ms, better capacity utilization over 80% by dynamically rerouting traffic, releasing innovations by powering two vital network services: low-latency and segmentation, and providing better customer experience [8].

D. Segment Routing

Segment Routing (SR) is a source routing mechanism developed according to SPRING architecture. In the SR-enabled network, a packet is steered across the network by following an ordered list of instructions, either topological or service-based, called "segments". A segment can be local to an SR node, or it can be global and unique within an SR domain. Segment routing provides a mechanism to forward a packet in an SR-enabled network in a controlled manner by following the instructions imposed on the source SR node, while offloading path state from all intermediate and end nodes in the SR domain. Segment Routing is described in RFC8402 "Segment Routing Architecture" [9].

Segment in Segment Routing represents instruction. Segment is encoded as an MPLS label when applied to MPLS data plane; in IPv6 architecture segment is encoded as an IPv6 address within a new IPv6 Routing Header Type. There are different types of Segments: IGP-Prefix Segment represents IGP prefix and has Prefix-SID value which is the Segment Identifier (SID) of the IGP prefix segment; IGP-Adjacency Segment is IGP segment attached to a unidirectional adjacency or a set of unidirectional adjacencies, and has Adj-SID; and there are other types of segments as well. Segment Identifier (SID) is commonly used to refer to a Segment, although they have different meanings.

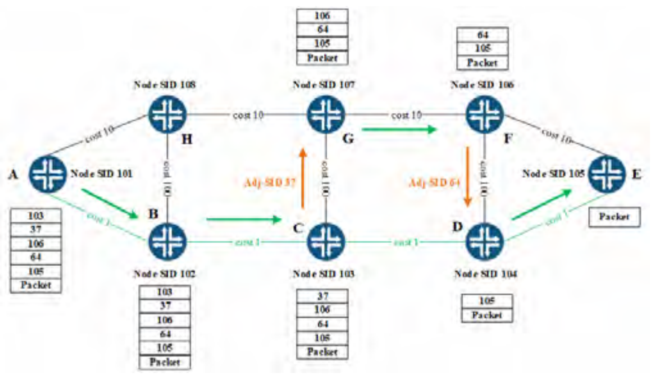

Fig. 3 Packet steering in SR-enabled network

The Fig.3 shows example of packet steering in a SR enabled network. On the picture is presented simple network design, eight routers connected in a partial mesh topology. Each link is marked with a link cost of 1/10/100; preferred link is lower cost link. Green colored links represent least cost best path calculated by IGP from node A to E, that packet will take by default. With SR enabled in the network, packet is forwarded through an ordered list of instructions from node A to E through a predefined path which may not be least cost best path. Each node has a manually configured Node SID with unique value in the SR domain. Each link has Adjacency SID with local scope to the node. Numeric values chosen for Node SIDs and Adjacency SIDs are arbitrary values in this example. Segments' imposition is done at node A, with top segment instructing packet forwarding to C via B which is best IGP route. At node C packet is instructed to take a route over link with Adjacency SID=37; then at node G packet is forwarded over best IGP route to node F; from there over link with Adjacency SID=64 to node D, and then take a best IGP route to the destination node E.

IV. SRV6 AS A FUTURE CHOICE

A. *SRv6 features*

Segment Routing for IPv6 (SRv6) as a new protocol which combines Segment Routing (SR) and IPv6, keeps IPv6 protocol on track for the future by the technical community and networking equipment vendors. Most of the vendors, like Cisco, Ericsson, Huawei, Juniper, Nokia, ZTE, etc. have a strong commitment in supporting SRv6 implementation in their product portfolio.

One of the biggest advantages of the SRv6 is network programmability. Network programmability is not a new and unknown capability, Simple Network Management Protocol (SNMP) is one of the earliest and not very successful attempts to provide network programmability. Then rise of SDN in the early 2010, introduces more serious implementations of the network programmability. SDN and network programmability concepts from the SRv6 perspective shall be anticipated as a complementary, while SDN is about controlling and managing networks through a set of Application Programming Interfaces (APIs), network programmability is the ability to understand and implement requests passed through these APIs [10].

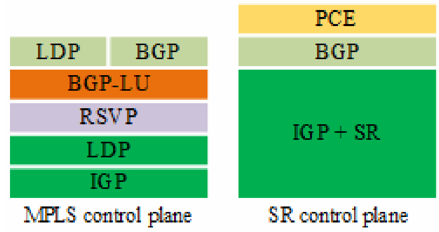

Fig. 3 MPLS control plane versus SR control plane

With SR and IPv6 there is also simplification in the control plane in comparison to MPLS control plane as depicted on the Fig.4. MPLS control plane consists of protocols like IGP for route redistribution, then LDP for label redistribution, RSVP for label distribution and MPLS Traffic Engineering, then BGP-LU for Seamless MPLS, and on top LDP and BGP for overlay MPLS VPN applications. In the SRv6 control plane there are only two protocols in the underlay, IGP and Segment Routing, and BGP in the overlay. Path Computation Element (PCE) on top is a network programmability enabler.

SRv6 unique features brings support for the following use cases: Service Function Chaining (SFC), Multicast (SPRAY) and 5G, as described in the "SEGMENT ROUTING ACG Research Paper" [5].

B. *SRv6 Segments*

SRv6 network programmability is enabled by encoding functions into IPv6 Segment Routing Header (SRH). SRH architecture is outlined in this section.

SRH is presented on the Fig.5 and described in RFC8754 "IPv6 Segment Routing Header (SRH)". SRH is IPv6 Routing Extension Header with Routing Type=4. It consists of fields common for Routing Header type and described in RFC8200 "Internet Protocol, Version 6 (IPv6) Specification", like: Next Header, Header Extension Length, Routing Type and Segments Left. Other fields are described in RFC8754 "IPv6 Segment Routing Header (SRH)".

As depicted on the Fig.5, "Segment List []" field is 128 bit IPv6 address. Segment List [0] indicates the last segment in the path, while Segment List [n] indicates the first segment of a path that has to be processed. In SRv6 enabled network, for every packet passing SRv6 node, the Segments Left field is decremented by 1, and the IPv6 Destination Address (DA) field positioned in the IPv6 header is updated by the value of the active segment "x" (Segment List[x]) [11].

SRv6 segments are identified using Segment Identifiers (SIDs) encoded as an IPv6 address. SRv6 SID is consisting of Location, Function and Arguments parts as presented on Fig.5, [11].

Segment Routing over IPv6 (SRv6) and Multiprotocol Label Switching (MPLS) are key technologies for telecom operators. SRv6 offers flexibility and programmability by embedding routing instructions in the IPv6 header, simplifying network operations and enabling seamless integration with IPv6 infrastructure. MPLS, [12], a well-established technology, efficiently directs data flows using short path labels rather than IP addresses, [13], ensuring high-speed and scalable transport. While MPLS is renowned for its maturity and stability, SRv6 provides a modern approach with enhanced capabilities for network automation and service deployment, making it a strategic choice for operators looking to innovate and future-proof their networks.

SRv6 (Segment Routing over IPv6) can be leveraged for various future services, offering enhanced flexibility and programmability in network operations. Here are some potential applications, [14]:

- Network Slicing: SRv6 enables the creation of multiple virtual networks on a shared physical infrastructure, tailored to specific service requirements, crucial for 5G and beyond.
- Traffic Engineering: SRv6 allows precise control over packet paths, optimizing network resources and improving service quality.
- Service Function Chaining: SRv6 can steer traffic through a sequence of network functions (e.g., firewalls, load balancers), facilitating complex service deployments.
- Enhanced VPN Services: SRv6 simplifies the deployment and management of VPNs, providing improved scalability and security.
- Edge Computing: By leveraging SRv6, operators can efficiently route data to edge computing nodes, reducing latency and enhancing performance for applications like IoT and real-time analytics.
- Automation and Orchestration: SRv6's programmability supports advanced automation and orchestration, streamlining network management and reducing operational costs.

Overall, SRv6 offers future-proof solution for emerging telecom services, enabling operators to innovate and meet evolving customer demands.

V. CONCLUSION

Emerging new services and new technologies is an ongoing and unstoppable trend in the world today. Technology is ever-present in people’s everyday lives. Digital transformation of the businesses is an ongoing process. All-in-all technologies are continuing to reshape our world in many ways.

Widely adopted MPLS technology experience many challenges in coping with the new requirements posed by new services and technologies. One of the biggest challenges is supporting dynamic and real-time changes in the network infrastructure to support future trends.

Segment Routing is a promising technology that can be seamlessly deployed in MPLS and IPv6 networks and in every network segment with possibility for end-to-end implementation: WAN, metro, access, aggregation, core, data center, cloud and virtualized environments. Segment Routing is built around concretely defined use cases: Fast Re-Routing, Traffic Engineering, Software Defined Networks, Unified Fabric, Enhanced OAM Features. Segment Routing for IPv6 is specifically intended for Network Programmability, Stateless Service Chaining, Multicast, 5G, and many others. IETF SPRING working group developed standards for implementing all those use cases.

The future of SRv6 in telecom networks is promising due to its flexibility, programmability, and seamless IPv6 integration. It enables efficient network slicing, advanced traffic engineering, and streamlined service function chaining, crucial for 5G and beyond mobile networks as well as IoT services. The programmability of SRv6 enhances automation and reduces operational costs. As telecom operators aim to modernize and future-proof their network infrastructure to be flexible to introduction of new services with specific demands, SRv6 is seen as a critical enabler of next-generation services and operational efficiency.

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The impact of SD-WAN on the Quality of Services compared to Traditional WAN

Mitigation of packet loss, latency and jitter

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***Abstract*— In recent years, businesses have rapidly embraced digital transformation. This shift has led to a wide array of applications operating over networks, each with unique Quality of Service (QoS) requirements, including packet loss, latency, and jitter. Some of these new applications demand exceptionally high performance, making it challenging to accurately manage traffic and fulfill Service Level Agreements (SLAs). Traditional WANs are increasingly struggling to meet these evolving SLA requirements. In this context, SD-WAN offers a promising solution. As an extension of Software-Defined Networking (SDN) to wide area networks, SD-WAN simplifies the complexity of manual data routing by virtualizing the control plane, enabling efficient data traffic management. By decoupling the control plane from the data plane and utilizing SDN principles, SD-WAN optimizes the use of physical devices more effectively and efficiently. The experimental results presented in this paper, using the Packet Duplication feature in Cisco SD-WAN, demonstrate that Cisco SD-WAN significantly enhances overall network performance and QoS compared to traditional WAN systems. The network emulation software EVE-NG is used as a primary tool for this research experiment.**

Keywords*— *EVE-NG; Jitter, Latency; Packet duplication; Packet Loss; SD-WAN

I. Introduction

Recent years have witnessed a significant leap in network technology development. With the rapid expansion of networks and the emergence of increasingly sophisticated applications, enterprises and organizations require reliable and high-performing Wide Area Networks (WANs) to effectively transmit critical data between their branches, data centers, Software as a Service (SaaS), and other cloud-based applications.

Software Defined Wide Area Network (SD-WAN) has emerged as an attractive solution for enterprise networks due to its ability to accommodate these needs. SD-WAN is a promising technology that has recently garnered significant attention from both industry and academia [1]. The objective of this paper is to analyze the impact of SD-WAN compared to traditional WAN in terms of Quality of Service (QoS) and network performance, with a particular focus on packet loss as a key performance parameter.

This analysis is based on an experimental SD-WAN design using Cisco's implementation methods focusing on the Packet duplication feature. The experimental SD-WAN setup was implemented in a lab environment using the network emulation software EVE-NG. The research presented in this paper aims to analyze the performance of Cisco SD-WAN, demonstrating that Cisco SD-WAN concepts can positively impact performance parameters compared to traditional WAN.

The rest of the paper is organized in the following manner. Section 2 provides an overview of packet switching mechanisms in traditional WANs and introduces Cisco Express Forwarding as a new packet switching method. Section 3 covers Cisco SD-WAN technology, detailing the main components of each plane within this solution. Section 4 describes retransmission-based error recovery as the most used method for packet loss recovery in traditional WANs. It also examines the packet duplication feature in Cisco SD-WAN as a mechanism to prevent packet loss. Additionally, this section includes research methodology, a brief explanation of the tools, and the experimental SD-WAN design. Lastly, the interpretation of the results and analysis of the experiments are explained. Section 5 summarize the paperwork with the conclusions and future work.

II. Characteristics of Traditional WAN

In the initial phases of Cisco router development, the mechanism for packet switching was known as process switching. But, as networking technology improved, Cisco innovated new mechanisms for packet switching known as fast switching and Cisco Express Forwarding (CEF) to improve packet handling capabilities and meet the escalating demands of evolving network infrastructures [2].

CEF provides optimization of network performance and scalability using the forwarding information known as Forwarding Information Base (FIB), and the cached adjacency information known as Adjacency Table. It's very less CPU intensive, provides faster speed and updates its FIB and Adjacency Table immediately. It demands minimal CPU resources, delivers rapid speeds, and quickly updates its FIB and Adjacency table.

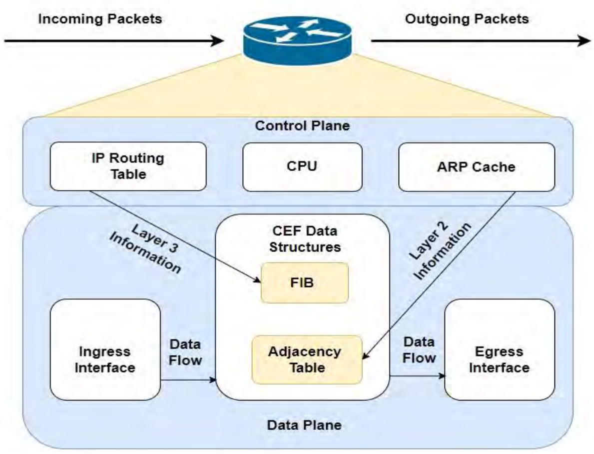

Fig. 1. CEF Process Flow.

The FIB is formed directly from the routing table and stores the next-hop IP address for every destination within the network. Whenever there is a routing or topology change within the network, the IP routing table is updated, and these changes are updated in the FIB. CEF uses the FIB to make switching decisions based on IP destination prefixes.

The adjacency table stores the directly connected next-hop IP addresses and their corresponding next-hop MAC addresses, along with the MAC address of the egress interface. The adjacency table is sourced with data from the ARP table.

An overview of the CEF process flow is illustrated on Fig. 1. When a packet enters the router, packets undergo a transformation process. Initially, the router discards layer 2 information, preparing for determining the packet's destination. This determination is made by referencing the CEF table, or FIB, which guides the router in making a forwarding decision.

After determining the forwarding path, it directs the router to a specific entry in the adjacency table. The router retrieves the Layer 2 rewrite string from the Adjacency table, which enables the router to put a new Layer 2 header to the frame. Finally, the packet is switched out to the outgoing interface toward the next hop [3].

III. Characteristics of SD-WAN

SD-WAN operates within the framework of software-defined networking (SDN) technology, which involves the separation of a router's control plane from its data (forwarding) plane. This architectural approach provides increased network automation, operational simplicity, and centralized capabilities for provisioning, monitoring, and troubleshooting.

In the control plane, network policies such as routing and security are enforced by making decisions about how packets should be routed through specific routers and ports. On the other hand, the data plane focuses on packet forwarding, and contains minimal intelligence required to transfer, or discard packets between ports within the same device.

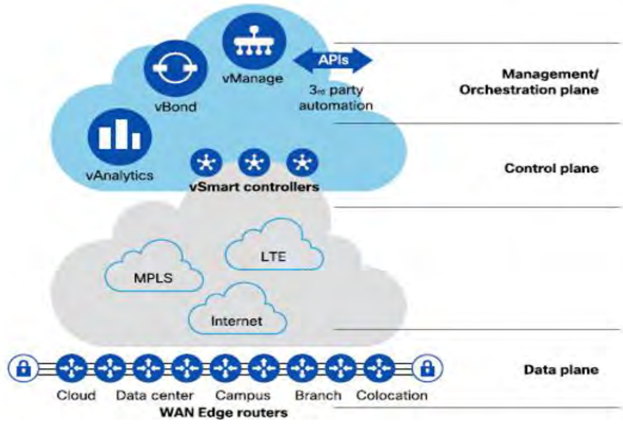

Fig. 2. Application of SDN Principles to the WAN [4].

The SDN principles applied to the WAN are provided on Fig. 2. The Cisco SD-WAN solution is made up of four planes: Data plane, Control plane, Management plane, and Orchestration plane. Below are described the main components of each plane.

Cisco vManage is the Management Plane of the SD-WAN system. Users are accessing vManage in order to centrally administer all SD-WAN edge devices, including tasks like creating device templates, deploying configurations, diagnosing issues, continuously monitoring, and conducting overlay traffic engineering [4].

Cisco vSmart acts as the control plane component within the SD-WAN system. The vSmart controller functions as the central hub of the overlay fabric, distributing routing details, policies, and security setups to the SD-WAN edge devices through the Overlay Management Protocol (OMP). This protocol operates between the vSmart controllers and WAN Edge routers, facilitating the secure exchange of control plane information, such as route prefixes, next-hop routes, cryptographic keys, and policy specifics [4].

Cisco vBond acts as an orchestrator within the SD-WAN system. The orchestration plane plays a crucial role in establishing communication between data plane and control plane. This connection between the control and data planes occurs through various transport circuits such as the Internet, MPLS (Multiprotocol Label Switching), LTE, 4G, and others.

Cisco WAN edge routers have only Data Plane, or forwarding plane of the SD-WAN system. Their primary role involves establishing the network fabric and only forwarding traffic, without actively learning from other WAN edges. Instead, all pertinent information is acquired from the controllers. The controllers relay necessary data to the WAN edges, which then incorporate this information, including routing tables and policies. As a result, the resources of WAN edges are fully dedicated to packet forwarding tasks since they are relieved from calculating optimal paths or populating routing tables [4].

The overall data forwarding process is similar between the traditional WAN and SD-WAN. Cisco WAN edge routers can execute essential functions such as Border Gateway Protocol

(BGP), Open Shortest Path First (OSPF), Access Control Lists (ACLs), QoS, and various routing policies alongside overlay communication tasks. These routers ensure secure connectivity with all the control components and establish Internet Protocol Security (IPSec) tunnels with other WAN edge routers to construct the SD-WAN overlay network. Furthermore, each WAN edge router establishes a control channel with every control element, facilitating the exchange of configuration, provisioning, and routing information [4].

IV. Comparison of the Network Performance between SDWAN and the Traditional WAN

A. Packet Loss Analysis

The most significant and challenging networks encounter is packet loss. During transmission, packets may be dropped or lost, preventing them from reaching their destination due to significant performance fluctuations in the current best-effort Internet and bit errors in communication channels [5]. Packet loss on the Internet can be attributed to crucial components of the network infrastructure, including routers and the communication links that connect them.

Generally, packet losses commonly arise from various factors including network congestion, overloaded devices, and issues with network hardware. Higher packet loss rates or increased latency can intensify delays, amplifying the impact of packets failing to reach their intended destinations.

In traditional WAN packet loss recovery mechanisms typically rely on retransmission-based error recovery as the most used transport layer approach to recover packet errors and losses. This mechanism involves the retransmission of lost packets upon the detection of errors.

Errors in packet transmission can be identified if the sender receives either a duplicate acknowledgment, or a negative acknowledgment due to a missing sequence number. To provide feedback, the receiver sends an acknowledgment upon successful delivery of data. If any data is missing or received with errors, the receiver sends either duplicate acknowledgments or negative acknowledgments. Upon receiving a negative acknowledgment or multiple duplicate acknowledgments, the sender initiates retransmission of the affected data [6].

Retransmission mechanisms are usually rejected in real-time audio and video streaming over the Internet due to their inherent retransmission delays. These delays can cause video packets to miss their intended playout time. When a packet needs to be retransmitted, it arrives at least three times the round-trip time after the transmission of the original packet. This delay may exceed the strict delay requirements of real-time audio and video streaming applications, where acceptable delay times typically range between 100 ms and 200 ms. Consequently, any retransmission of lost packets must occur within 100 ms after the data loss to maintain the integrity of the audio and video stream [7].

IP is a fundamental network layer protocol within the TCP/IP suite. It operates as a connectionless protocol on the internet, offering no assurances regarding packet delivery or performance metrics like latency, jitter, packet loss, or bandwidth. Consequently, it is easier to encounter congestion or network degradation, which can compromise the QoS. Real-time applications are affected more severely by packet loss. For this purpose, in situations where packet loss is higher, or the media quality is essential, the packet duplication feature is used. Packet duplication is one of the mechanisms to preventpacket loss. It's a feature where the sender, to prevent packet loss, sends duplicate packets over redundant WAN links, or multiple IPsec tunnels. This is illustrated on Fig. 3.

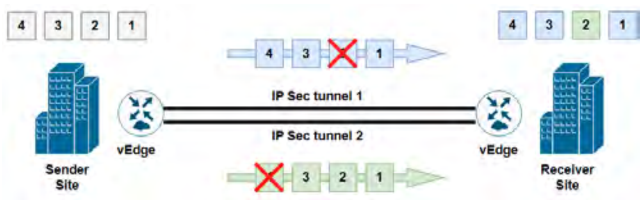

Fig. 3. CISCO SD-WAN Packet Duplication Overview.

If a packet is lost along the transient path, the receiving vEdge router can leverage an alternate copy of the same packet received through another tunnel. In scenarios, where no packets are lost, any redundant duplicates are simply discarded without incident. Through this packet recovery mechanism successful recovery rates often approach nearly 100 % [8 - 9].

This method requires more bandwidth and other resources. Because of this the packet duplication feature is commonly used only for critical traffic such as credit card authorizations, transactions, and specific applications. Credit card transactions are typically very small flows, however if the packet is lost in transit and is required to be transmitted, then the user experience can be slowed down dramatically.

By implementing QoS mechanisms alongside the packet duplication feature, the critical application flows can be prioritized without significantly impacting bandwidth usage. This ensures that essential traffic is delivered reliably and efficiently, even in challenging network conditions.

B. Research Methodology

For this research experiment, the network emulation software EVE-NG (Emulated Virtual Environment - Next Generation) is used as the primary tool. The version of the EVE-NG is 5.0.1-24 Community edition [10].

In EVE-NG, virtual machine images are used to create virtual network devices such as routers, switches, firewalls, and servers. These images can be used to create complex network topologies and test different network configurations [11]. The images that are imported in EVE-NG and the resources that are allocated for the devices for this experimental SD-WAN design are shown in Table I.

Additionally, the tool NetEm is used to emulate packet loss because in the most cases the emulators cannot reach a loss that can be useful for analysis. NetEm is an open-source network emulator for Linux that can simulate various network conditions, including packet loss, latency, packet duplication, bursts, congestion, and packet re-ordering [12].

TABLE I. IMAGES AND RESOURCES FOR EVE-NG [10]

Device	Image	Resources
vManage	vtmgmt-19.2.31	4 vCPU, 24 GB RAM
vSmart	vtsmart-19.2.31	2 vCPU, 2 GB RAM
vBond	vtbond-19.2.31	2 vCPU, 2 GB RAM
vEdge	vtedge-19.2.31	2 vCPU, 2 GB RAM
Windows server	winserver-S2012-R2-x64	12 GB RAM
Switches	I86bi_linux_l2-ipbasek9-ms.high_iron_aug9_2017b.bin	1 GB RAM
Internet router	L3-ADVENTERPRISEK9-M-16.4-2T.bin	1 GB RAM
MPLS router	L3-ADVENTERPRISEK9-M-16.4-2T.bin	1 GB RAM
NetEM	Linux-netem	4 GB RAM

Network emulators play a crucial role for research experiments. They allow for the controlled testing of realistic network scenarios, something that cannot be accomplished using only real network devices without emulation features.

The experimental SD-WAN design analyzed in this paper consists of four branch sites and one controller site and it is given on Fig. 4. The controllers, including vSmart, vManager, and vBond, along with the CA server, are located at the controller site. The vEdges are deployed at the branch sites. The branches are interconnected in a fully meshed topology, and each site has internet connectivity. There are also two WAN transports such as Internet and MPLS.

The NetEm tool was attached to both MPLS and Internet links of the WAN edge router located in one of the branch sites. Packet loss was applied to the stream of the sender. Moreover, random emulated delays were applied to each flow to prevent global synchronization. The delay contributes to the overall stability and efficiency of the network.

The analysis is conducted by randomly adding packet loss to the network flows before the packets are queued, accomplished through the utilization of the network emulator NetEm. The percentage values (%) of packet loss that are specified for this analysis are 1 %, 2 %, 4 %, 8 % and 16 %. The following delay values (in milliseconds) were used: 5, 20, 30, 80 and 200. This packet loss and delay are correlated to the real-world values about these parameters while using the Internet and MPLS [13].

ICMP packets are used as a common method for packet loss testing by sending multiple pings from one branch location to another. Each of the packet loss levels were tested for 1000 ICMP packets that were sent to vEdge4 from the other vEdge devices. One of the WAN transport links is used for sending the original packets, while the other link is used for sending the duplicate packets. The packet duplication values are consistent across the network.

Moreover, following the completion of each test, the outcomes were thoroughly examined. In the event of any discrepancies detected, the test case was re-executed.

C. Interpretation of the Results

The tunnel statistics or packet counters indicate that some packets are transmitted through one tunnel and others through the secondary tunnel. On the vEdge devices sending ICMP traffic, we observe that 1000 packets are transmitted, and the counters on the vEdge in the receiver site show that it has received 1000 duplicate packets.

The findings indicate that reconstructed packets were present across all levels of emulated packet loss, demonstrating an improvement in reducing packet loss percentage and delivering enhanced Quality of Service (QoS) within Cisco SD-WAN compared to traditional WAN. Packet loss is expressed as a percentage, determined by comparing the total number of packets sent to the number received.

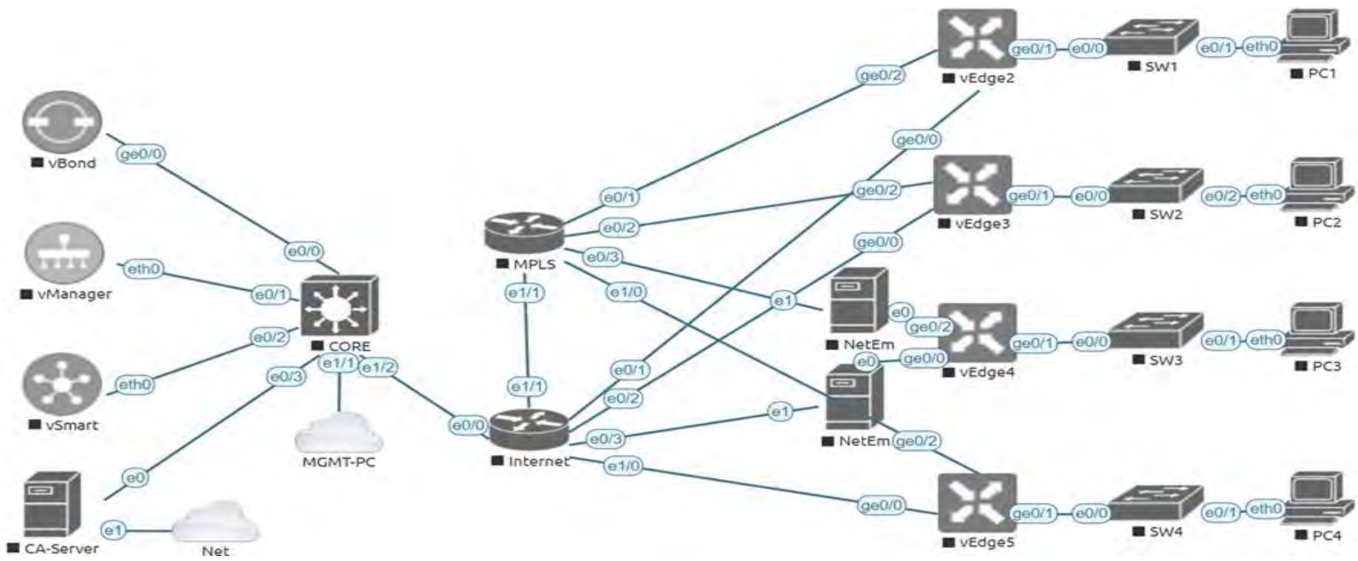

Fig. 4. Experimental Network Topology Design.

TABLE II. PACKET LOSS MEASUREMENT USING PACKET DUPLICATION

Parameter	Device				
	vEdge3 to vEdge4	*vEdge3 to vEdge4*	*vEdge5 to vEdge4*	*vEdge2 to vEdge4*	*vEdge5 to vEdge4*
Emulated packet loss (%)	1	2	4	8	16
Sent packets	1000	1000	1000	1000	1000
Received packets	990	980	970	950	880
Duplicated packets	1000	1000	1000	1000	1000
Reconstructed packets	10	20	30	50	120
Packets lost	10	20	30	50	120
Reconstructed packets (%)	100	100	100	100	100

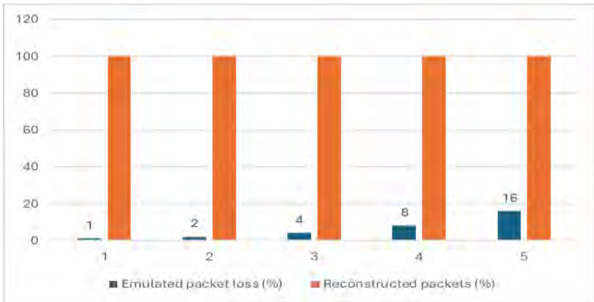

Fig. 5. Percentage of Packet Loss Reconstruction.

The results of the performance tests using packet duplication are shown in Table II. The data in Table II is essential for evaluating SD-WAN performance and its ability to maintain data integrity under different packet loss conditions. The role of duplicated packets in reconstructing lost ones is crucial for ensuring reliable communication across the network.

The experimental results indicate that the packet duplication feature can achieve 100 % of reconstructed packets, regardless of whether there was a light packet loss of 1 %, or a heavy packet loss of 16 %. The reconstruction success rate using packet duplication is shown on Fig. 5.

D. Jitter and Latency

Jitter characterizes the variations in packet arrival times, affected by factors like transmission delays, processing durations, and network congestion. Conversely, latency denotes the time interval for a data packet to journey from its point of origin to its designated destination within a network.

An acceptable level of jitter is typically around 30 milliseconds (ms). Latency, the time it takes for a packet to travel from source to destination, should ideally be under 300 ms for most applications. Additionally, packet loss should be kept below 1 % to maintain a reliable network performance.

TABLE III. SLA REQUIREMENTS FOR APPLICATIONS [14 - 17]

Application	Packet Loss	Latency	Jitter
VoIP	< 1 %	< 150 ms	< 30 ms
Video conferencing	< 1 %	< 150 ms	< 30 ms
Online gaming	< 1 %	< 100 ms	< 20 ms
Streaming media	< 1 %	< 200 ms	< 30 ms
SCADA systems	< 1 %	< 100 ms	< 30 ms

Each application has specific SLA requirements to ensure optimal performance. For instance, different applications might have varying needs for latency, jitter, and packet loss. The SLA requirements of some applications are given in Table III.

In the traditional WAN the internet cannot provide the requirements for certain applications. Also, in traditional routing only routing table and destination IP are important, other features are not available. The router can forward the packet with a comparison of destination IP and routing table.

Cisco SD-WAN cannot directly reduce the jitter, as jitter is an inherent characteristic of the network path itself. Instead, Cisco SD-WAN has a feature called Application Aware Routing (AAR) that can provide the application requirement needs by continuously measuring latency, jitter and packet loss using methods such as IP-SLA probes to make intelligent decisions about routing traffic. By doing so, they can select the optimal path and prioritize critical data, ensuring better overall network performance and reliability, minimizing latency, and consequently, jitter [18].

Furthermore, applying QoS mechanisms such as traffic classification, scheduling, queuing, shaping, and policing on the WAN router interface can significantly reduce latency, jitter, and packet loss for critical application flows. These methods help prioritize essential traffic, manage bandwidth efficiently, and ensure that high-priority applications receive the necessary network resources for optimal performance.

Voice over IP (VoIP) is sensitive to network conditions such as delay and jitter, which can significantly diminish voice quality, making it unacceptable for the average user. VoIP generally tolerates delays up to 150 ms before the call quality deteriorates to an unacceptable level [21-22].

TCP optimization and session persistence features can effectively mitigate issues related to high latency such as satellite links. With TCP optimization, a WAN Edge router functions as a TCP proxy, managing the connection between the client and server. This proxy role helps optimize data flow and manage packet loss, thereby enhancing performance. Session persistence, on the other hand, maintains a single TCP connection for multiple request-response exchanges, rather than establishing a new connection for each interaction [19].

V. CONCLUSION AND FUTURE WORK

According to the packet loss analysis during the transmission it can be concluded that packet duplication feature in Cisco SD-WAN can reduce packet loss and improve reliability by reconstructing the lost packets. Packet duplication feature can mitigate the effects of packet loss by adding redundant packets to the sender to reconstruct lost packets. The experimental results indicate that the packet duplication feature can achieve 100 % of reconstructed packets. Packet duplication feature is particularly beneficial for some applications that cannot tolerate data loss, such as VoIP, video conferencing, real-time analytics, emergency services, financial transactions, etc.

Most applications consider a low packet loss level (1 % - 2 %) acceptable. However, a packet loss rate of 5%, or higher can notably affect both network performance and user experience [20].

Additionally, Cisco SD-WAN can mitigate jitter through traffic prioritization and QoS mechanisms. One of the key benefits of SD-WAN is the ability to transition from traditional WANs, which rely on expensive legacy transport methods, to higher-capacity, lower-cost broadband options such as the internet. This shift can significantly reduce transport costs while still leveraging the benefits of low-cost transport using packet loss mitigation techniques [23].

The cost perspective was not observed in this paper. However, companies can benefit from SD-WAN despite its higher cost compared to traditional WAN because it ensures reliable performance for critical applications. Poor network quality for the critical application traffic can lead to significant business disruptions, making SD-WAN a valuable investment to protect business operations.

Based on the analysis and findings presented in this paper, future research directions for Cisco SD-WAN could focus on developing adaptive packet duplication mechanisms that intelligently can be activated based on current network conditions, balancing performance improvement and bandwidth overhead.

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Optimization and Testing of Smart Contracts for Generation and Verification of Academic Diplomas

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***Abstract*— Smart contracts are an integral part during the creation of a blockchain system for the generation and verification of diplomas. Every transaction in the blockchain network actually represents a smart contract when it comes to data management, because there must necessarily be an agreement between parties involved for its execution. Smart contracts have unique characteristics that are related to the nature of the environment where they are executed, the blockchain network, the programming language that is used, and even the blockchain platforms that are used. The optimization and testing of the smart contract plays a very important role in terms of reducing the cost, the functionality of the smart contract, the execution time and above all the prevention of any possible attack that can be threatened during the execution of smart contracts. In this paper, we highlight and analyze the properties of smart contract and its deployment for generation and verification of academic diplomas. Further, the smart contract related testing techniques on Ethereum platform are explored.**

Keywords—smart contract, execution, development, testing, optimize, Ethereum, blockchain, generation, verification, diploma.

I. INTRODUCTION

Smart contracts play a very important role in terms of the execution of transactions in a system for generation and verification of diplomas, whether they are transactions of various payments, generation of diplomas, verification of diplomas and other academic documents, as well as many other processes that are related to data management in higher education institutions [1]. Considering that each transaction execution in the blockchain network has its own cost, it is very important to optimize the code and test them before they are deployed in the blockchain network. For this reason, different techniques and tools are used that enable and facilitate blockchain programming. Nevertheless, it is important to acknowledge that smart contracts are not without their constraints, which stem from the programming languages used to code them, the blockchain platforms on which they are performed, and other technological limits. Smart contracts exhibit more compatibility on the Ethereum platform, resulting in benefits and restrictions that are inherently linked to the platform. Solidity is the predominant programming language used for writing smart contracts, however there are other languages available. Still, the majority of these languages are designed specifically for the Ethereum platform. The Integrated Development Environment is also very important, with which it is possible for smart contracts to be tested, optimized and executed in test form, before they are executed on the blockchain network. As for blockchain system development tools, for generating and verifying diplomas, frontend part, backend, truffle suite, metamask and blockchain storage are needed [2].

Blockchain systems are seen as the only option for digitizing diplomas, among others, even though they face certain challenges and limitations. This is due to the nature of the blockchain, which is mainly composed of nodes, and each node contains a distributed ledger, in which all the activities carried out within the blockchain network are recorded. One of the practical implementations that we have proposed for the generation and verification of diplomas is the DIAR system, which is clearly defined with a conceptual model, with systematic architecture, up to the definition of smart contracts and their architecture [1]. The DIAR system improves upon previous practical implementations and aims to address various issues related to diploma generation and verification. It places particular emphasis on tokenizing diplomas and storing them as tokens in blockchain storage. This approach simplifies the process of generating and verifying diplomas, especially in situations where there are challenges and limitations in creating blockchain systems for higher education institutions. What is most important about smart contracts is that they are transparent, and the same can be seen by all participants who are in the blockchain network. Among other things, all the nodes that are part of the blockchain network can contain a piece of the contract in their public ledger. Smart contracts are immutable, which means that during the moment that the same is deployed in the blockchain network, it cannot be changed or deleted, only if other mechanisms are used to destroy the entire blockchain network, through very complicated techniques, which brings major financial consequences and, such as the regeneration of many other structures of the blockchain network [3].

This paper primarily emphasizes the significance of smart contracts in the development of blockchain systems for the creation and authentication of diplomas. The novelty of the paper lies in the fact that it describes the importance of smart contracts and their implementation in higher education institutions. Important smart contract processes such as their optimization, testing, implementation of intelligent agents in their programming environments are also described. At the same time, through the paper, we hope to arouse interest among developers for the implementation of blockchain systems for the management of academic credentials, which obviously depends on the successful implementation of the smart contract.

II. BACKGROUND

This section includes a review of the literature regarding smart contract implementations, and in particular in higher education institutions. It also describes some types of attacks that threaten smart contracts and what measures are taken to overcome attacks and increase the security of smart contracts. The security of transactions in the blockchain network, including the Ethereum platform, is closely related to the mining process, an important process, through which the blocks within the nodes that are in the blockchain network are validated. In the Ethereum platform, many consensus mechanisms are used during this process, and it requires great computing power to solve the puzzle, and finally to verify the hash value of the block, and then to insert or verify the data that is stored in advance [3]. Smart contracts are useful in many spheres of life, however, some practical cases of their usability include: Financial contracts, Prediction market, Digital Identity, Supply Chain Management, Health care industry, Tokenization [4].

Smart contract application in higher education institutions, particularly for certificate creation and verification, is now a topic of debate owing to potential abuse. We have highlighted several obstacles and limitations in this area [5]. The main obstacles and constraints include the unchangeable nature of smart contracts, high expenses for execution and upkeep, challenges in managing data within blockchain systems, absence of standardized smart contracts, difficulties in reusing and adapting them. Moreover, complexities in transferring diplomas from traditional systems to blockchain systems, scarcity of blockchain and smart contract developers and users, limited knowledge and literature in this domain, and lack of developer interest due to the economic advantages offered by other fields like cryptocurrencies, are also some of the remaining challenges.

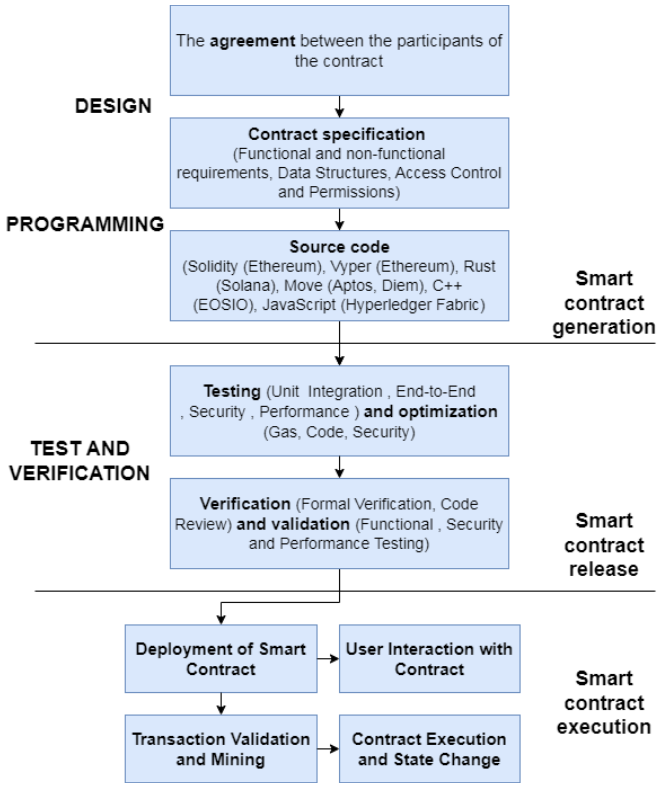

FIGURE 1. Smart contract life cycle.

According to [6], smart contracts have a life cycle, which includes their generation; smart contract release, which includes optimization, testing, code verification, and other post-deployment procedures; and finally the execution of the smart contract. Figure 1 presents, among other things, the life cycle of a smart contract, presented in the form of a block diagram. During the contract generation phase, we specified the agreement between the parties included in the contract, the contract specification including all the details of their design, and the coding in a certain programming language. The second phase includes testing, optimization and validation of the smart contract. And finally, during the execution, four more important processes are specified as well: deployment of smart contracts, user interaction, transaction validation and mining, and contract execution and state change.

Smart contracts provide the benefits of immutability, security, and transparency for performed services. These benefits are highly dependent on the framework and platform used for deployment. Smart contracts incur specific costs that directly impact their execution speed, performance, and security [7]. The execution of the smart contract is done automatically, only after the prerequisites set by both parties performing the transaction are fulfilled. The main advantage of smart contracts that have been used in recent days is security and privacy protection, as they are executed without the intervention of a third party [8]. Each smart contract represents a digital object in a blockchain system [9]. A significant drawback of smart contracts is their limited compatibility with platforms other than Ethereum. This raises skepticism about their ability to achieve optimal performance, since they are not widely used or interoperable with other platforms. Every transaction on the Ethereum platform represents a smart contract. To support the work of smart contract developers, online environments called Remix IDE have been created. Figure 2 shows the use of smart contracts and their role in different spheres [10].

Regarding the application of smart contract in higher education institutions, they are used in digital certificates, for the process of storing, verification and validation of certificates, as a supporting tool for many processes such as online learning, various online trainings for students and academic staff, the management of the bookstore in the institution of higher education, student payments, students' knowledge evaluate, student evidence, registration process [11].

III. SMART CONTRACT DEPLOYMENT

Smart contracts are actually sequences of code that enable decentralized systems to communicate with the blockchain, communication which is carried out in a quasi-Turing-complete virtual machine, which we know as the Ethereum Virtual Machine (EVM). EVM is considered as a distributed machine, which enables the execution of smart contracts by consuming Gas Ether. Smart contracts are immutable, but if during execution they show various errors that bring great negative consequences to the network, then the blockchain network must be completely destroyed, which can undoubtedly bring negative consequences [12]. After the smart contract is written in a programming language, then it continues with the process of deploying them, which is obviously much more difficult than in centralized applications, and requires more additional tools to be installed, which are part of EVM. The simplified structure of a smart contract in Solidity is described below through Listing 1.

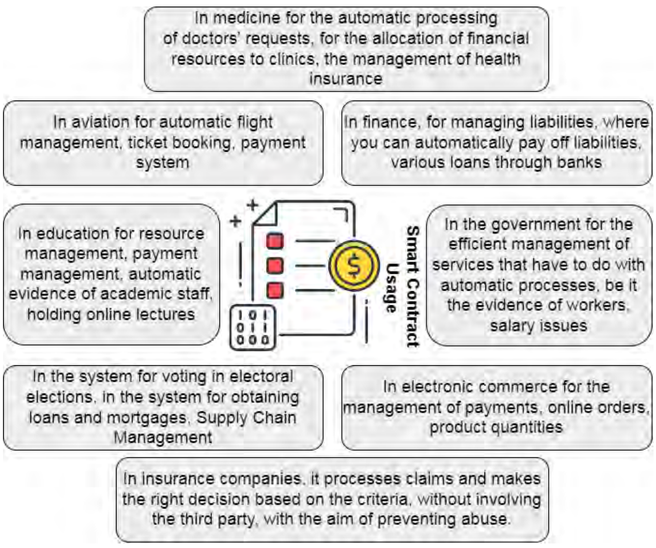

FIGURE 2. Smart contract usage

```
1. Smart contract Exp{
2. Defining non-constant attributes ( address,
   mapping);
3. Defining constant attributes (structures);
4. Defining constructor (Example);
5. Defining modifier, functions();
6. RECEIVE() external pay function;
7. FALLBACK() external pay function;
8. Events (insert, verify data from/in blockchain
   storage)
```

LISTING 1. Smart contract example in Solidity

Once the smart contract has been completed, it must be compiled, using any of the methods such as the Solidity Compiler (solc), RemixIDe, Truffle, Hardhat, etc. Then we have to continue with the configuration of other equipment necessary for setting up the blockchain environment, such as Metamask, Ganache, Truffle, Node.js and others. And then, in order to deploy a smart contract, we must open an ethereum owner account, as well as open the same account in Metamask. Only after the transaction is confirmed by the Metamask wallet, where at the same time we confirm the expenses for the realization of the transaction, then the same smart contract is executed and the same can be seen in a transparent form in Etherscan, where in a detailed form we have all the details of the implementation of contract, as well as the successful or unsuccessful execution of the same.

Figure 3, among others, presents an example of the execution of the smart contract in Etherscan, where, among other things, we have given the details that for each transaction, the address of the sender and recipient of the smart contract, Gas fee, hash value of the transaction, the transfer of tokens as well as many other details. When discussing the generation and authentication of credentials in blockchain systems, there are two crucial processes: the production of diplomas and the verification of diplomas using the data that has been created.

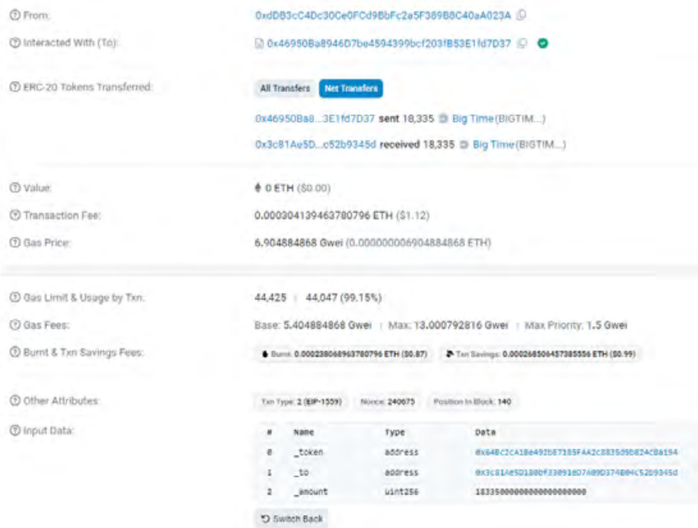

Figure 3. Etherscan smart contract execution

Here, we are discussing the act of inputting data into blockchain storage, while the verification procedure involves determining the authenticity of a particular diploma. This verification is often conducted by a private organization that has a partnership with the higher education institution. Figure 4 shows the process of deploying the smart contract for the insertion of diplomas, this phase which was carried out in RemixIDE to first test the same, before executing it in the blockchain network. In a simplified form, we have presented the smart contract code for generating diplomas in Solidity, in Listing 2.

```
// SPDX-License-Identifier: MIT
    pragma solidity ^0.8.0;
    contract InsertDiploma{
    struct Diploma {defining Diploma details;}
    mapping(address => Diploma[]) private diplomas;
event DiplomaAdded( diploma details);
function addDiploma( diploma details);
    public diplomas[msg.sender].push(Diploma(all student details));
    emit DiplomaAdded(student details);}
    function getDiplomas(address studentAddress) public view returns (Diploma[] memory) {return diplomas[studentAddress]; }}
```

LISTING 2. Diploma generation smart contract example

IV. SMART CONTRACT OPTIMIZING AND TESTING

When talking about smart contract development tools, which simultaneously enable the testing and optimization of their code, it is worth noting that most of the tools are created by private companies for profitable purposes, but there are also those known as community tools, which are free and open to all developers. There are many tools for smart contract analysis on the Ethereum platform, but some of them are: Oyente, Gasper, E-Evm, Osiris, SolMet, Zeus, Vandal, Remix-IDE, SmartCheck, EtherTrust and others. The main characteristic of most of these analysis tools is that they are created with Python, and very few in C++, Java and other programming languages [14]. One of the most useful tests of code sequences in smart contracts is mutation testing. Through this type of testing, mutations are introduced in the original code and based on the scheme compiled based on this type of testing, it can be seen whether errors are detected in the execution of the smart contract. The methods and ways in which this type of testing works are given in [15]. Fuzzing testing is another method of testing the source code of the smart contract, where a large number of test cases are created in advance to test the program, abnormal behaviors during the execution of the program. This type of testing is mostly used when there is a strict program structure, or when the functional requirements of the system being tested are clearly defined. Oyente is another type of testing, which aims to detect various attacks that threaten the system, various exceptions that have not been handled well. It also uses different symbols to simulate different inputs to explore different execution paths.

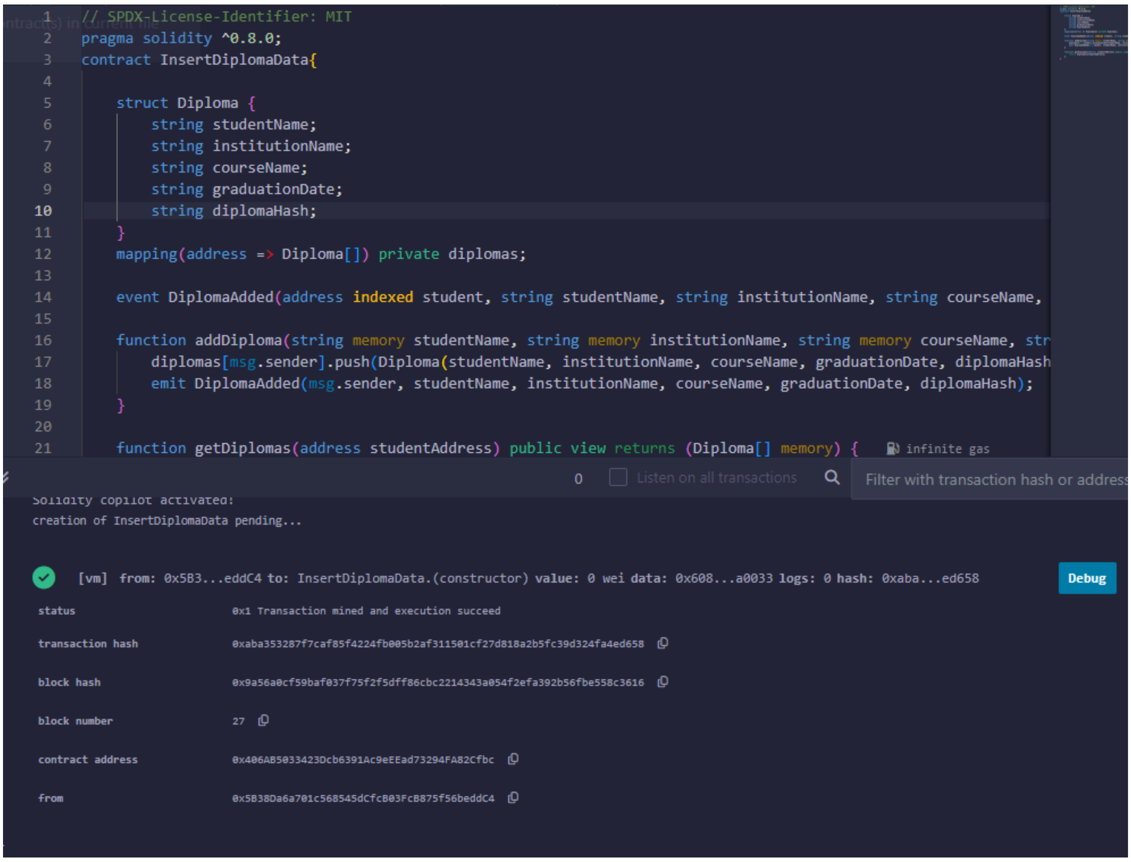

Figure 4. Deploy smart contract for generation diploma

Above all, it has the ability to simulate the Ethereum Virtual Machine, to test the behavior of the smart contract in different conditions [6]. Remix IDE is also an analysis tool for testing and optimizing smart contracts, especially those coded in Solidity. It is open source, and developers are free to test and analyze the smart contract. SmartBug is also a framework for smart contract analysis, open source. The framework aims to compare the performance and accuracy of the systems by using techniques for comparing real and simulated contracts. Also using specific techniques to reveal the weaknesses of the system in general [4]. Aroc is a framework that has the ability to automatically detect and adjust on-chain smart contracts, which is challenging due to the smart contract deployment process. The essence of Aroc's operation is in the generation of patch contracts, to detect malicious transactions in advance [16]. Optimizing the smart contract through GasSaver, an analysis tool, can be done in several ways within the source code, reducing the unnecessary use of loops and conditions, analyzing the operation logic and using as little unnecessary code as possible, reducing unnecessary variables that only increase the cost and execution time [1]. From the systematic analysis regarding ethereum smart contract analysis tools, it was found that one of the most used analysis tools is "re-entrancy". One of the methodologies used as static tools for smart contract analysis is symbolic execution, while fuzz testing is a dynamic methodology. However, what is evident is that during the use of optimization and testing methods, the so-called hybrid analysis is used, which consists of a combination of dynamic and static analysis[4]. To see how the optimization and testing of the smart contract is carried out, we use RemixIDE, an integrated development environment, which, in addition to other features, has an integrated intelligent agent that is able to clarify different code sequences of what they have a role. Also, RemixIDe enables to pre-calculate the cost of smart contract execution, showing for each code sequence separately the execution costs. Figure 5 shows an interface of testing the smart contract, clarifications of the intelligent agent, and calculation of the cost of the smart contract.

V. CONCLUSION

The implementation of blockchain systems for the management of big data, especially in higher education institutions for the generation and verification of diplomas, is seen as the only hope to prevent possible misuse of these very important academic documents. Although there are various practical solutions available, one notable system is the DIAR system. However, the implementation and complete digitization of services in higher education institutions remain a significant challenge. Additionally, the maintenance of these systems is considerably more expensive than centralized systems. When considering blockchain systems, and the management of big data, in this case diplomas, inseparable parts are smart contracts, which actually represent the essence of programming blockchain systems. Implementing smart contracts presents several hurdles. Nonetheless, we have prioritized the testing and optimization of these contracts to proactively minimize costs and mitigate any possible attacks. An ongoing challenge for academics is the potential use of smart contract and blockchain systems in higher education

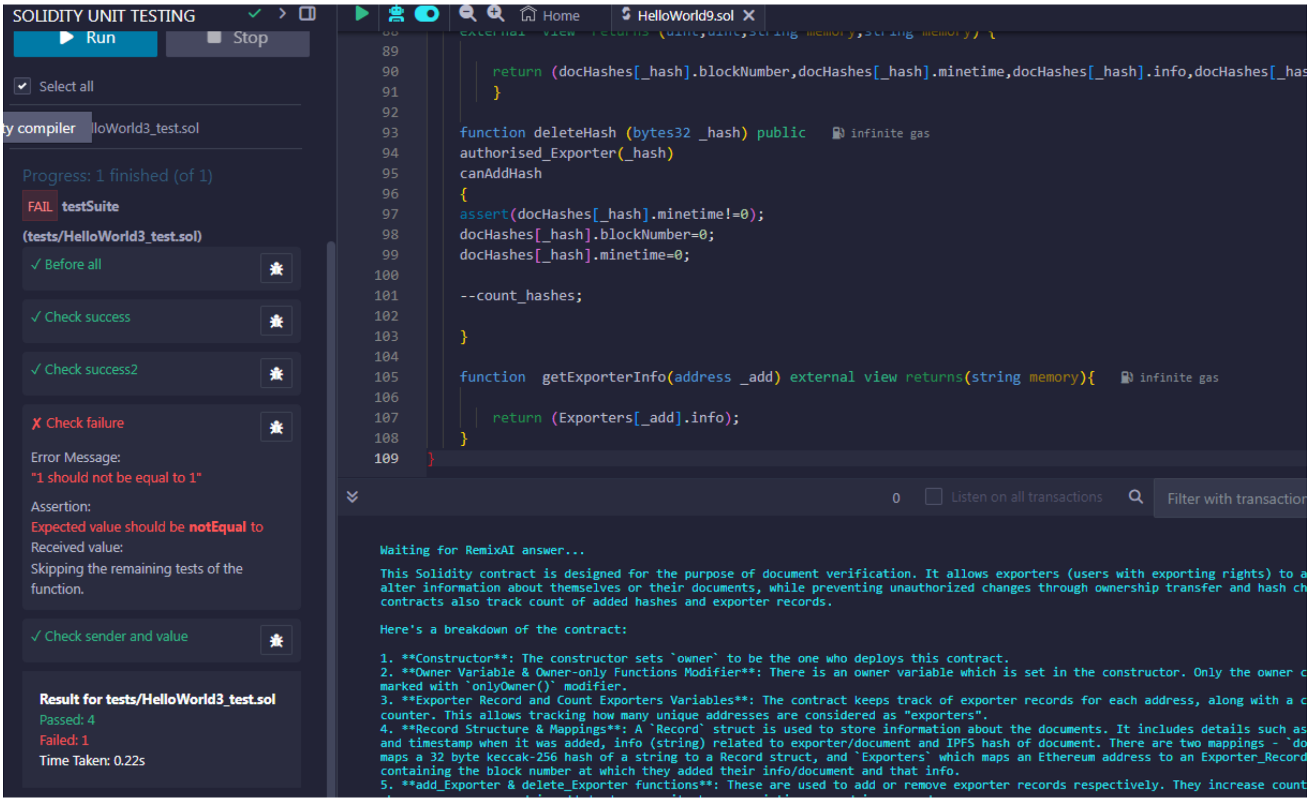

Figure 5. Testing smart contract through RemixIDE

institutions. Anyhow, we believe this implementation would permanently resolve several issues related to the creation and authentication of diplomas. To date, there is no information about the successful implementation of any blockchain system for the generation and verification of diplomas. There are many challenges in this direction, and different researchers are giving their contributions to overcome and implement such a system that would enable the generation and verification of diplomas in real time, and with this would facilitate the work in higher education institutions.

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AI Strategies for Reducing Carbon Footprint in the ICT Sector: An Evaluation through the Science-Based Targets Initiative

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***Abstract*—This paper examines the methods used by Information and Communications Technology (ICT) companies to reduce their carbon emissions by utilizing Artificial Intelligence (AI) technology within the Science-Based Targets Initiative (SBTi) framework. ICT enterprises may make a substantial contribution to global climate objectives by aligning their carbon reduction efforts with scientifically established targets. This research assesses the effectiveness of contemporary AI-driven techniques, including energy efficiency, predictive maintenance, and sophisticated data analytics, in monitoring emissions. Furthermore, it examines the difficulties, advantages, and pragmatic factors involved in using AI into sustainability efforts within the ICT sector. The findings highlight the crucial role of AI in revolutionizing the ICT sector to achieve significant reductions in emissions and improve overall sustainability.**

Keywords—AI, Science-Based Targets, ICT sector, carbon footprint reduction, sustainability, climate change, greenhouse gas emissions, energy efficiency, predictive maintenance, emission tracking

I. Introduction

The ICT industry plays a major role in worldwide carbon emissions due to the growing need for digital services and the heavy reliance on energy-intensive data centers, networking infrastructure, and end-user devices. In the face of the urgent difficulties posed by climate change, the ICT industry is increasingly compelled to embrace sustainable techniques that effectively decrease its carbon emissions. An effective approach to accomplish this objective is by utilizing AI technologies.AI has the capacity to completely transform the approach of ICT organizations towards managing their energy usage and greenhouse gas (GHG) emissions. It provides cutting-edge solutions for optimizing operations and improving efficiency.

The SBTi offers a rigorous framework [1] for firms to establish ambitious emissions reduction targets that are aligned with the objectives of the Paris Agreement. By pledging to these objectives, ICT companies may synchronize their sustainability initiatives with internationally acknowledged climate targets, guaranteeing that their actions make a significant contribution to the wider battle against climate change. By incorporating AI technologies into the SBTi framework [2], there is a distinct chance to improve the efficiency of these goals. This can be achieved by utilizing AI's predictive analytics, energy management, and real-time monitoring capabilities to significantly reduce emissions.

This paper seeks to examine the existing ways utilized by ICT enterprises to decrease their carbon emissions through AI-driven methods inside the SBTi framework [3]. The text explores the several AI strategies employed to enhance energy efficiency, optimize equipment maintenance, and precisely monitor pollutants. In addition, the paper discusses the difficulties and advantages of implementing these AI methodologies, emphasizing the practical and ethical factors that need to be considered. This paper aims to examine how the combination of AI with sustainability in the ICT sector might lead to substantial environmental advantages and support the advancement of a more sustainable future.

The paper is structured to provide a thorough examination of the tactics utilized by ICT companies in the adoption of AI-driven SBTs to reduce their carbon emissions [4].

The current section highlights the significant role of the ICT industry in global GHG emissions and emphasizes the urgent requirement to adopt AI technology in line with the SBTi. This section presents a summary of the influence of the ICT sector on worldwide carbon emissions and emphasizes the immediate requirement for sustainable practices. This text explores the function of the SBTi in directing enterprises towards significant reductions in emissions. It also highlights the potential of AI technology to facilitate these transformations.

Section II examines various AI solutions aimed at mitigating the environmental consequences of the ICT industry. The areas covered include energy optimization, predictive maintenance, advanced data analytics, and real-time pollution monitoring. This section is a comprehensive summary of the methods and strategies employed by ICT firms to enhance sustainability through the use of AI.

Section III analyzes the challenges that ICT organizations encounter when incorporating AI technology into SBTs, focusing on impediments relating to data quality, privacy issues, financial and technological barriers, and organizational change. This section provides a comprehensive analysis of these challenges, offering useful perspectives on the complexities involved in achieving AI-powered SBTs.

Section IV explores the benefits of adopting AI-driven SBTs for ICT organizations. The paper highlights enhancements in environmental performance, compliance with legislation, operational effectiveness, market prospects, and company standing. This section also emphasizes the broader impact of AI-powered SBTs on innovation and interactions with stakeholders.

Section V presents a concise overview of the research results and gives guidance for ICT businesses to effectively implement AI-powered SBTs. The paper outlines potential methods that the industry can use to reduce its carbon emissions and contribute to global climate objectives. This section proposes potential avenues for future research and technical breakthroughs that could improve the incorporation of AI in attaining sustainability objectives.

Section VI provides a summary of the main discoveries and emphasizes the significance of AI in promoting sustainability in the ICT industry. This section focuses on the significant impact that AI technologies can have in reducing carbon footprints. It emphasizes the need for ongoing research, smart investments, and collaborative efforts to progress these technologies. Furthermore, it necessitates tackling the obstacles and ethical concerns in order to guarantee the responsible implementation of AI, thereby promoting the achievement of global climate objectives and paving the path for a more sustainable future.

The paper aims to offer a thorough understanding of how AI can be efficiently utilized to reduce carbon emissions in the ICT business, aligning with the goals of the SBTi. This will be accomplished through a systematic analysis of these factors.

II. Background and Motivation

The ICT sector significantly contributes to worldwide GHG emissions, representing around 2-3% of the total global emissions [5]. The substantial influence is propelled by the increasing need for digital services, the expansion of data centers, and the widespread use of electronic devices. With the rapid advancement of digital transformation, the ICT sector is projected to have a larger environmental impact, which would worsen the existing issues caused by climate change.

Urgent and imaginative solutions are needed to tackle the environmental impact of the ICT sector. The SBTi offers a structured approach for firms to establish ambitious emissions reduction targets that are grounded in scientific evidence and aligned with the objectives of the Paris Agreement. The purpose of these aims is to ensure that the increase in global temperature remains much below 2°C compared to pre-industrial levels, and to actively strive to restrict the warming to 1.5°C. By adopting knowledge-Based Targets (SBTs), ICT companies may ensure that their actions are in line with the most up-to-date climate knowledge and make a significant contribution to global climate goals [6].

AI is being increasingly utilized to bolster sustainability initiatives in diverse areas, including the ICT sector. AI technologies have the ability to enhance energy efficiency, optimize data center operations, and enable proactive maintenance, resulting in reduced operational emissions [7]. The capacity of AI to analyze extensive quantities of data in real-time enables more precise monitoring and control of energy use and emissions, rendering it a crucial element of contemporary sustainability efforts.

This paper examines the incorporation of AI into the SBTi framework to improve the ICT sector's capacity to achieve its goals for reducing emissions. Through the utilization of AI-powered solutions, ICT firms can not only attain substantial reductions in their environmental impact but also acquire operational efficiencies and earn a competitive edge. The following sections of this paper will explore certain AI applications, the difficulties of implementation, the advantages of AI-driven SBTs, and future perspectives for improving sustainability in the ICT sector.

III. AI Technologies and Their Applications in the ICT Sector

AI technology can greatly decrease the carbon footprint of the ICT sector by reducing energy consumption, improving operational efficiency, and enabling better monitoring of emissions. This section examines different AI-driven methodologies that are being employed to accomplish these objectives.

A. Energy Optimization

AI systems have the capability to examine extensive quantities of data in order to detect trends and inefficiencies in energy usage. Machine learning models are used to forecast energy consumption and enhance the efficiency of data centers, which are one of the most energy-intensive elements of the ICT infrastructure. For example, AI has the ability to adaptively regulate cooling systems in data centers in order to sustain ideal temperatures, resulting in decreased energy consumption while maintaining performance [8]. Furthermore, AI has the capability to include renewable energy sources into the power supply combination with greater efficiency, guaranteeing a consistent and environmentally-friendly energy flow [9].

B. Predictive maintenance

Predictive maintenance utilizes AI to forecast equipment malfunctions in advance, enabling prompt maintenance and minimizing operational interruptions. This method can be implemented in the ICT sector to encompass servers, networking devices, and other essential infrastructure. AI aids in scheduling maintenance tasks during non-peak hours by accurately forecasting when a component is expected to break. This helps minimize disturbance and energy waste [10]. Implementing this proactive maintenance strategy not only increases the longevity of the equipment but also leads to significant energy conservation.

C. Emission Monitoring with Advanced Data Analytics

AI-driven data analytics systems facilitate the immediate tracking and documentation of GHG emissions. These technologies can collect data from several sources, such as IoT devices, sensors, and operational logs, in order to give a complete understanding of an organization's carbon footprint. Subsequently, AI algorithms can examine this data to pinpoint areas with high emissions and propose specific actions to decrease emissions [11]. Thorough and ongoing monitoring is essential for ICT firms to achieve their SBT and adhere to regulatory obligations.

D. Monitoring emissions in real-time

AI technologies enable the continuous monitoring of pollutants by employing sophisticated sensors and data processing methods. These systems have the capability to identify variations in emission levels and offer quick feedback, facilitating prompt correction measures. AI can be utilized to manage network traffic in order to minimize energy consumption or to alter server workloads for the purpose of achieving a balance between performance and energy efficiency [12]. Continuous monitoring guarantees prompt identification and resolution of any deviations from emission reduction targets.

By adopting these AI-based approaches, ICT organizations can greatly diminish their environmental impact by decreasing their carbon emissions, all the while improving their operational effectiveness and dependability. The following part will address the difficulties and moral problems linked to the incorporation of AI technologies in sustainability initiatives.

IV. Implementing AI strategies within the SBTi Framework

By incorporating AI initiatives into the SBTi framework, there are exciting opportunities to decrease the carbon emissions of the ICT sector. Nevertheless, the process of integrating these components is filled with difficulties that need to be properly managed in order to achieve successful implementation. Data quality and availability are significant barriers. AI algorithms depend on enormous quantities of precise, high-quality data with a high level of detail in order to operate efficiently. Obtaining such data in the ICT sector can be challenging because of fragmented sources and uneven gathering methods. Therefore, it is crucial to guarantee the accuracy and uniformity of data for the effectiveness of AI-powered sustainability projects [13].

Another notable concern revolves on the matter of privacy and security. The implementation of AI in the surveillance and control of emissions requires the gathering and examination of significant volumes of data, which gives rise to problems of privacy and security. ICT firms must use rigorous measures to uphold data privacy and safeguard sensitive information from breaches. Implementing strong cybersecurity measures and adhering to regulatory norms for data protection are essential to address these concerns [14].

Additionally, there are significant obstacles in terms of both finances and technology. Implementing AI technology for sustainability necessitates substantial financial resources and advanced technological infrastructure. Small and medium-sized firms (SMEs) in the ICT industry may find it challenging to assign the required resources, which can be especially overwhelming. Moreover, the process of incorporating AI technologies into current workflows and procedures can be intricate and time-consuming. Companies must assess the cost-benefit ratio and investigate funding options to facilitate the implementation of AI-driven sustainability initiatives [15].

The legislative framework for AI and environmental sustainability is always changing, which further complicates the situation. ICT enterprises must effectively negotiate intricate legal frameworks and remain up-to-date with evolving rules to guarantee adherence. Moreover, market instabilities, such as volatility in energy costs and the accessibility of renewable energy sources, can influence the efficacy of AI techniques. It is crucial for enterprises to interact with policymakers and industry stakeholders in order to foresee and adjust to changes in regulations and market conditions [16].

Implementing AI initiatives inside the SBTi framework requires organizational transformation as a crucial element. This entails cultivating a culture that promotes innovation, enhancing the skills of people, and harmonizing corporate procedures with sustainability objectives. The reluctance to embrace change and a limited comprehension of AI technologies can impede the implementation of these initiatives. Leadership and ongoing education are essential for driving organizational transformation and ensuring the successful implementation of sustainability initiatives powered by AI [17].

ICT companies can utilize AI technologies to overcome these problems and achieve their science-based ambitions, so making a significant contribution to global climate goals. This integration not only promotes environmental sustainability but also improves operational efficiency and competitiveness in the changing market environment. In the following section, we will examine the advantages and influence of AI-powered SBTs in the ICT industry.

V. Future Directions and Recommendations

Integrating AI into the SBTi framework has demonstrated significant promise in decreasing the carbon emissions of the ICT sector. Nevertheless, the continual development of new ideas and deliberate progress are crucial in order to fully utilize the capabilities of AI and continue to promote sustainability. This section provides an overview of potential future paths and suggestions for ICT firms seeking to improve their sustainability endeavors by utilizing AI.

An important future focus is the development of AI algorithms and models designed specifically to optimize energy usage and reduce emissions. Improving the complexity of machine learning models to handle bigger information and deliver more precise predictions would increase the efficiency of AI in managing energy consumption and decreasing emissions. The research should prioritize the development of AI solutions that are both high-performing and energy-efficient, thereby reducing the environmental impact of AI technology [18].

Effective collaboration and knowledge exchange among key industry stakeholders, such as technology providers, legislators, and academic researchers, are essential for fostering innovation. Implementing universal benchmarks for data acquisition, manipulation, and presentation can enhance the accuracy and uniformity of data, which are important for the effectiveness of AI-powered sustainability projects. Collaborations between ICT corporations and academic institutes can expedite the advancement and utilization of state-of-the-art AI technologies specifically designed for the distinct requirements of the ICT industry [19].

ICT businesses should prioritize investing in renewable energy sources and integrating them with AI technologies. AI has the capability to enhance the utilization of renewable energy by accurately forecasting energy requirements and effectively controlling energy storage systems. ICT firms may greatly diminish their dependence on fossil fuels and decrease their overall carbon emissions [20] by investing in AI-powered renewable energy solutions.

Employee training and organizational change management are crucial elements for effectively integrating AI. It is imperative for companies to allocate resources towards enhancing the abilities of their staff to guarantee they are equipped to effectively utilize AI technologies. In addition, cultivating a culture that promotes innovation and sustainability inside the firm can encourage the implementation of AI-driven practices and contribute to the attainment of SBTs [21].

AI adoption in sustainability efforts must prioritize ethical considerations. It is crucial to retain trust and prevent potential negative consequences by guaranteeing openness, accountability, and justice in AI systems. ICT organizations ought to establish rigorous ethical norms and governance frameworks to supervise the utilization of AI in sustainability endeavors, guaranteeing that these technologies are employed responsibly and for the benefit of society [22].

Finally, ongoing surveillance and enhancement are crucial. ICT businesses should conduct periodic evaluations of the effectiveness of their AI-powered sustainability initiatives and implement any necessary modifications to enhance results. This entails keeping abreast of the most recent developments in AI and sustainability, while also adjusting to new regulatory mandates and market circumstances.

ICT firms may enhance their sustainability endeavors and make substantial progress in lowering their carbon emissions by prioritizing these future directions and recommendations. Integrating AI into the SBTi framework not only helps achieve environmental objectives but also improves operational efficiency and competitive edge.

VI. CONCLUSION

The significant role of the ICT sector in global GHG emissions calls for immediate and inventive measures to reduce its environmental footprint. By incorporating AI into the SBTi framework, we can effectively reduce carbon footprints, improve operational efficiency, and promote sustainability.

This paper has examined many AI-driven approaches, including energy optimization, predictive maintenance, advanced data analytics, and real-time emission monitoring, that can significantly contribute to decreasing the carbon footprint of ICT operations. These solutions empower ICT firms to detect inefficiencies, forecast and preempt equipment malfunctions, and consistently oversee and control their emissions with more efficiency.

Nevertheless, there are difficulties associated with effectively using AI techniques inside the SBTi framework. Challenges pertaining to the quality and accessibility of data, protection of privacy and security, financial and technological obstacles, legal and market concerns, and the necessity for organizational change must be resolved. To overcome these issues, it is necessary for all stakeholders, such as ICT firms, technology suppliers, legislators, and academic researchers, to collaborate and work together.

In order to progress, it is crucial to consistently develop and make strategic improvements in AI technology. In order to successfully implement AI-driven sustainability practices, it is imperative to focus on the following key factors: enhancing the complexity and energy efficiency of AI models, promoting collaboration and knowledge exchange, allocating resources to renewable energy sources, and establishing strong ethical rules.

The advantages of incorporating AI into the SBTi framework go beyond its environmental effects. ICT organizations have the potential to improve their operational efficiency, reduce costs, and increase their competitiveness in the market. Furthermore, by their dedication to science-based aims and use of AI technology, ICT enterprises can make a substantial contribution to worldwide endeavors in addressing climate change.

To summarize, AI has the capacity to significantly impact the sustainability efforts of the ICT sector. ICT companies may achieve significant reductions in their carbon footprint and contribute to global climate goals by tackling obstacles, embracing future directions, and implementing recommendations. This will pave the way for a more sustainable future by harnessing the power of AI.

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Static, Dynamic, and High-Order Functional Connectivity Analysis in Schizophrenia and Bipolar Disorder Differentiation

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***Abstract*—Schizophrenia and Bipolar Disorder are complex psychiatric conditions with a large range of overlapping symptoms and differentiating between the two poses a diagnostic challenge. This paper explores the potential of resting-state functional magnetic resonance imaging (rsfMRI) to distinguish the disorders by comparing classifications based on static, dynamic, and high-order functional connectivity, calculated as Pearson's correlation coefficients between each pair of Intrinsic Connectivity Network timecourses. To assess the discriminatory ability of the different methods to the insight of brain's organization and function, we classify the connectivity networks with Logistic Regression and evaluate the models by computing the AUC (Area Under Curve) score. The model trained for the classification of Static Functional Connectivity achieved an AUC score of 59% and proved to be the best approach for differentiating the two disorders. This research contributes to understanding the importance of evaluating different methods of Functional Connectivity Analysis for psychiatric diagnosis.**

***Index Terms*—Schizophrenia, Bipolar Disorder, rs-fMRI, static functional connectivity, dynamic functional connectivity, high order functional connectivity, classification, AUC;**

I. Introduction

Schizophrenia and Bipolar Disorder are two distinct yet often intricately intertwined psychiatric conditions that represent significant challenges in the domain of mental health diagnosis. Schizophrenia is characterized by positive symptoms like hallucinations and delusions, and negative symptoms such as social withdrawal, anhedonia, and avolition, along with cognitive symptoms like impaired attention and working memory [1]. In contrast, Bipolar Disorder is marked by episodes of mania where individuals experience increased energy, racing thoughts, and engage in risky behavior, followed by episodes of depression characterized by feeling low and fatigued, having appetite and sleep changes, and finding it hard to concentrate [2]. The clinical manifestation of shared symptoms, overlapping comorbidities, and intricate variations within each disorder make it difficult for precise diagnosis [3].

Traditional diagnostic approaches, while valuable, may falter in providing the precise discrimination between Schizophrenia and Bipolar Disorder, which is crucial for providing effective clinical intervention. Despite extensive research, the underlying pathological mechanisms of SZ and BP remain unknown, with emerging evidence pointing to differences in brain connectivity as a potential key to understanding these conditions [4], [5]. The emergence of advanced neuroimaging techniques and computational capabilities made it possible to gain transformative insights into psychiatric diagnoses. Resting-state functional magnetic resonance imaging (rs-fMRI), as a powerful neuroimaging technique, captures the intrinsic neural activity by measuring the low-frequency fluctuations in blood-oxygen-level-dependent (BOLD) signals, providing an intricate view into the functional organization of the brain [6]. Functional connectivity, derived from rs-fMRI data, allows us to uncover the interactions between different regions of interest.

Research has predominantly focused on static functional connectivity (SFC), assuming that the underlying connectivity remains stationary throughout the scan [7]. However, emerging findings have underscored the significance of dynamic interactions in understanding brain disorders. Dynamic functional connectivity (DFCN), constructed through techniques such as the sliding window approach, capture the temporal fluctuations in brain connectivity and offer a dynamic perspective on brain function [8]. By going a step further, high-order functional connectivity (HFCN) have emerged as a promising avenue for exploring the intricate spatial interactions across multiple brain regions. HFCNs, constructed through methods like clustering, delve deeper into the complexity of brain region interactions [9].

In this paper, we explore the role of connectivity analysis in the differentiation between Schizophrenia and Bipolar Disorder. We systematically compare static functional connectivity, dynamic functional connectivity, and high-order connectivity analysis, exploring their respective strengths and potential contributions to aid the diagnostics for distinguishing between the two disorders. In Section II we present the dataset and applied methodology, in Section III we explore the results and in Section IV we evaluate our findings and discuss the broader implications of our study.

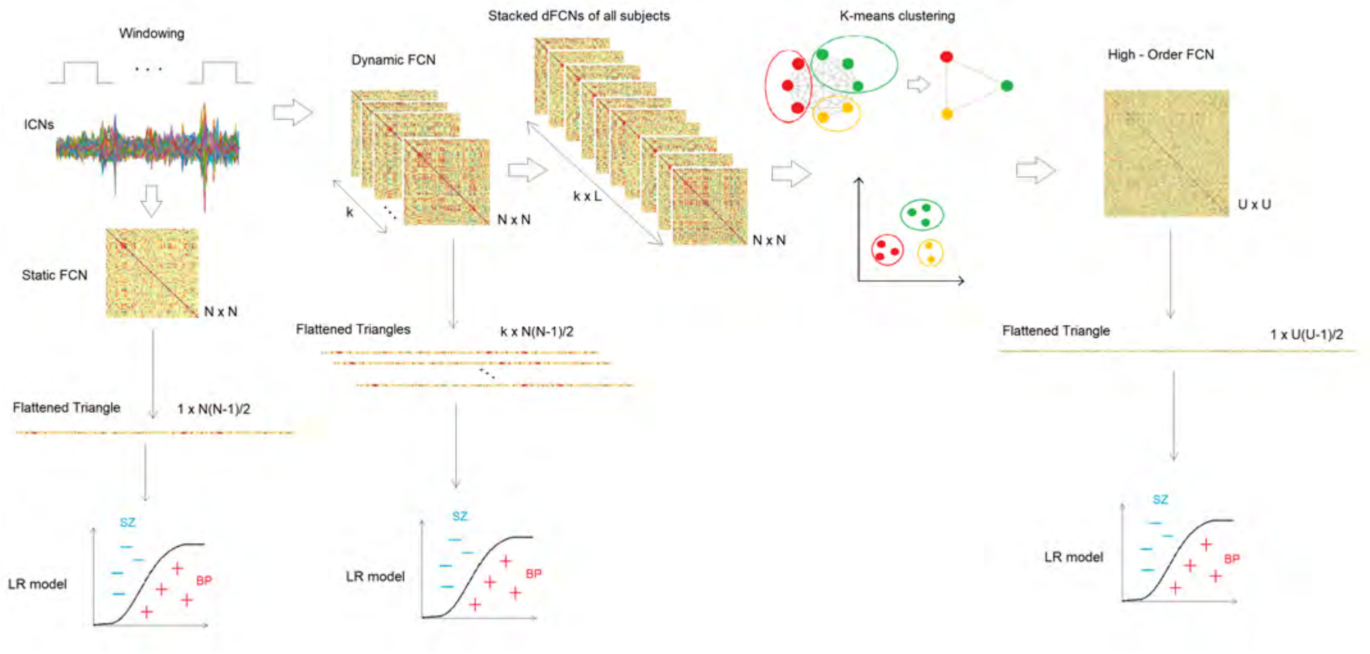

Fig. 1. Methodology. Computing the Static Functional Connectivity as pairwise Perason's correlation coefficient of all ICN timecourses. Because of symmetry, the lower triangle of the sFCN matrix is flattened and classified using the LR model. The dynamic FCNs are calculated using sliding windows on the ICNs. Each of the dFCNs' lower triangles is flattened and stacked for classification purposes. For obtaining the high-order FCN, the dFCNs for all subjects are stacked for unsupervised k-means clustering. By computing the mean correlation coefficient of the clusters, the dimensionality of the high-order network is reduced. By computing the correlation coefficients between the clusters' means we get the hFCN with dimensions UxU, where U is the number of clusters. The lower triangle of hFCN is also flattened for classification purposes.

II. Materials and Methods

A. Materials

The dataset used in this work consists of 183 BP and 288 SZ subjects for training, annotated by a medical professional, and 315 unlabeled patients for testing, provided by The Brain Space Initiative is the scope of the IEEE SPC challenge [10]. The dataset consists of timecourses of 105 intrinsic connectivity networks (ICNs) estimated using the GIFT toolbox [11], extracted from the rs-fMRI derived from a multi-spatial-scale spatially constrained ICA template [12], and their corresponding functional connectivity network calculated as Pearson's correlation between each pair of ICN timecourses. For this paper we used the provided ICN timecourses and standardized their length to 100 samples to match the shortest length in the dataset.

The provided features were extracted from the original datasets [13], [14] in several steps. Quality control was applied to identify high-quality data. Each subject's rsfMRI data were preprocessed using a standard procedure, including rigid body motion correction, slice timing correction, and distortion correction. Preprocessed subject data were registered into a common space, resampled to 3 mm^3 isotropic voxels, and spatially smoothed using a Gaussian kernel with a 6 mm full width at half-maximum (FWHM). A multi-spatial-scale template of 105 ICNs obtained from 100k+ subjects was used and a constrained ICA approach to obtain subject-specific ICN time courses. To calculate FCN, we standardized the ICN time courses to a length of 100 samples further used for computing connectivity. [10]

The training dataset consists of ICN timecourses and their FCNs for 471 subjects, appropriately labeled, whereas the test set contains unlabeled features for 315 subjects.

B. Static Functional Connectivity

Static functional connectivity analysis is a widely used approach in neuroimaging and neuroscience to study the patterns of functional interactions between different brain regions under the assumption that these patterns remain relatively constant [15]. The static functional connectivity provided in the dataset is computed for varying ICN time course lengths. For an appropriate comparison of the methods, we computed the static functional connectivity for each subject l by computing Pearson's correlation between each pair of ICN timecourses with a standardized length of 100:

$$W_{ij}^{(l)} = \frac{\sum_{k=1}^{M}(x_{ik}-\bar{x}_i)(x_{jk}-\bar{x}_j)}{\sqrt{\sum_{k=1}^{M}(x_{ik}-\bar{x}_i)^2}\sqrt{\sum_{k=1}^{M}(x_{jk}-\bar{x}_j)^2}} \quad (1)$$

where $W_{ij}^{(l)}$ is the Pearson's correlation coefficient between vectors x_i and x_j, pair of ICN timecourses from $\mathbf{X} \in \mathbb{R}^{M\times N}$, matrix of all timeseries where $M = 100$ is the length of the timecourses, and $N = 105$ is the number of ICNs for subject l. x_{ik}, x_{jk} are the value of the time series for regions i and j, respectively at time point k. $\bar{x}_i$ and $\bar{x}_j$ are the respective means for i and j ICN timecourses. The resulting matrix

$\mathbf{W}^{(l)} \in \mathbb{R}^{N\times N}$ represents the static functional connectivity for subject l. Due to the symmetry in the correlation analysis, for classification purposes, the lower triangle is flattened in a vector with length $\frac{N(N-1)}{2}$, in our case 5460.

C. Dynamic Functional Connectivity

Dynamic functional connectivity network (dFCN) analysis aims to capture the time-varying patterns of functional connectivity within the brain by using a sliding window approach [16]. This partitioning allows examination of how functional connectivity patterns change over time, revealing the brain's dynamic interactions. The number of subseries K in dFCN analysis can be calculated as $K = \lceil \frac{M-L}{s} \rceil + 1$ where M represents the total duration of the time series data, L is the length of the sliding window and s is the step size or increment at which the window is moved along the time series. The choice of window length L is a critical parameter in dFC analysis. In the context of dFC, each subseries, denoted as $\mathbf{X}^{(l)}(k)$, represents a windowed portion of the brain's functional connectivity data. For the $l-th$ subject, $k-th$ segment of all N ICN timecourses is given as $\mathbf{X}^{(l)}(k) = [x_1(k), x_2(k), \ldots, x_N(k)] \in \mathbb{R}^{L\times N}$. For each $k-th$ temporal functional connectivity matrix, where $1 < k \leq K$, $W_{ij}^{(l)}(k)$ is computed as Pearson's correlation coefficient, equation (1). This method results in computing K correlation matrices $\mathbf{W}^{(l)} \in \mathbb{R}^{N\times N}$. The dFCN analysis explores the temporal variability of the functionally connected regions i.e. the spatiotemporal dynamics of the brain's intrinsic connectivity. For classification purposes, the lower triangle part of the correlation matrix of each window k, $\mathbf{W}^{(l)}(k)$ is extracted in a vector, and stacked together. Each column in the matrix represents a correlation time series $h_{ij}^{(l)} = [W_{ij}^{(l)}(1), \ldots, W_{ij}^{(l)}(K)] \in \mathbb{R}^K$ between each pair of ICN timecourses. The total number of correlation time-series $N(N-1)/2$, therefore stacked correlation time-series result in a matrix with dimensions $K \times\ 5460$. For generating the dFCNs, two parameters are crucial: the window length - L and the sliding step - s. In our experiments, we used combinations of $L = [10, 20, 30, 40, 50]$ and $s = [5, 10, 15, 20, 25]$ respectively.

D. High Order Functional Connectivity

High-order functional correlation is obtained using the correlations' correlation principle [17]. Using the correlations' correlation principle, high-order order connectivity for each pair of correlation time series $h_{ij}^{(l)}$ and $h_{mn}^{(l)}$ is computed as Pearson's correlation coefficient $H_{ij,mn}^{(l)} = corr(h_{ij}^{(l)}, h_{pq}^{(l)})$, extracting information up to four brain regions characterizing more complex interaction patterns, indicating how the correlation between $i-th$ and $j-th$ ICN timecourses affects the correlation of $p-th$ and $q-th$ ICN timecourses. According to this principle of high-order functional connectivity, the computation is equivalent to N^4. In the dataset used in this work $N = 105$, the number of high-order connections is in the millionth order. For the reduction of the network, clustering is applied. Calculating the mean of the clustered correlation time series generates a small-scale high-order functional connectivity without losing vital information. For unsupervised clustering, the low triangle matrix of the dFCNs per subject are stacked together and K-means clustering is applied to divide $\{h_{ij}\}$ into different U clusters. The clustering algorithm will assign h_{ij} with similar variations across time to the same cluster Ω_u, where $1 < u \leq U$. The mean correlation series for patient l from cluster u are calculated as:

$$\overline{h}_u^{(l)} = \frac{\sum_{(i,j)\in\Omega_u} h_{ij}^{(l)}}{|\Omega_u|} \tag{2}$$

where $|\Omega_u|$ is the number of correlation series in the cluster. High-order connectivity is then calculated as Pearson's correlation coefficient between the mean correlation series of the clusters $\overline{h}_u^{(l)}$ and $\overline{h}_v^{(l)}$ as $H_{uv}^{(l)} = corr(\overline{h}_u^{(l)}, \overline{h}_v^{(l)})$. This method reduces the complexity of high-order connectivity from N^4 to U^2. The lower triangle of the resulting $H_{uv}^{(l)} \in \mathbb{R}^{\mathbb{U}\times\mathbb{U}}$ is flattened into a vector form with length $U \times (U-1)/2$. The cluster correlation series are then stacked per subject for further classification purposes. For generating high-order FCN, there are three key parameters, such as the window length L and the sliding step s characteristic for generating the dFCNs and another additional parameter U, or the number of clusters. For each pair of $L = [10, 20, 30, 40, 50]$ and $s = [5, 10, 15, 20, 25]$ hFCNs were calculated for $U = [10, 50, 100, 200, 300]$.

III. Results

We used a Logistic Regression model for differentiating between Schizophrenia and Bipolar Disorder of each of the high-dimensional features [18]. We trained the models and optimized the hyperparameters by 5-fold cross-validation over a parameter grid with the GridSearchCV algorithm [19]. For each experiment, the best models were used to predict soft probability scores of the test dataset provided [10]. The soft probability scores were then submitted for evaluation. Public and private AUC (Area under curve) scores are calculated for subsets of the testing dataset. We refer to public AUC as AUC Validation and private AUC as AUC Test.

In Table I and Table II, the results of the classification of high-order, and low-order FCNs are shown. The best AUC score is obtained with the classification of Low Order Functional Connectivity. It is important to note that shortening the ICN timecourses before computing the sFCN yielded worse AUC scores compared to the work in [20]. Therefore, for accurate diagnosis longer rs-fMRI sessions are crucial. The classification of functional connectivity has demonstrated a poorer performance compared to the classification of the Intrinsic Connectivity Network timecourses that achieved AUC Validation score of 0.705 and an AUC Test score of 0.63 [20].

IV. Conclusion

The differentiation between Schizophrenia and Bipolar Disorder is a challenging yet pivotal task for ensuring precise diagnosis and effective treatment of patients. We explored different network analysis methods on rs-fMRI data to achieve this objective. We proposed different methods based on static,

TABLE I
CLASSIFICATION OF HIGH-ORDER FCNS

U	10		50		100		200		300	
Parameters	**AUC Validation**	**AUC Test**	**AUC Validation**	**AUC Test**	**AUC Validation**	**AUC Test**	**AUC Validation**	**AUC Test**	**AUC Validation**	**AUC Test**
L=10, s=5	0.518	0.524	0.428	0.527	0.400	0.558	0.535	0.504	0.520	0.509
L=20, s=10	0.535	0.595	0.446	0.501	0.540	0.430	0.562	0.500	0.400	0.517
L=30, s=15	0.538	0.451	0.550	0.484	0.439	0.470	0.484	0.542	0.533	0.483
L=40, s=20	0.406	0.466	0.425	0.535	0.513	0.375	0.499	0.489	0.541	0.506
L=50, s=25	0.545	0.500	0.512	0.438	0.491	0.557	0.564	0.552	0.562	0.508

TABLE II
CLASSIFICATION OF LOW-ORDER FCN

Network, Parameters	**AUC Validation**	**AUC Test**
sFCN	0.550	0.590
dFCN L=10, s=5	0.547	0.591
dFCN L=20, s=10	0.545	0.567
dFCN L=30, s=15	0.541	0.556
dFCN L=40, s=20	0.566	0.561
dFCN L=50, s=25	0.559	0.568

dynamic, and high-order functional connectivity and achieved the best results by classifying the sFCNs. Taking into account both Validation AUC and Test AUC, low-order functional connectivity yielded better differentiation between Schizophrenia and Bipolar Disorder. In the future scope of our work is accessing the statistical significance of the scores achieved by each method. Computing the functional connectivity from shorter rs-fMRI temporal measurements adversely impacts the discriminative power of the models. Therefore, for further development of systems for automatic diagnostics, measuring brain activity during longer rs-fMRI sessions is crucial for precise and accurate results. Another possible impediment to the predictive value of the different connectivities is the fact that they were calculated on a coarser, network level, and not between the activity of brain regions as commonly done in network neuroscience [21].

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Comparative Sentiment Analysis and Semantic Meaning in Text using sentiment models from Hugging Face and Power Automate

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***Abstract*—This paper outlines an innovative approach utilizing Artificial Intelligence models for determining the semantic meaning of sentences. In linguistics, it is crucial to understand how we interpret texts and uncover the underlying messages conveyed by the authors through their sentences. Today, we are witnessing significant advancements in technology and decision-making, driven by previous experiences, diverse databases and knowledge systems. This wealth of data is processed using various robotic systems and artificial intelligence models. Large corporations often receive extensive customer reviews and feedback on their products, but manual reading and analysis can be challenging. In this article we will show how utilization of the Hugging Face models and Power Automate models can do deeply semantic analysis on text and how the punctuation marks can impact the way how the text is written and the whole meaning. Hugging Face can assist by using its advanced natural language processing models to automatically analyze and interpret extensive customer reviews and feedback, streamlining the process. Power Automate can help by automating the collection, organization, and initial analysis of customer reviews and feedback, reducing the manual workload. The synergy between both technologies will be described, as well as their powerful utilization to explore a range of innovative applications to showcase their versatility and practicality.**

Keywords—Hugging Face, Power Automate, AI, Robotic Process Automation, Intelligent systems;

I. INTRODUCTION

The rapid evolution of IT technology and the development of new AI systems are driving numerous scientific innovations and creating abundant opportunities for researchers. Not only are these innovations changing traditional businesses, but they are also opening new areas of research. Researchers can now utilize sophisticated AI models to explore complex datasets, develop intelligent systems, and solve previously inconceivable problems [1]. The integration of AI in various domains is fostering a collaborative environment where interdisciplinary research thrives, leading to groundbreaking discoveries and the continuous expansion of human knowledge [2].

Social media, large corporations, banking systems, educational platforms, universities, and other institutions or industries regularly receive diverse feedback and reviews reflecting user satisfaction levels. These insights are crucial for business growth and determining future strategies. Feedback varies, encompassing customer perspectives and internal organizational assessments. A thorough understanding of feedback can drive substantial growth within organizations. The demand for analyzing feedback, emails, and documents is growing, posing challenges for humans due to potential errors in manual processing. Integration of robotic processes with AI models is the key of how this information's could be processed and analyzed with different statistical methods and significantly reducing the occurrence of errors.

Hugging Face provides a platform to develop and test custom models or utilize pre-built natural language processing models for language detection and text classification [3]. On the other hand, Power Automate (PA) enables the development of Robotic Process Automation (RPA) workflows that automate repetitive tasks and minimize errors [4],[5]. PA also offers pre-built AI models for language detection and semantic analysis of text, enhancing its automation capabilities.

Through this paper, we will explore the capabilities of AI models in understanding languages and discerning the impact of punctuation marks within sentences. Utilizing models from both Hugging Face and Power Automate (PA), we will conduct comparative analyses across various scenarios.

II. HUGGING FACE AND ITS FEATURES

Hugging Face is an open-source collaborative platform that provides a range of tools that allow anyone to develop, train, and deploy NLP and ML models [6]. It is offering a user-friendly, easily accessible environment for developers, researchers, and enthusiasts to build sophisticated AI applications by utilizing open-source code. The platform supports a wide range of NLP tasks, such as sentiment analysis, translation, and text summarization and offers an extensive library of pre-trained models, making it easier to implement state-of-the-art AI solutions. Hugging Face is a leading AI platform that offers a robust inference API for deploying models as a service, allowing for seamless integration into applications. Ensures scalable and efficient model inference, making it suitable for production environments. Hugging Face provides several powerful libraries and tools for natural language processing (NLP) tasks, including model architectures, pre-trained models, tokenization, training pipelines, etc. There are a wide range of pre-trained models for various NLP tasks, such as text classification, named entity recognition, question answering, and more. We can choose a specific architecture (e.g., BERT, GPT, RoBERTa) and load a pre-trained model using the AutoModel class [7].

Hugging Face is widely utilized in scientific and engineering fields for the analysis of complex data sets.

These features make Hugging Face a powerful and versatile platform for anyone working with machine learning and AI [8].

A. *Fundamental Technologies*

Hugging Face utilizes several fundamental technologies to support its suite of tools and libraries. These technologies forms are impacting the progress of their offerings, enabling advanced natural language processing (NLP) and machine learning capabilities. Here are the key fundamental technologies used by Hugging Face:

Python is an effective programing language for utilizing Hugging Face's natural language processing (NLP) features, allowing users to develop, train, and employ sophisticated language models with ease [9].

Transformer Architecture provides APIs and tools to easily download and train state-of-the-art pretrained models [10]. These models support common tasks in different modalities, such as: NLP (text classification, named entity recognition, question answering) computer vision (image classification, object detection, and segmentation), audio (automatic speech recognition and audio classification) and multimodal (table question answering, information extraction from scanned documents). Transformers support framework interoperability between PyTorch, TensorFlow, and JAX. Hugging Face's core technology is built around the transformer architecture, which is the basis for many models like BERT, GPT, T5.

PyTorch and TensorFlow are both popular open-source deep learning frameworks that facilitate the development and deployment of machine learning models, particularly in the domain of neural networks [11],[12].

Tokenization is the process of breaking down a sequence of text into smaller units called tokens shown in Fig.1. The main goal of tokenization is to create a standardized and structured representation of textual data that can be easily processed by machine learning algorithms and natural language processing (NLP) models [13]. Hugging face implements advanced tokenization techniques that convert text into numerical input suitable for models, including Byte-Pair Encoding (BPE), WordPiece, and SentencePiece tokenizers [14].

Data sets is a library and repository that offers a vast array of curated datasets for various NLP tasks. Hugging Face Datasets provides a valuable resource for finding and working with diverse and well-structured datasets.

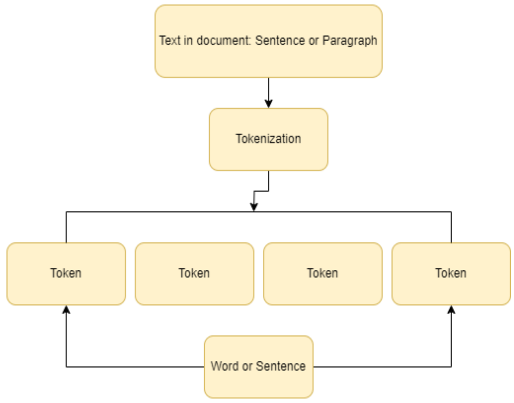

Fig.1. Process of tokenization of a sentence or word

III. POWER AUTOMATE AND ITS FEATUTRES

Power Automate is a cloud platform that supports RPA systems. It is a Microsoft product that provides a low-code platform for automating workflows across various applications and services. Power Automate is enabled by default in all Office 365 applications and comes with more than 150 standard connectors that can be utilized and create various automations on the processes. The tool offers an equal number of premium connectors available for purchase to increase automation capabilities. With its user-friendly interface and extensive library of pre-built templates, Power Automate empowers organizations to increase productivity, efficiency, and collaboration by automating routine tasks and processes [15].

A. *Robotic Process Automations in Power Automate and AI connectors*

RPA seamlessly replicates and streamlines business operations, mimicking human actions such as logging into applications, data entry, email correspondence and other repetitive tasks [15]. In PA we can easily develop bots that can execute different tasks. Developing the bots is with configuration of pre-build connectors. There are two options for building bots, desktop bots or cloud flows, additionally there are several ways of real time monitoring them [16].

In order to add intelligence to automated processes, forecast results, and enhance corporate performance, PA includes its own AI Builder feature. With its direct integration with PA, AI Builder directly integrates the power of Microsoft AI through experience, AI Builder enables you to build and deploy AI models effortlessly, empowering you to make data-driven decisions and automate tasks with ease [17].

B. *AI Builder transforming business capabilities*

Below are mentioned some of the capabilities utilization of the AI Builder models, also check the Fig.2. for overview of business automation:

- Low Code/ No code capabilities
- Speed up business processes with AI insights
- Custom Model Training
- User friendly interface
- Seamless integration with over 250 connectors
- Predictive Analysis
- Sentiment Analysis
- Object detection

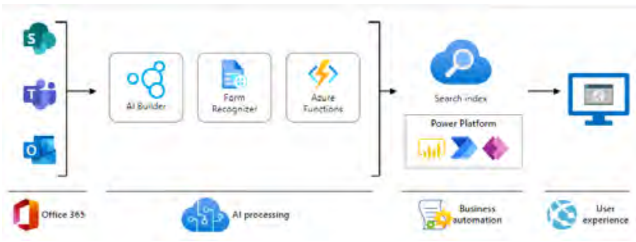

Fig.2. Extracting text from objects using PA and AI connectors [18]

IV. DIFFERENCES BETWEEN SEMANTIC MEANING AND SENTIMENT ANALYSE IN TEXT

The semantic meaning of a sentence refers to the interpretation of its content, focusing on the meaning and concepts conveyed by the words and their arrangement. This includes understanding the relationships between words, the context in which they are used, and the overall message or idea being conveyed. Semantic analysis seeks to understand not only the literal meaning of words, punctuation marks, but also implied, inferred, or nuanced meanings, which may be affected by context, tone, and cultural or situational factors.

Sentiment analysis, also known as opinion mining, is a natural language processing (NLP) technique used to determine the emotional tone or attitude expressed in a piece of text. It involves classifying the sentiment of the text into categories such as positive, negative, or neutral. Sentiment analysis is commonly used to analyze customer reviews, social media posts, and other forms of unstructured text data to gauge public opinion or emotional responses.

Sentiment analysis is detecting emotional tone and how is written in message, while semantic meaning aims to understand the actual meaning of the text. Both are crucial for comprehensively analyzing and understanding human language.

V. UTALIZATION OF HUGGING FACE AI MODEL

Hugging Face is widely used across various industries for tasks such as sentiment analysis, translation services, content moderation, chatbots and virtual assistants, document summarization, voice recognition and image classification. In this paper we will focus more on the sentiment analysis and how changing parameters in text can impact getting different results. For that purpose, in this scenario is utilized the model nlptown/bert-base-multilingual-uncased-sentiment, shown in Fig.3 the implementation of the model.

```
# Load tokenizer and model
model_name = "nlptown/bert-base-multilingual-uncased-sentiment"
tokenizer = AutoTokenizer.from_pretrained(model_name)
model = AutoModelForSequenceClassification.from_pretrained(model_name)
```

Fig.3 Implementation of the AI model

This model is multilanguage and can recognize different languages in text documents. While detecting the semantic meaning and sentiment analysis in sentences we will use parallel two languages for comparation: English and Macedonian.

A. Semanic meaning and sentiment analize of the sentences in English

1) With punctuation marks

This model was tested by sending a list of sentences that are well formatted and using punctuation marks Fig.4.

```
PS C:\Users\Aneta\Desktop\Hugging Face> python .\test3.py
Sentence: "This book was truly inspiring and I recommend it to everyone!🖤
Sentiment: {'label': '5 stars', 'score': 0.8869526386260986}
```

Fig.4. Results after sending a sentence with using emoji and punctuation marks

The results were also analyzed for the semantic meaning, in the above sentence we can determine that the user experience is highly positive. The model assigned the highest grade, despite the confidence score being around 88%.

Interesting here is that in Fig.4. emoji is added at the end of the sentence. After testing that part and deleting the emoji we got almost the same results from the model, with only difference in the score precent 87%, Fig.5.

```
Sentence: "This book was truly inspiring and I recommend it to everyone!"
Sentiment: {'label': '5 stars', 'score': 0.8756318092346191}

Sentence: "I didn't like the book; the story was too boring and predictable!"
Sentiment: {'label': '2 stars', 'score': 0.5620238184928894}

Sentence: "The book was well-written, but it didn't leave a strong impression on me."
Sentiment: {'label': '3 stars', 'score': 0.5407010912895203}
```

Fig.5. Results for the text classification by the model

With the above results reading the sentences with the marks that are used is understandable, for the human but also for the AI model. It is clearly summarized that the second sentence is with negative meaning and the third sentence is with neutral meaning.

Reading the metrics and the score value the conclusion is that the border between the levels of negative, neutral or positive reaction is based on the characters that are included in the text.

2) Without punctuation marks

Without punctuation marks, sentences can become confusing and their meaning ambiguous, especially for humans. But how do the AI models behave if there are not any punctuation marks in the sentence?

According to the sentences that were used for this testing, it can be notable that the present of how comfortable the model is reducing as shown at the Fig.6.

```
Sentence: "This book was truly inspiring and I recommend it to everyone"
Sentiment: {'label': '5 stars', 'score': 0.8503599762916565}

Sentence: "I didn't like the book the story was too boring and predictable"
Sentiment: {'label': '2 stars', 'score': 0.5230246782302856}

Sentence: "The book was well-written but it didnt leave a strong impression on me"
Sentiment: {'label': '3 stars', 'score': 0.49882516264915466}
```

Fig.6. Representation of the results from the sentences without punctuation marks

If we compare the results now without punctuation marks and before, example for the first sentence: “This book was truly inspiring and I recommend it to everyone”, the semantic meaning is still clear, but the model reduce the score from 88% to 85%. Imagine the difference and how much this scope will be reduced if the text is bigger and if the checking is based on many sentences without knowing where the sentence is beginning or ending.

B. *Semantic meaning and sentiment analize of the sentences in Macedonian*

1) *With punctuation marks*

Similar to the previous example we did the same analysis, but now utilizing a different language for the same meaning of the sentences. In Fig.7. there is a representation of one sentence with additional emojis.

```
Sentence: „Не ми се допадна книгата приказната беше премногу досадна и предвидлива 🤣🤣🤣“
Sentiment: {'label': '2 stars', 'score': 0.3722081780433655}
```

Fig. 7. Sentence in Macedonian language with using an emojis

The score is around 37% and the feedback of the model is that the semantic meaning of the sentence is with negative understanding.

```
Sentence: „Не ми се допадна книгата, приказната беше премногу досадна и предвидлива.“
Sentiment: {'label': '2 stars', 'score': 0.4401301145553589}

Sentence: „Книгата беше добро напишана, но не ме остави со некој посебен впечаток.“
Sentiment: {'label': '3 stars', 'score': 0.5224579572677612}
```

Fig.8. Some other sentences on Macedonian

It is notable that comparing the sentences with the English meaning and Macedonian meaning the model is doing good classification and the results are approximately the same Fig.8.

The results of accuracy depend on how well the model is trained to recognize the characters and the meaning of the sentences.

2) *Without punctuation marks*

Already we mentioned how difficult can be reading of the text without punctuation marks for humans but also for the models. If we are not sending the corresponding data, the models can bring decisions in the wrong way.

```
PS C:\Users\Aneta\Desktop\Hugging Face> python .\test3.py
Sentence: „Оваа книга беше навистина инспиративна и ја препорачувам на секого“
Sentiment: {'label': '5 stars', 'score': 0.2559511959552765}

Sentence: „Не ми се допадна книгата приказната беше премногу досадна и предвидлива“
Sentiment: {'label': '2 stars', 'score': 0.3717970848083496}

Sentence: „Книгата беше добро напишана но не ме остави со некој посебен впечаток“
Sentiment: {'label': '3 stars', 'score': 0.4831456243991852}
```

Fig.9. Simple sentences in Macedonian language

Due to the brevity of the sentences here we can see that the model behaves as expected and there are small deviations in percentages, compared to when punctuation is used Fig.9.

VI. Utalization of Power Automate and AI Connectors

In this section we will explore the synergy between the services and how utilization of AI connectors can enhance productivity and reduce human errors. There are many areas of usage as decision making, sentiment analysis of customer feedback or email responses in automated way, document processing for different organizations, integration with other services and workflow customizations.

It is used model for sentiment analysis, Fig.10., with sending the same example set of data as was tested with the Hugging Face model.

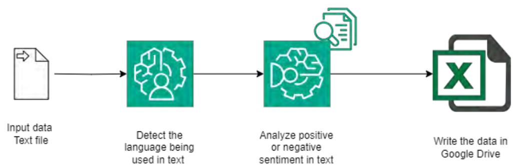

Fig.10. Used AI model in Power Automate flow

Power Automate has many features including AI Builder utilization. With the AI builder there are a lot of capabilities that can be achieved, such as recognition of images, text classification s, automatically filling documents, sending approval messages etc.

In the following part we will focus on the results from the analysis in testing with the builder connector, where we will conclude what are the differences.

A. *Semanic meaning and sentiment analize of the sentences in English*

1) *With punctuation marks*

Utilization of the punctuation marks and additional emojis in Power Automate connectors are having results as the human will give while reading the sentences. That we can see on the bellow Fig.11., the model with confidence of approximately

80%, that is high level of confidence of the model – bring decision that the sentiment of the meaning is negative.

Fig.11. Sentiment analysis with included punctuation

2) *Without punctuation marks*

An interesting comparison can be seen in the analysis of a sentence with and without punctuation marks. When punctuation marks were used, the model determined that the sentiment was negative, with a confidence score of 80%. However, using the same sentence without punctuation marks yielded completely different results: the model classified the sentiment as positive, but with a confidence score of around 49%.

This example clearly demonstrates how changes in sentence structure and the inclusion of additional characters can significantly impact the model's confidence score. The tokenization of sentences and the separation of words, as well as punctuation marks, are crucial factors in the model's final decision-making process.

B. Semantic meaning and sentiment analize of the sentences in Macedonian

Unfortunately, the model in Power Automate didn't support the Macedonian language and we couldn't test the collected data on it. In addition, we are providing which languages are supported by the AI Builder Fig.12.

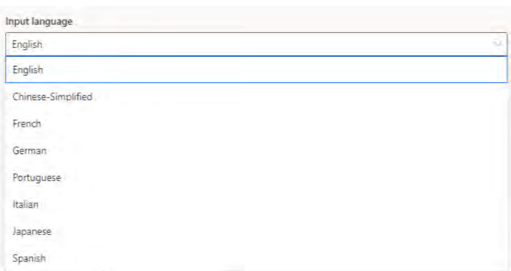

Fig. 12. Supported languages by PA

VII. Comparative Sentiment Analysis From Utilization The Both Models

Based on the results that were accumulated from the separate analyzes on the input text data in Hugging face model and Power Automate model we detected various end parameters. These results will be used to visualize the differences and statistics from the model comparisons.

A. Comparation results between the models for sentences in English

In Power Automate and Hugging face for the same data that we tested we got the following results from Fig.13. for

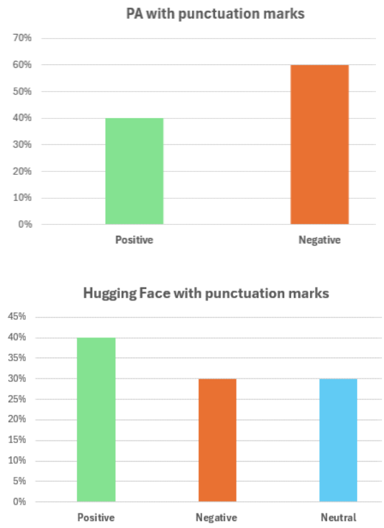

Fig.13. Results with punctuation marks

The data that was selected for testing in both models without punctuation marks give the bellow results Fig.14:

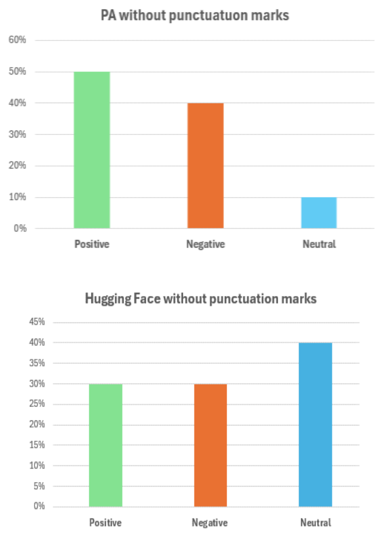

Fig.14. Results without punctuation marks

Statistics can point out the main difference between the fact when some special characters are used or not. The metrics show how the confidence of the models can change if the prompt that is sent is not the same, even if the actual meaning of the sentence is same.

B. Visualisation of the results for the text in Macedonian language from Hugging Face

Below on Fig.16. is shown while utilization of Hugging Face model, the percentage of confident from the model is changing from positive 38% with punctuation marks to 30% without them. Devise for the negative from 31% it is increasing to 40 %.

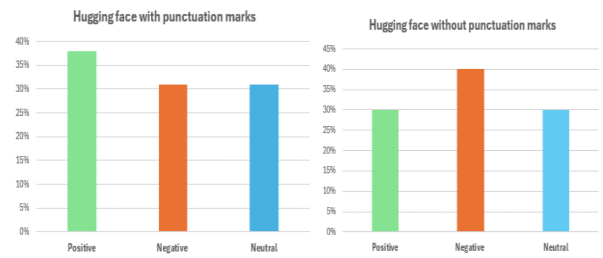

Fig.16. Text with/without punctuation in Macedonian language

VIII. Conclusion

Semantic meaning of the words/sentences is crucial for effective communication, allowing us to convey and understand ideas accurately. In the realm of natural language processing (NLP), it involves tasks like named entity recognition, sentiment analysis, and machine translation, which rely on understanding the underlying meaning of the text to provide accurate and relevant outputs.

This paper focuses on the reliability of text sentiment models and the accuracy of information processed by bots. The analysis demonstrates that small changes in text, such as adding or removing punctuation marks, can yield different results across various models. This highlights the significant impact of AI and raises several important questions:

- How can we determine if our chosen model is the right one?
- Can we fully trust the analysis provided by AI models?

While AI models have made significant growth, several factors can influence of their analysis: data quality, model testing, context and nuance. The semantic analysis conducted on both models reveals that their results can vary, prompting further inquiry into the reliability. When some organization decides to integrate an AI model into an organization, it is crucial to thoroughly test the model with various scenarios to prevent future issues with production data. Human oversight can catch errors that AI might miss and provide a deeper understanding of complex scenarios.

In conclusion, even if AI models are strong tools, it is wise to proceed carefully when analyzing them and to support their conclusions with thorough testing, continuous assessment, and human expertise.

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Optimizing Sensor Configuration on OCOsense for Accurate Detection of Facial Gestures

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***Abstract*—Understanding emotional states from facial expressions is of crucial role in many domains from mental health monitoring and diagnosis to assistive technologies and human-machine interaction. The smart glasses OCOsense™ equipped with novel optomiography (OMG) sensors can gather valuable data for the facial expressions and the real-time analysis could provide valuable insight into the human behaviour and well-being. However the use of multiple such sensors limits the practical usage time of these glasses up to 3 hours. This research aims to identify which sensors bring the most relevant data for recognizing group of facial gestures, and thereby extend the battery life. The analysis for finding the most relevant sensors will be done by training several Random Forest models with different sensor combinations and comparison of their performance metrics. We concluded that a seven-sensor combination meets our criteria for achieving these objectives, giving accuracy of 84.67% and prolonging the battery life up to 6 hours.**

***Index Terms*—smart glasses, facial expressions, high power consumption, relevant sensors, Random Forest**

I. Introduction

Facial expressions serve as a universal language of emotion and are crucial part of nonverbal communication, helping individuals to interpret and respond to emotions of others [1]. Wearable technologies varying from hand-worn devices such as smart watches, jewelry items like smart rings to head-worn devices, like earables and smart eyewear are a powerful tool for providing insight into understanding human behaviour and well being. Such wearable device are the smart glasses OCOsense™, which use novel method for real time tracking face activations. They are equipped with 13 different sensors, including 12 miniaturized navigation and proximity optomyography sensors (OMG) and 1 inertial measurement unit, which we excluded from our study. The OMG sensors are optical non-contact sensors measuring facial skin movements. [2] [3] However using multiple such sensors exhausts the battery life, providing only from 2 to 3 hours usage time. In our study, we perform in depth technical analysis and validation of the glasses for recognizing facial expressions including smile, frown, eyebrow raise, squeezed eyes and winks. We focus on exploring which sensor combination provides high recognition accuracy while extending the battery life of the glasses.

II. Dataset / Sensors

A. *OCOsense™ smart glasses*

For this study we use OCOsense™ smart glasses. They are equipped with 6 OCO™ sensors, a 9 axis IMU and altimeter. They use two LiPo batteries of 220mAh, resulting in 440mAh [1].

The OCO™ sensors, patented by Emteq Labs, use a novel optical non-contact approach, optomyography (OMG), to measure skin movement that results from underlying myogenic activity. The OCO™ sensors consist of combination of two sensors: (i) an optical navigation sensor, measuring the relative movement on the skin's surface in two dimensions X and Y; and (ii) an optical proximity sensor, measuring the distance of the skin from the sensor, Z dimension [2].

These sensors are positioned within the frame of the OCOsense™ glasses, so that they cover facial muscles groups associated with affective changes. The sensor positions are over the frontalis muscle (on both sides of the forehead), zygomaticus major muscle (left and right side of the cheeks), and the left and right temples. Fig. 1 shows the OCOsense™ glasses with the respective sensor placements [2].

Fig. 1: Positions of the OCO™ sensors on the OCOsense™ glasses

OCO™ sensors are power-efficient, consuming between 37-68mW, with navigation sensors consuming more power than proximity sensors. They are sampled at 50Hz and streamed via Bluetooth low energy (BLE) to a mobile device or tablet [2].

B. Dataset

For this study we used dataset with data collected from 20 participants, 12 females and 8 males, with age range between 19 and 24 years. During the data collection, the participants were asked to perform three repetitions of the three categories of facial expressions: (i) forced short maximal intensity expressions (including smile, frown, eyebrow raise, squeezed eyes); (ii) eyes gestures (including left wink, right wink and hard blink); (iii) lips gestures (including half left smile and half right smile). The participants held neutral facial expression between each posed expression. On Fig. 2 is shown the distribution of the facial expressions in a dataset.

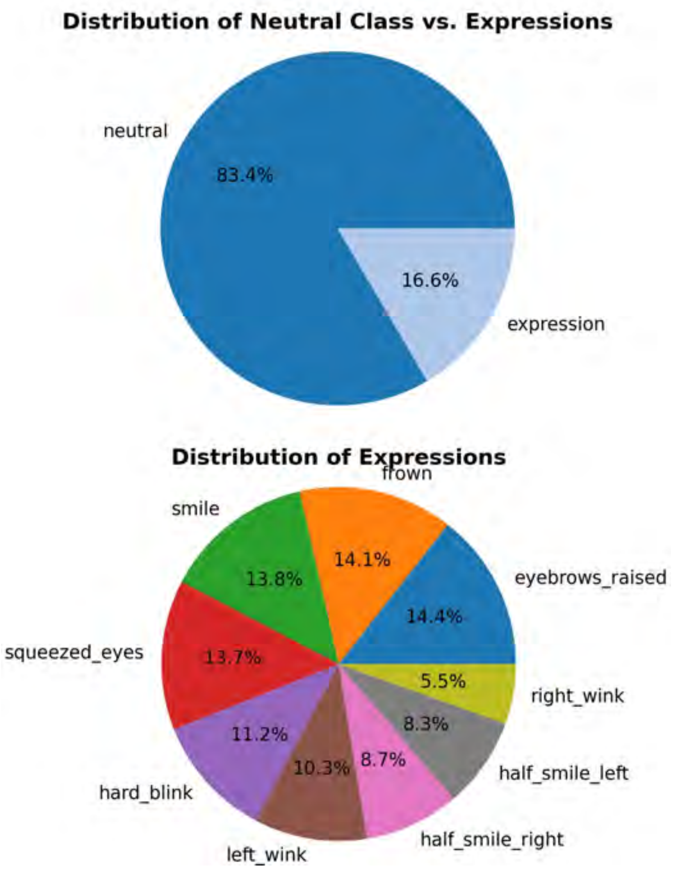

Fig. 2:
Distributions of Facial Expression Classes in the Dataset

C. Signal Analysis for Facial Expressions

Sample visualization of the sensor data with regards to the classes is shown on Fig. 3. After inspecting the data visualization, several distinct patterns appeared for each gesture:

1) Smile: As expected, the sensors located over both sides of the cheeks catch significantly higher signals in vertical direction and some noticeable patterns in horizontal direction. Therefore most relevant sensors for smile would be navigation sensors and proximity sensors on both cheeks. For the half smiles, notable sensor responses are recorded by only the left or the right side sensors on the cheeks, respectively.

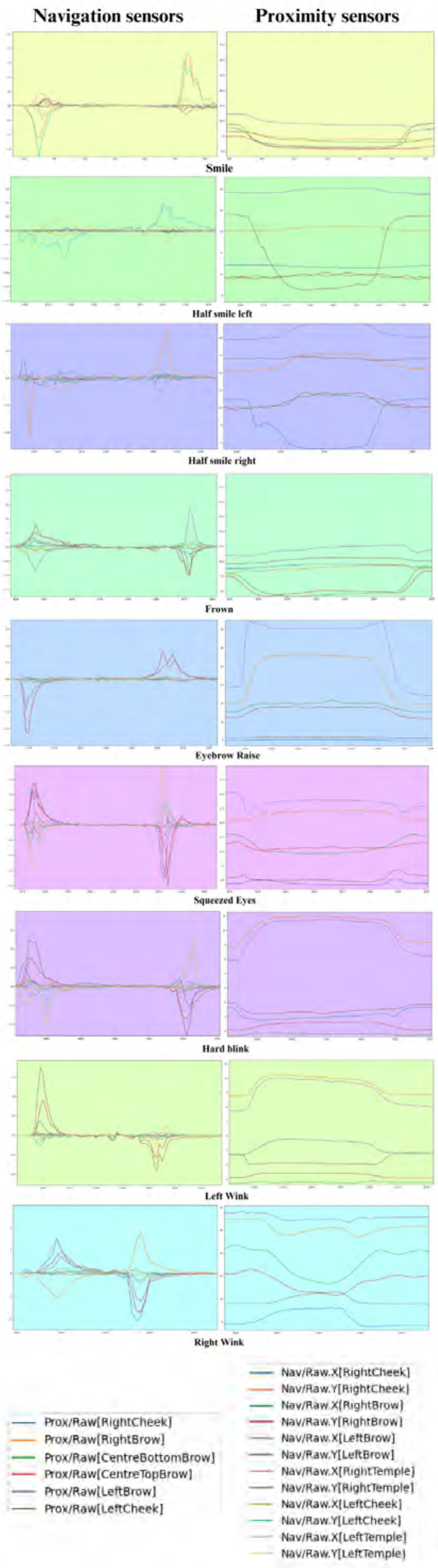

Fig. 3: Visualization of Sensor Signals representing performed Facial Expressions

2) Frown: The sensors positioned above the eyebrows and on both sides of the forehead, show significant peaks in the signals in horizontal axis. The most relevant sensors for this gesture are the navigation and proximity sensors around the forehead.

3) Eyebrow raise: Here we have prominent variations in the vertical direction around the eyebrows region. Most relevant sensors are again the proximity and navigation sensors on the forehead.

4) Squeezed eyes: We have noticeable changes on both X and Y-axis around the cheeks and eyebrows region. In this case, navigation and proximity sensors on the brows and cheeks are most relevant.

5) Winks: For the winks, determining the most responsive sensors can be visually complex, as it varies by individual. Significant sensor readings may appear on the X- and Y-axes from sensors located on the cheeks, Y-axis measurements from sensors near the eyebrows, or X-axis readings from sensors positioned near the temples. This variation highlights the personalized nature of facial movements during a wink. While for the hard blink, the navigation sensors around the eyebrows capture the most significant data.

III. Methodology

A. Preprocessing

The raw sensor data went under preprocessing which included re-labeling, filtering, standardization, segmentation and feature extraction [4]. The first step was manual relabelling because the signals were time-shifted relative to the actual moment when the participants made the expressions, due to their reaction time. For our study, we took the data only from the navigation and proximity sensors. Then a second-order Butterworth low-pass filter [5] with cut-off frequency of 5Hz was applied to the obtained signals. The purpose of the filtering was to achieve greater stability of the signals by filtering the noise and lowering the variations in the signals between different participants. Next, the data was standardized using Standard Scaler [6]. After standardization, based on the results from the experiments done in [4], the data underwent window segmentation, with window size of 15 samples, equivalent to 300 milliseconds.

After the segmentation, 7 statistical features per sensor were extracted: mean, standard deviation, minimum, maximum, range, interquartile range and root mean square [7]. This resulted in 126 extracted features.

B. Correlation between sensors

The correlation matrix between the sensor's data using mean feature is given on Fig. 4.

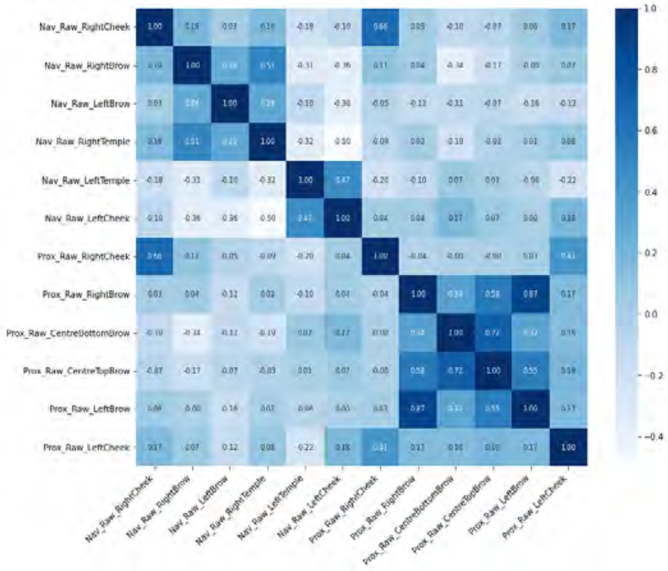

Fig. 4: Correlation matrix between sensor data

After analyzing the correlation matrix, several conclusions were be derived. The high positive correlation present between the proximity sensors on the left and right eyebrow and between the sensors placed between the eyebrows suggest synchronized movements most likely due to symmetric facial expressions. However besides the high correlation between the sensors on the eyebrows, they should be retained since they are critical for distinguishing the left and right wink. Moderate positive correlation is also present between sensors on the temples and between those on both left and right temples and on the eyebrows. Weak correlation is present between the navigation sensor on the right cheek and nearly all other sensors, reinforcing the need of keeping this sensor. A negative correlation such as that observed between the navigation sensors on the left cheek and on right temple and on the eyebrows suggest opposite movements in those areas while making the gestures.

C. Model Training and Evaluation

The features dataset was used as an input for training 5 classification models. The idea was to identify which model handles the sensor data most effectively and therefore performs effective classification. These models were used: Random Forest [8], XGBoost [9], Decision Tree [10], Support Vector Machines (SVM) [11] and K-Nearest Neighbours [12]. Then performance metrics were calculated including: accuracy, precision, recall and F1 score. The models were trained using leave-one-out cross validation with 20 folds, where each fold represents data of one person. However, the test set in each fold represents the data of only one person (a different person's data each fold), whereas the training set is the data from the remaining 19 people. The average performance was measured across all 20 folds. This evaluation approach is more reliable than the ones that use the same person's data for training and testing. Using the same person's data would give overly optimistic results if the intended use of the model is to classify the gestures of previously unseen data [13]. The labelling for the gestures is given on Table I.

The performance review of the trained models is shown in Table II.

Based on the evaluation metrics, Random Forest stands out as the most effective classifier, with 84.69% accuracy, 84.99%

TABLE I: Label Encoding

Label	**Encoded Label**
left_wink	0
right_wink	1
hard_blink	2
half_smile_left	3
half_smile_right	4
smile	5
frown	6
eyebrows_raised	7
squeezed_eyes	8

TABLE II: Performance Metrics of the Trained Models

Model	Accuracy	Precision	Recall	F1 Score
RandomForest	0.8469	0.8499	0.8438	0.8339
XGBoost	0.8325	0.8491	0.8316	0.8179
DecisionTree	0.6505	0.6609	0.6493	0.6346
SVC	0.8385	0.8413	0.8327	0.8246
KNeighbors	0.7561	0.7606	0.7528	0.7334

precision, 84.38% recall, and 83.39% F1 score. Support Vector Machines and XGBoost also demonstrated competitive performance while Decision Tree and K-nearest Neighbours have lower overall performance across all metrics. This means ensemble methods handle the nature of data better.

Next, a hyperparameter optimization was done on the Random Forest model using manually selected number of estimators and depths. The results from this experiment are shown on III.

TABLE III: Hyperparameter Optimization Results for Random Forest Model

Estimators	Max depth	Accuracy	Precision	Recall
10	NaN	0.78	0.79	0.78
10	5.0	0.70	0.72	0.69
10	7.0	0.76	0.77	0.75
25	NaN	0.83	0.83	0.82
25	5.0	0.73	0.77	0.73
25	7.0	0.78	0.79	0.77
50	NaN	0.83	0.84	0.83
50	5.0	0.74	0.77	0.73
50	7.0	0.79	0.80	0.78
75	NaN	0.84	0.85	0.84
75	5.0	0.75	0.78	0.74
75	7.0	0.79	0.81	0.79

This experiment showed that the default Random Forest model (with 100 estimators and not selected maximum depth) outperforms the hyperparameter optimized models. The classification report (a) and confusion matrix (b) of the winning Random Forest model with default parameters are shown on Table IV.

The confsuion matrix reveals overall good classification performance of the model for each gesture, nevertheless with notable misclassifications between the half smiles and squeezed eyes and raised eyebrows.

Next, we will train Random Forest models with different sensor combination data. We will use mean accuracy as an evaluation metric for the quality of the classification and therefore determining the best sensor combination.

TABLE IV: Performance review of Default Random Forest Model

	precision	recall	f1-score	support
0	0.92	0.97	0.95	970
1	0.88	0.87	0.87	1005
2	0.87	0.88	0.87	1014
3	0.90	0.91	0.91	974
4	0.71	0.73	0.72	983
5	0.83	0.77	0.80	775
6	0.80	0.74	0.77	685
7	0.88	0.95	0.91	982
8	0.80	0.76	0.78	981
accuracy			0.85	8369
macro avg	0.84	0.84	0.84	8369
weighted avg	0.85	0.85	0.85	8369

(a) Classification Report

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	940	15	2	0	0	6	5	0	2
1	15	872	7	0	36	27	9	39	0
2	2	16	891	2	7	51	11	34	0
3	8	8	2	890	9	2	46	0	9
4	12	23	7	30	714	7	36	6	148
5	20	20	73	0	16	599	3	31	13
6	16	30	10	45	41	7	505	16	15
7	0	3	17	4	5	23	1	928	1
8	5	7	19	13	174	3	13	0	747

(b) Confusion Matrix

D. Sensor Combinations

Next we will examine the trade-offs between the performance of the glasses and the sensors, their number and type. A brute force (exhaustive) search will be performed to analyse all possible 4095 combinations of the sensors.

Based on the visualization analysis, the correlation matrix and more expressiveness on the left side of the face [14], four hypotheses are proposed:

- navigation sensors will give more relevant data than proximity sensors

- 6 would be an optimal number of sensors to achieve accuracy approximately 80%

- the sensors on the left side to be more relevant than those placed on the right side of the face

- there are no significant patterns or variations appearing on the signals from the proximity sensor placed on the center top brow.

The maximum accuracies from the trained Random Forest models with different number of used sensors are given on the bar plot on Fig.5.

As we increase the number of sensors from 1 to 7, we observe a consistent enhancement of the accuracy, while from 7 to 12, there are no significant improvements. The highest accuracy of 85.37% was achieved with 9 sensors combination (highlighted in red on the bar plot). This combination included 5 navigation sensors (for both temples, both cheeks and right brow) and 4 proximity sensors (for both cheeks, right brow and centre bottom brow).

However the second best accuracy score achieved with 7 sensor combination (marked in green on the bar plot) (84.67%) is close enough to the one with the 9 sensors. The overall

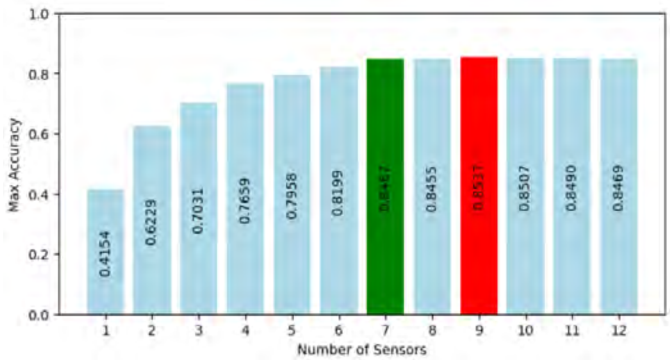

Fig. 5: Bar Plot for Accuracies for Different Numbers of Sensors

performance characteristics of this model is given on Table V. The default and the 7 sensors Random Forest models exhibit nearly equivalent performance in classification.

TABLE V: Performance of 7 sensors Random Forest Model

	precision	recall	f1-score	support
0	0.89	0.96	0.92	970
1	0.89	0.88	0.88	1005
2	0.85	0.88	0.86	1014
3	0.90	0.92	0.91	974
4	0.71	0.68	0.69	983
5	0.85	0.82	0.84	775
6	0.82	0.74	0.78	685
7	0.90	0.94	0.92	982
8	0.77	0.76	0.76	981
accuracy			0.84	8369
macro avg	0.84	0.84	0.84	8369
weighted avg	0.84	0.84	0.84	8369

(a) Classification Report

	0	1	2	3	4	5	6	7	8
0	929	12	4	8	0	8	9	0	0
1	34	882	10	0	30	16	3	29	1
2	4	20	890	7	12	49	9	18	5
3	12	9	4	897	6	0	30	0	16
4	15	25	19	23	664	13	36	11	177
5	20	13	61	2	8	636	4	26	5
6	17	24	14	55	28	2	507	16	22
7	1	5	21	0	6	20	8	921	0
8	8	6	22	7	179	4	10	0	745

(b) Confusion Matrix

Consequently for power efficiency, we propose using the 7 sensor combination that includes 3 navigation sensors (on both temples and left cheek) and 4 proximity sensors (on both cheeks, center bottom brow and right brow).

IV. Conclusion

In this study we focused on identifying the most relevant sensors to optimize the battery life of the smart glasses OCOsense™ without compromising the accuracy of facial expression recognition. Through visualization and machine learning model training using Random Forest, we found out that a combination of 7 sensors achieved a high accuracy of 84.67%. Therefore, we propose employing the seven-sensor combination, which includes three navigation sensors (located on both temples and the left cheek) and four proximity sensors (located on both cheeks, the center bottom brow and the right brow). This optimization strategy will preserve high accuracy rate for facial expression recognition and extend the operational lifespan of OCOsense™ glasses for up to 6 hours of usage.

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A System for Real-Time Voice Control of Robots in Macedonian

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***Abstract*—Verbal communication has always been the fastest and most convenient way of exchanging information. Due to these advantages, technological advancements have been made for using verbal communication for human-device interaction using voice control systems, or Human-Machine Interfaces (HMIs) or Robotic User Interface (RUIs). These systems are based on the use of Artificial Intelligence (AI), i.e. Machine Learning (ML) to perform Automatic speech recognition (ASR). We present a prototype system for voice control of robotic devices in Macedonian. The central building block of our system is the ASR module based on Convolutional Neural Networks (CNNs). The dataset used for training and evaluation of the module is custom made and contains short voice commands in Macedonian. We present experimental results obtained using different CNN architectures, as well as different speech features: raw audio, Mel-Scaled Spectrograms, Mel-Frequency Cepstral Coefficients (MFCCs) and Wavelet Scalograms. These were evaluated in multiple scenarios. The system also comprises an audio input module, a voice activity detection module, a feature extraction module and a robot control module. The performance of the system was tested both using our collected database and in real-time by deploying trained models on a mobile robotic device and controlling it via voice commands. The results show that the proposed system successfully performs the task of voice control of a robotic device using short commands in Macedonian, when the speaker and the environment match the training data.**

***Index Terms*—Automatic Speech Recognition (ASR), Voice Control, Robotic Devices, Human-Machine Interface, Real-Time**

I. INTRODUCTION

Technology now dominates interaction, moving from manual to automated methods due to its efficiency and accuracy. Voice control systems, known as Human-Machine Interfaces (HMIs), use voice commands to operate devices, reducing the need for manual input and specialized training for operating with them [9][10].

Voice control systems are powered by Artificial Intelligence (AI), specifically through Machine Learning (ML) and Deep Learning (DL) algorithms. These algorithms are adapted to perform the task of Automatic speech recognition (ASR) on a limited set of speech commands. ASR is a subfield of AI [7] [23] and it performs the task of conversion of voice sequences or speech into written form or text. Its use empowers the development of human speaking abilities and speech understanding abilities on artificial devices. Furthermore, ASR serves as a key interface in human-robot interactions. [8] [11].

Creating an ASR system is challenging, especially for tightly localized languages. They convert speech to text using two main approaches:

- Traditional Hybrid approach based on Hidden Markov models and Gaussian mixture models [18] [19] [21] [22],
- Deep Learning approach based on Machine Learning and Deep Learning algorithms.

Speech is a time-varying audio signal influenced by factors such as pronunciation, speed, and volume, which complicates its storage, processing, and feature extraction [24] [25]. Variability among speakers, including differences in accent and speaking style, as well as acoustic conditions like background noise and interference, further complicate the task. The primary challenge is to collect and prepare a diverse dataset that accurately represents various environments and speaker characteristics. A comprehensive and varied dataset is crucial for developing a robust ASR system capable of performing well in different settings.

ASR is essential for many applications [12]. It enhances the accessibility for individuals with disabilities by converting spoken language into text, boosts efficiency in transcription, customer support, and voice-controlled devices, and supports hands-free operation in contexts like driving or cooking. ASR also aids multilingual communication and data analysis, making it a key technology for virtual assistants and automation, and improves experiences in education, healthcare, and content search.

Although ASR technology has advanced significantly since the mid-20th century, development for smaller languages like Macedonian remains limited. While Google Cloud Speech-to-Text supports Macedonian, there are few voice control systems for this language. This paper introduces a real-time voice control system for a SparkFun JetBot mobile robot, utilizing Macedonian commands and tested on the NVIDIA Jetson Nano V3. The robot assembly is shown in Fig. 1.

Fig. 1. The robot assembly controlled by voice commands

II. History of ASR for Macedonian language

Despite the limited prevalence of the Macedonian language, researcher's interest in ASR is evident. The lack of sufficient public datasets makes the task more challenging but not impossible. There have been a few notable attempts to develop Macedonian ASR systems. These contributions collectively represent significant progress in the field of ASR for the Macedonian language.

In 1986 [13], Stevo Bozinovski noted early progress in controlling robots with voice commands through the Japanese-built Wabot-1. While the Japanese team described the robot's construction, they did not explain how signals were processed. The AIR project later provided the first detailed description of speech processing for robot control in 1986 [14], with its findings published in 1989 [15]. This made Macedonian the second language, after Japanese, to be understood by robots.

Kraljevski et al. developed a system for recognizing spoken numbers in Macedonian, focusing on isolated, single-speaker digit recognition [1]. Using a small speech corpus of the first ten digits and a hybrid model of Hidden Markov Models (HMM) and artificial neural networks, their system achieved 85% accuracy. This system found applications in security, military, communications, and voice dialing. They later expanded their work to create an Interactive Voice Response (IVR) system for automated telephone interactions [2]. This IVR system, which recognized digits from 0-9 and was designed to be speaker-independent, achieved 80% accuracy with unknown speakers and 100% with familiar ones. It utilized the Dynamic Time Warping (DTW) algorithm to account for speech variability.

Matovski et al. developed a Macedonian speech recognition system for smart home applications, utilizing the Dynamic Time Warping (DTW) algorithm [5]. The system was designed to recognize isolated commands, and ten specific words related to household devices. They conducted two experiments: an offline test comparing words spoken by different speakers and an online test using a Raspberry Pi with a smaller dataset. The system achieved 95% accuracy in recognizing commands from previously unknown speakers.

Gerazov significantly advanced Macedonian ASR systems, beginning with a digit recognition system using the HTK toolkit [16] and HMMs with MFCC features. This system achieved 100% accuracy in recognizing digits from a single speaker [3]. He later expanded the system to include 36 words for a voice dialing application, covering categories such as names and commands. This expanded system achieved nearly 99% accuracy, even in noisy environments [17]. Additionally, Gerazov developed a speaker-independent ASR system with a 188-word dictionary, reaching 94.52% accuracy in recognizing pure speech [4].

Mitrovski et al. developed a real-time transcription system for Macedonian news using the Kaldi toolkit [6][20]. This system achieved low latency and accurately transcribed news broadcasts. They tested various acoustic models on a dataset of news audio recordings and their transcriptions, resulting in faster and more efficient text annotation compared to manual methods.

III. Dataset

Macedonian is a low-resourced language with very limited speech datasets. To build a Voice Control System, a dataset was needed with specific commands spoken by multiple speakers in various acoustic environments. The final dataset included approximately 32 hours of speech commands and about 22 hours of background noise. The data collection process involved two distinct phases: an initial recording phase and an augmentation phase. The initial phase, conducted during the RoboMac 2023 competition for the ChatBot category, generated the base dataset. The subsequent augmentation phase expanded this dataset to improve its size and diversity, enhancing system reliability. Furthermore, recordings with background noise were captured at various locations to simulate real-world conditions and refine the system's ability to differentiate between commands and non-commands.

The dataset contained recordings from seven native female speakers. Each recording contained 10 commands, which were the five basic commands but multiplied and shuffled in different orders. The 5 basic commands are: go (оди /'ɔdi/), left (лево /'lɛvɔ/), right (десно /'dɛsnɔ/), backward (назад /'nazad/), and stop (стоп /'stɔp/). All sequences were recorded in four distinct acoustic environments: an empty classroom with reverberation, a soundproof speech studio with no reverberation, a semi crowded room with background noise and a large conference hall, applying differing levels of intensity and speed of pronunciation. The recordings were made with the speaker standing and a microphone placed on a table, as the robot is intended to be controlled from a standing position while remaining on the ground.

To prepare the dataset for training and evaluation, several preprocessing steps were applied. All recordings were converted to ".WAV" format, and any discrepancies in sampling rates were resolved by resampling all files to 44,100 Hz. The audio sequences were then segmented into smaller recordings, each containing a single command with a maximum duration of one second. A custom algorithm was used for this segmentation. Lastly, the dataset was augmented. This augmentation process included adding background noise, simulating reverberation, adjusting gain, and applying time-stretching to the original recordings. This technique was used to artificially increase the size and diversity of the dataset.

The augmented dataset consisted of 175,160 recordings. This included 104,500 audio recordings with single commands, where 9,500 were original recordings and 95,000 were augmented versions. The remaining 70,660 recordings contained random background noise, making up two-thirds of the total single command recordings. This larger amount of noise data was necessary to capture a wider variety of real-world conditions, helping the model to better identify and filter out background noise. The spread of the augmented dataset is given in Table 1. The original dataset, before augmentation, contained 15,833 recordings, including 9,500 single command recordings and 6,333 background noise recordings, as given in Table 2. Table 3 details the number of speakers, the total duration of command and noise recordings, and the overall length of the datasets.

TABLE I. SPREAD OF AUGMENTED DATASET

Structure of augmented dataset	
Original commands	9 500
Commands with added reverberation	9 500
Commands with added background noise	28 500
Commands that have their sound amplified	9 500
Commands that have their sound reduced	9 500
Speeded up commands	9 500
Slowed down commands	9 500
Commands that have their sound amplified and are speeded up	9 500
Commands that have their sound reduced and are slowed down	9 500
Random background noise	70 660
Total	175 160

TABLE II. SPREAD OF ORIGINAL DATASET

Structure of original (basic) dataset	
Original commands	9 500
Random background noise	6 333
Total	15 833

TABLE III. ORIGINAL VS AUGMENTED DATASET SUMMARY

	Speakers count	**Speech duration**	**Rand. noise duration**	**Total duration**
Original dataset	7	2 h 54 min	1 h 56 min	4 h 50 min
Augmented dataset	7	31 h 56 min	21 h 35 min	53 h 31 min

IV. VOICE CONTROL (ASR) MODULE

The voice control system described in this paper consists of several interconnected modules:

- Audio input module,
- Voice activity detection module,
- Feature extraction module,
- Command recognition module,
- Robotic control module.

The system starts by capturing audio signals through a microphone, recorded in one-second intervals at a 44,100 Hz sampling rate and stored as 16-bit value arrays. A speech detection module then processes the audio to identify speech segments, which are sent to the feature extraction module. Here, they are converted into speech features like Mel-Scaled Spectrograms, Wavelet Scalograms, or MFCCs, but this step is omitted for systems based on a 1D CNN, where only time normalization occurs.

For 2D CNN systems, all extracted speech features are preprocessed to match the model's input format and saved as 400x400 pixel grayscale images. On the other hand, for 1D CNN architectures, signals are standardized to a fixed duration. These preprocessed features or raw signals are then passed to the command recognition module, where a pre-trained model predicts the command. The recognized command is sent to the robot's control module, triggering movement in the corresponding direction. If background noise is detected, the robot remains stationary. This process runs continuously until stopped via keyboard input. Fig. 2 illustrates the system's control flow and module interactions.

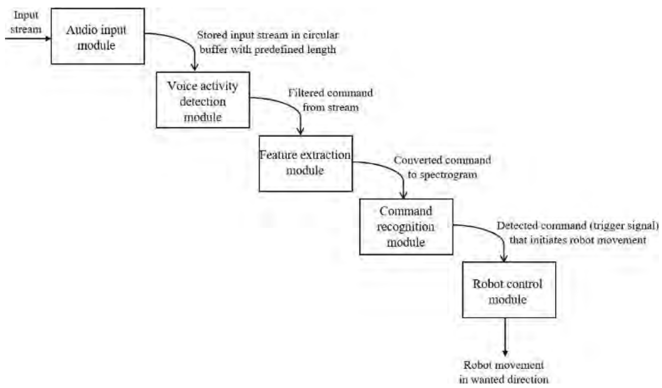

Fig. 2. Voice control system structure

V. SPEECH FETURES

The voice control system described in this paper uses classifiers based on either 1D or 2D CNNs. The 1D CNN expects audio recordings as input, while the 2D CNN requires images.

To convert audio signals into images, a preliminary step of feature extraction is done. This process involves transforming raw speech signals into various speech features, which can be saved as images. Common speech features are:

1. Raw Spectrograms,
2. Mel-Scaled Spectrograms,
3. Mel-Frequency Cepstral Coefficients (MFCCs),
4. Wavelet Scalograms,

In the context of this paper, the speech features utilized are from 2 to 4. Fig. 3 gives a representation of all commands represented as mentioned speech features, except as MFCCs.

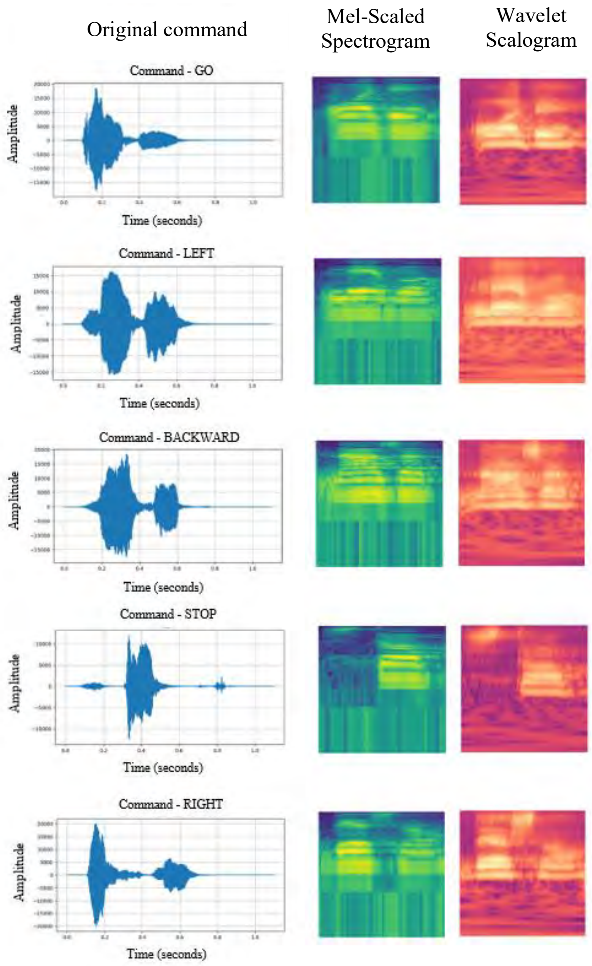

Fig. 3. Commands represented as speech features

VI. COMMAND RECOGNITION (ASR) MODULE

The command recognition module is implemented using both 1D and 2D CNNs, serving as classifiers. This module is divided into two primary blocks: Convolutional Block and Fully Connected Block.

A. 2D Convolutional Neural Network

In the 2D CNN architecture, the Convolutional Block handles feature extraction using 2D kernels of various sizes that move across the input data. This block consists of 4 VGG blocks, each containing two convolutional layers with varying numbers of filters. Every convolutional layer is followed by a ReLU activation function and a batch normalization layer. Max-pooling layers reduce the spatial dimensions of the feature maps by half after each VGG block, except the final one. The dimensionality of the feature maps continues to reduce by 50% with each VGG block. The feature maps from the last VGG block are processed through an average pooling layer, which was experimented with two separate configurations: spatial domain average pooling and channel-wise average pooling. The pooled output is then flattened into a one-dimensional vector, which serves as the input to the Fully Connected Block.

The Fully Connected Block consists of 3 dense layers followed by a Softmax output layer. The Softmax layer produces a probability distribution over the 6 command classes. This 2D CNN architecture processes inputs such as Mel-Scaled Spectrograms, Wavelet Scalograms, and MFCCs.

B. 1D Convolutional Neural Network

In the 1D CNN architecture, the Convolutional Block extracts features using 1D kernels corresponding to the one-dimensional nature of the input data. This block consists of 3 convolutional layers, each with different numbers of filters. Every convolutional layer is followed by a ReLU activation function and a batch normalization layer. After the first two convolutional layers, max-pooling layers reduce the dimensionality of the feature maps, while after the third convolutional layer, spatial average pooling is applied.

The Fully Connected Block in the 1D CNN consists of 3 linear layers and a Softmax classification layer. The Softmax function outputs a vector with 6 elements if background noise records are included in the dataset or 5 elements if not. The 1D CNN architecture processes uniform-length audio recordings.

VII. COMMAND RECOGNITION CLASSIFIER

The training process of the classifier, which gives a model that serves as the core of the ASR module, involves several steps: collecting the dataset, preprocessing the dataset, extracting features from the dataset, generating metadata about the audio files from the dataset, splitting the dataset into train/test subsets, defining classifier architecture, training and testing the classifiers, and comparing and interpreting the obtained results (accuracy graphs, loss graphs, confusion matrices).

Steps 7 and 8 are repeated until a classifier with accuracy that fully meets the requirements and expected results in terms of the performance of the voice control system is obtained. The goal is to develop a classifier that is fully capable of recognizing voice commands in real-time. A visual representation of the implementation flow is shown in Fig. 4.

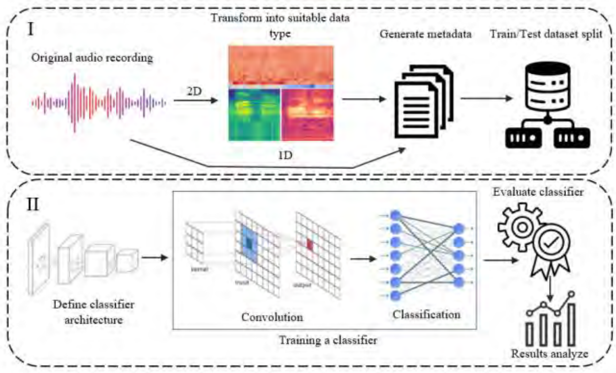

Fig. 4. Flow for implementing command recognition classifier

TABLE IV. RESULTS FROM EVALUATION ON CUSTOM DATASET

<table>
<tr><td rowspan="3">1D CNN</td><td colspan="5">Known speaker</td><td colspan="5">Unknown speaker</td></tr>
<tr><td colspan="3">Original commands recordings, no background noise recordings</td><td colspan="2">Original commands recordings with background noise recordings</td><td colspan="3">Original commands recordings, no background noise recordings</td><td colspan="2">Original commands recordings with background noise recordings</td></tr>
<tr><td colspan="3">99.4 %</td><td colspan="2">87.2 %</td><td colspan="3">90.10 %</td><td colspan="2">63.65 %</td></tr>
<tr><td rowspan="12">2D CNN</td><td colspan="5">Known speaker</td><td colspan="5">Unknown speaker</td></tr>
<tr><td colspan="5">Spatial domain average pooling</td><td colspan="5">Channel domain average pooling</td></tr>
<tr><td colspan="2">Mel Spectrograms</td><td colspan="2">MFCC</td><td>Wavelet Scalograms</td><td colspan="2">Mel Spectrograms</td><td colspan="2">MFCC</td><td>Wavelet Scalograms</td></tr>
<tr><td colspan="2">Batch size</td><td colspan="2">Batch size</td><td>Batch size</td><td colspan="2">Batch size</td><td colspan="2">Batch size</td><td>Batch size</td></tr>
<tr><td>16</td><td>32</td><td>16</td><td>32</td><td>16</td><td>16</td><td>32</td><td>16</td><td>32</td><td>16</td></tr>
<tr><td>99.71 %</td><td>97.55 %</td><td>89.72 %</td><td>98.80 %</td><td>99.51 %</td><td>91.55 %</td><td>95.66 %</td><td>89.00 %</td><td>87.45 %</td><td>93.34 %</td></tr>
<tr><td colspan="5">Spatial domain average pooling</td><td colspan="5">Channel domain average pooling</td></tr>
<tr><td colspan="2">Mel Spectrograms</td><td colspan="2">MFCC</td><td>Wavelet Scalograms</td><td colspan="2">Mel Spectrograms</td><td colspan="2">MFCC</td><td>Wavelet Scalograms</td></tr>
<tr><td colspan="2">Batch size</td><td colspan="2">Batch size</td><td>Batch size</td><td colspan="2">Batch size</td><td colspan="2">Batch size</td><td>Batch size</td></tr>
<tr><td colspan="2">16</td><td colspan="2">16</td><td>16</td><td colspan="2">16</td><td colspan="2">16</td><td>16</td></tr>
<tr><td colspan="2">99.32 %</td><td colspan="2">98.74 %</td><td>99.09 %</td><td colspan="2">89.32 %</td><td colspan="2">88.52 %</td><td>88.95 %</td></tr>
</table>

VIII. EXPERIMENTS

The experiments involved training classifiers using predefined neural network architectures and specially prepared datasets. Training was conducted over multiple epochs, with dataset split into smaller batches to manage GPU memory constraints. Both training and testing were done in batches, with the final prediction being the cumulative result of all batch-level predictions.

A. 1D experiments

The 1D CNN experiments were conducted under two distinct setups. In the first setup, models were trained exclusively on dataset containing clean, original audio recordings, and no background noise recordings. In the second setup, models were trained using a format of the dataset that included original audio recordings mixed with background noise recordings. Testing for both setups was performed on known and unknown speakers. During these experiments, four models were trained over 30 epochs with a batch size of 64. The training duration for each model was approximately 1 hour.

B. 2D experiments

For the 2D CNN experiments, two key techniques for restructuring the convolutional block outputs were applied: spatial averaging and channel averaging of the feature maps. Spatial averaging involved average pooling across the spatial dimensions (height and width) of the feature maps, while channel domain averaging involved pooling across the channel dimension (depth).

These techniques were tested using three different input types of data: Mel-Scaled Spectrograms, MFCCs, and Wavelet Scalograms. All models were trained and tested with a batch size of 16, although initial trials with a batch size of 32 were halted due to GPU memory constraints. Each model underwent 30 epochs of training, with the total process taking approximately 10-11 hours per model. Training and testing were conducted with both known and unknown speakers to assess the model's performance across different speaker conditions.

IX. RESULTS

Model evaluation occurred in two phases: using a custom dataset and in real-time.

A. Evaluation on custom dataset

Accuracy results from the final training epoch are shown in Table 4, categorized by CNN architecture, speaker type, feature type, and pooling technique. The highest accuracy, 99.71%, was achieved by a 2D CNN model trained with Mel-Scaled Spectrograms, a batch size of 16, and spatial averaging of feature maps, tested on known speakers. Models using Mel-Scaled Spectrograms performed best, followed by those using Wavelet Scalograms, while MFCC-based models were least effective. Generally, models performed better with known speakers but still showed strong real-time performance with unknown speakers if trained with sufficient examples.

B. Real-time evaluation

In real-time evaluation, each model was tested with a sequence of 12 words: 10 commands and 2 random words, spoken by a known speaker from the training data. This assessed the model's ability to identify commands and distinguish them from non-commands and background noise. Some models struggled, possibly due to overfitting, underfitting, or data distribution issues. Real-time results are shown in Table 5, with correct predictions in green and incorrect ones in red. Model 18 achieved the highest real-time accuracy at 91.67%, correctly predicting 11 out of 12 words. Accuracy was calculated using Eq. 1:

$$accuracy = ((TP + TN) / ((TP+TN) + (FP + FN))) \cdot 100 \quad (1)$$

where TP is true positives, TN is true negatives, FP is false positives, and FN is false negatives.

CONCLUSION

We developed a Macedonian voice control system for a mobile robot, consisting of audio input, voice activity detection, feature extraction, command recognition, and robot control modules. Key steps included data collection, preprocessing, feature extraction, and training CNN classifiers. Testing revealed that models using Mel-Scaled Spectrograms or Wavelets performed best, with a 2D CNN achieving 99.71% accuracy on familiar speakers when evaluated on custom dataset. In the real-time evaluation, our top model achieved 91.67% accuracy, detecting 11 out of 12 words, demonstrating the system's effectiveness.

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TABLE V. RESULTS FROM EVALUATION IN REAL-TIME

	Left	Left	Backward	Rand. word	Stop	Backward	Right	Rand. word	Go	Stop	Left	Go	Acc.
Model 1													58.3%
Model 2													50 %
Model 3													66.67 %
Model 4													66.67 %
Model 5													66.67 %
Model 6													50 %
Model 7													66.67 %
Model 8													83.33 %
Model 9													0 %
Model 10													0 %
Model 11													0 %
Model 12													16.67 %
Model 13													83.33 %
Model 14													75 %
Model 15													66.67 %
Model 16													75 %
Model 17													33.33 %
Model 18													91.67 %
Model 19													33.33 %
Model 20													25 %

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Optimizing Chewing Rate Estimation: Insights from Sensor Data using OCOsense glasses and Machine Learning

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***Abstract*—Mastication, the initial stage of digestion, is crucial for regulating food intake. This study explores the use of OCOsense smart glasses, equipped with optical sensors, to estimate chewing rates by capturing facial muscle movements. Data from 34 participants consuming different foods (almonds, bananas, cereal bars, and a meal) were collected. The sensor data, sampled at 50 Hz, was processed using the tsfresh library to extract time-series features. Machine learning algorithms, like Random Forest, SVM and K-Nearest Neighbors were applied to these features the results were compared in the search of the most objective and accurate model. The Random Forest regressor was the most effective, achieving an R2 score of 0.89 during a 5-fold Cross-Validation and confirmed the model's robustness, indicating strong predictive performance without overfitting. The findings demonstrate the potential of combining sensor technology with machine learning to monitor chewing behaviour accurately. This approach can significantly contribute to promoting healthier eating habits and improving dietary behaviour, with practical applications in health monitoring and dietary management.**

***Keywords*—chewing rate; machine learning; OCOsense smart glasses**

I. INTRODUCTION

Mastication is the first stage of digestion in most mammals. It is an intermittent rhythmic act in which the tongue, facial, and jaw muscles act in coordination to position the food between the teeth, cut it up, and then prepare it for swallowing [1]. Many studies assert the fact that more extensive chewing generally promotes greater feelings of fullness and temporarily reduces hunger. When oral processing time is increased by prolonged chewing, energy intake is reduced [2]. These conclusions underscore the vital role of mastication in promoting satiety and regulating food intake, which is crucial for leading a healthy lifestyle. By being more mindful and diligent in chewing, individuals can enhance their feelings of fullness and effectively manage their energy intake.

Given the relationship between facial movements and chewing detection, a variety of remote sensing approaches have been proposed recently. Regarding the commercially available smart glasses, that are equipped with stereo speakers and microphones that communicate with smartphones via Bluetooth have been explored for chewing detection [3]. Another approach involves a system that extracts meaningful features from food-eating sounds using signal processing techniques and deep learning models, classifying them into their respective food classes [4]. Both of these techniques rely on microphones for data acquisition. However, the OCOsense smart glasses used for chewing detection in our case differ significantly in that they do not employ a microphone. Instead, they use alternative sensing technologies, offering a non-intrusive and privacy-preserving method for detecting chewing movements, using sensors, which will be further described below and shown in Figure 2 on page 2.

A large number of muscles participate in the movements of the lower jaw. When considering chewing, only four deep muscles of the head are activated. They are: masseter muscle (m. masseter); temporal muscle (m. temporalis); lateral pterygoid muscle (m. pterygoideus lateralis) and medial pterygoid muscle (m. pterygoideus medialis) [5]. These four main muscles (shown on Figure 1 on page 2) of mastication attach to the ramus of the mandible and function to move the jaw (mandible). The cardinal mandibular movements of mastication are elevation, depression, protrusion, retraction, and side to side movement [6]. The mastication muscles, whose main function is chewing, also take part in the food intake, yawning and speech. The force of contraction of these muscles is manifested by pressure between the dental arches. Chewing pressure varies from 20 kg/cm^2 for front teeth and 30-80 kg/cm^2 for healthy lateral teeth. Theoretically, the force of pressure could reach 400 kg/cm^2. This is important due to the fact that the masticatory muscles heavily influence the shaping of the mandible and the maxilla. When the temporalis is activated, it contracts its anterior and middle fibers and assists the rise of the lower jaw. All muscle fibers pass through the opening formed by the zygomatic arch and the lateral side of the skull and converge on the coronoid process of the mandible [5].

All of these movements can be precisely recorded by the sensors embedded in the OCOsense smart glasses. They are positioned over some of the major muscles which are used for mastication. Although the zygomaticus muscle is not entirely included in the mastication process, it presents as a significant factor when detecting chewing. Therefore, we also took into consideration the results which the sensor placed over the zygomaticus muscles supplied.

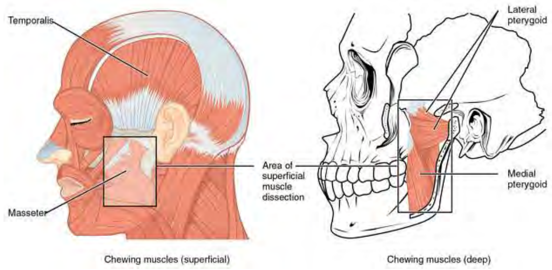

Fig. 1: Mastication muscles

After the data collection and visualization, we utilized the 'tsfresh' library [7] to extract relevant features from the time-series data. Later, the extracted features were organized into a single CSV file and subjected to training and testing across various ML regression models. We employed cross-validation techniques alongside scatter plots and other visualization methods to distinguish the model which yielded the most valuable results. After this, we conducted feature selection and hyperparameter optimization to minimize the Mean Absolute Error (MAE) and augment the R2 Score. Through extensive analysis, we compared the performance of individual models, aiming to showcase the effectiveness of supervised learning techniques in estimating chewing rates. The rest of the paper is organized as follows: Section 2 describes our dataset, Section 3 explores the methodology. Section 4 presents the results, and a comparative analysis of the models' performance. Finally, Section 5 concludes the paper and suggests future directions for research. The insights gained from our data, collected with OCOsense smart glasses, provide valuable input for machine learning algorithms designed to estimate chewing rates and promote safe eating habits. The model demonstrated an overall score of 0.879 (R2-score). This innovative approach highlights the practical applications of our research in improving dietary behaviors, mandible shape and health overall.

II. Dataset

This study was conducted over data collected from 34 applicants using the OCOsense smart glasses. The population consisted of 13 male and 21 female participants within a range of 24 $\pm$ 3.1 years.

The smart glasses are equipped with optical sensors to track the movement of the skin. The glasses utilize two types of sensors:

- Navigation Sensors: Measure the movement of the skin in the X and Y directions
- Proximity Sensors: Measure the movement of the skin in the Z direction

These sensors are placed over the brows, cheeks, and temples and sample data at a rate of 50 Hz meaning that the sensors collect an average of 50 samples per second. They are shown on Figure 2 on page 2. The OCO^{TM} sensors are positioned within the frame of the glasses and are represented by coloured rectangles, each targeting major facial muscles:

- Frontalis (red)
- Zygomaticus (green)
- Corrugator (purple)
- Temples (blue)

Additionally, the glasses are equipped with a 9-axis IMU (Inertial Measurement Unit) and an altimeter, represented in yellow, to provide comprehensive movement and altitude data. We will examine the sensor data in detail in Section III, Subsection III-A.

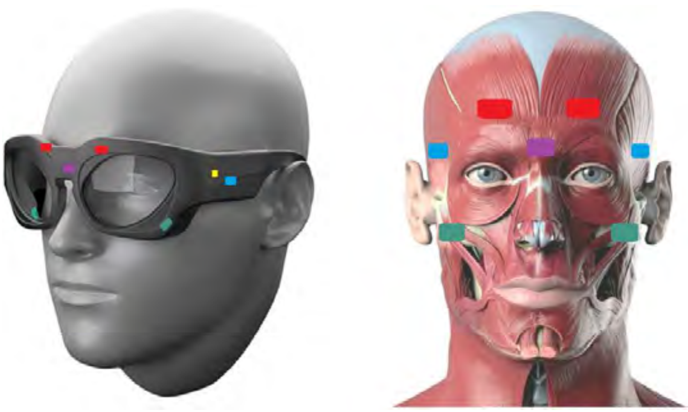

Fig. 2: OCOsense glasses and corresponding sensor placement

1) What kind of data?: For each participant, data is collected on the consumption of three different types of food: almond, banana, and cereal bar. Each type of food is consumed twice—once with chewing exclusively on the left side of the mouth and once with chewing exclusively on the right side of the mouth.

Additionally, for each participant, there is one data record of chewing a carrot, with no specified side for chewing, and one extended data record of consuming a proper lunch meal, such as a portion of chicken steak with rice and a small salad.

This methodology provides the following data for each participant: Almond left and Almond right, Banana left and Banana right, Cereal left and Cereal right, Carrot Rate and Eating. All of which is stored in CSV files containing a time series of sensor outputs.

The complete dataset consists of 8 distinct smaller datasets for each of the 34 participants on average. There are exceptions where one or more of these datasets might be missing for certain participants. These gaps can occur due to momentary conditions during the recording process or specific participants' inability to consume certain foods because of allergies or other obstacles.

In Section III, Subsection III-B, we will discuss combining all these smaller datasets into one comprehensive general dataset.

The dataset was collected in a controlled environment and labelled using a streamlined procedure to ensure consistency and accuracy.

III. Methodology

A. *Sensor data analysis*

In this section, we will delve into a more detailed and visual analysis of the sensor data collected by the OCOsense smart glasses. Our focus will be on understanding the specific information obtained from the navigation and proximity sensors, examining the data's accuracy and reliability, and exploring their response to the movement of the major facial muscles.

For clarity and simplicity, we will narrow our focus to a subset

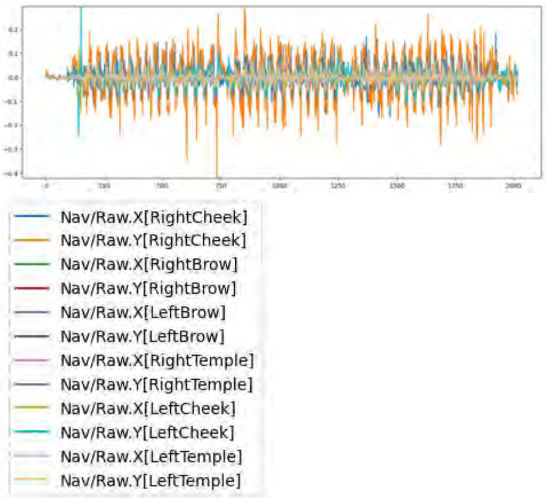

Fig. 3: All the proximity and navigation sensors for one eating instance (chewing an almond on the left side of the mouth)

of the sensors and perform the analysis on data collected from a single randomly selected participant.

Analyzing this plot (Figure 3, Page 3), we anticipate that the most valuable information about the number of chews will be found in the sensors with the highest amplitudes. Specifically, we are looking for sensors that show the largest changes in amplitude with each chew.

Based on our expectations and the evidence from the graphs, we believe that the sensors placed over the cheeks will be significant contributors to our analysis. Therefore, we have narrowed our selection to include only the cheek navigation sensors for better clarity and less cluttered plots. Additionally, we have highlighted the individual chewing intervals, which were labelled by a team that reviewed videos of the participants eating while wearing the glasses. The labelling team's task was to accurately count and label the number of chews per chewing interval (Figure 4, Page 3).

Continuing with the same method of elimination and selection, we focus on the sensors that provide the most information

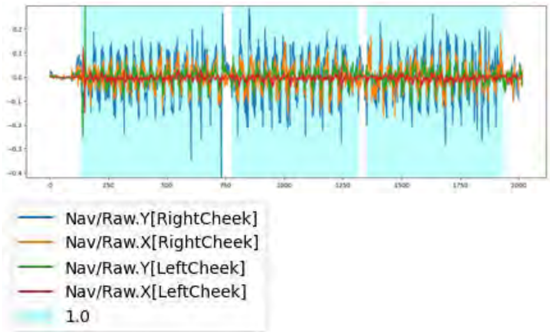

Fig. 4: Cheeks Navigation Sensors (X and Y axis)

about the number of chews. We continue exploring the signals from these sensors individually.

The amplitude of the Right Cheek Y Navigation sensor

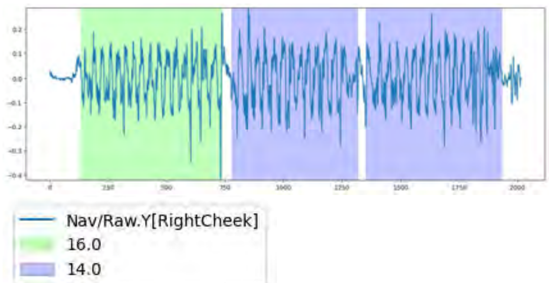

Fig. 5: Only the right cheek Y nav sensor

nears the value 0.1 exactly 16 times in the first interval of eating which is exactly the number of chews that this person performed according to the label (Figure 5, Page 3).

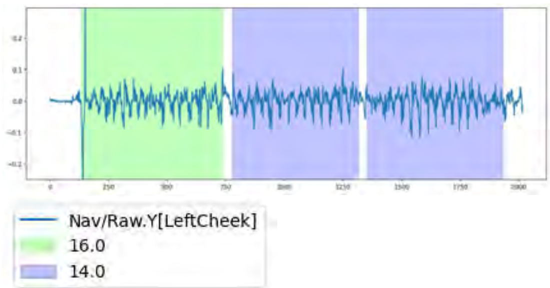

Fig. 6: Only the left cheek Y nav sensor

The amplitude of the Left Cheek Y sensor also shows 16 peaks in the first eating interval, similar to the right cheek sensor. However, it may not offer as precise information compared to the right cheek sensor. Thus, the sensor on the cheek opposite to the side where the applicant is chewing provides clearer information for each chew (Figure 6, Page 3).

B. Handling Time Series and Feature engineering

We used tsfresh, which is a Python package, to automatically extract a great quantity of time series characteristics, so-called features. This choice was motivated by the necessity to analyze a dataset organized chronologically, aligning with the primary characteristic of time series data: its sequential arrangement over time. The tsfresh package includes methods for evaluating and computing a diverse set of features that effortlessly capture the inherent temporal patterns in the data. The decision to extract frequency features was deliberate, aimed at capturing the periodicity or repetitive patterns present in the time series data. Frequency features provide insights into the repetitive behavior within the dataset, particularly in tasks involving periodic events, such as chewing segments in our case. Given the nature of the dataset as time series data, where observations are listed in chronological order, we chose tsfresh as it offered a solution for feature extraction. The features we used for this particular activity were some measures already predefined in the tsfresh.feature_extraction package. We opted for Standard deviation, Mean, Maximum, Minimum, Skewness, Kurtosis, Absolute energy, Normalized complexity invariant distance (CID_DE), Mean absolute change, Mean change, Sum of values, Median, Ratio of values beyond a certain number of standard deviations (r=1), Quantiles (10th, 50th, and 90th percentiles), Aggregated autocorrelation (mean, with a maximum lag of 40), Ratio of value number to time series length. After we executed training with different regressors and feature selection, we realized that the mean, standard deviation, skewness, kurtosis and aggregated autocorrelation (mean, with a maximum lag of 40) have proven to be most beneficial for the machine learning algorithm. That is because of the different propositions these features offer. For example, the mean feature provides a measure of the central tendency of the signal, which represents the average chewing activity over time. Averaging can be also used to set thresholds for detecting deviations that signify chewing events. The standard deviation is useful for filtering out periods of low activity and focusing on segments with higher variability, typically associated with chewing. Skewness and kurtosis can help differentiate between different types of chewing behaviors, and identify sharp, transient events within the signal that are often associated with individual chewing bites, respectively [8]. Lastly, aggregated autocorrelation measures the correlation of the signal with itself over different lags and provides information about repetitive patterns in chewing [9].

When working with time series data, it is crucial to extract some frequency features. For that manner, we made use of the tsfresh.feature_extraction package [7]. Because we work on a dataset with a large number of features, we calculated the fourier entropy [10].

$$H = sum_i(-p_i * log(p_i)) \tag{1}$$

To compute the Fourier entropy, a power-spectral-density of a time series (or portion thereof) is computed. The PSD is normalized to produce a probability-like distribution, and the entropy calculated as shown above in equation 1. The function fft_aggregated from feature_calculators was used in order to generate the spectral centroid (mean) and the variance of the absolute fourier transform spectrum. Chewing typically produces rhythmic movements and sounds within a specific frequency range. The frequency centroid can highlight this range by indicating where the bulk of the signal's energy is concentrated. The frequency variance measures the spread or dispersion of the frequency components around the centroid. During chewing, the variance may show distinct patterns due to the repetitive nature of the action. Low variance might indicate consistent chewing patterns, while high variance might suggest irregular or varied chewing actions. Non-chewing activities may produce different frequency patterns. The centroid and variance can help distinguish chewing from other facial movements or sounds (e.g., talking, drinking). Non-chewing activities might have different centroid values and higher or lower variance compared to chewing activities. Peaks that correspond to chewing cycles can be identified by tracking the frequency centroid and variance over time. We also found it useful to calculate the FFT coefficients, which offer fine-grained information about the presence and amplitude of different frequencies within the signal. Hence, dominant frequencies, that are characteristic of chewing, can be identified. It is also important to mention that FFT coefficients can be used as features for machine learning models, which is our main goal.

C. Model Evaluation and Selection

In practice, Neural Networks and Random Forests (among other Machine Learning algorithms) are widely and successfully used in different application areas. Data scientists typically employ precise criteria to select the optimal approach when tackling a problem. Key considerations often revolve around the size of the dataset, available time to achieve results, desired accuracy, and overall resource availability. These factors collectively guide decision-making in determining the most effective strategy for analysis and modelling. In our case, with a moderate dataset size and constraints on time and resources, coupled with the nature of our problem, we opted for the Random Forest algorithm. This decision was well-founded for several reasons: Random Forests not only achieve (at least) similarly good performance results in practical applications in many areas, they also have some advantages compared to Neural Networks in specific cases. This includes their robustness as well as benefits in cost and time. They are particularly advantageous in terms of interpretability. In practical applications, when faced with choosing between two models, the decision often leans towards the one with 91% accuracy that is well understood over a more accurate (93%) model that is less understood. This preference is particularly evident in critical domains like patient investigation and medical treatment [11]. The referenced study demonstrates that Random Forest achieves the highest accuracy in the majority of scenarios. Our empirical analysis supports this finding, as we compared Random Forest with other machine learning algorithms and obtained superior results.

Apart from Random Forest, we opted for K-Nearest Neighbors (KNeighborsRegressor), Support Vector Regression (SVR), and a Dummy regressor, which served as a baseline regressor.

To evaluate the performance of our models, we executed the Hold-out method, splitting the dataset into 80% training and 20% testing segments. The models were assessed using RMSE (Root Mean Squared Error), MSE (Mean Squared Error), MAE (Mean Absolute Error), and R2-score. The machine learning model RandomForestRegressor yielded an overall R2-score of 0.88718, highest of all four models, as expected. Detailed results are shown in Table I, Section IV.

D. Cross validation

Our dataset contains sensor data from different individuals eating different foods. In many real-world datasets, samples are not independent but grouped together based on certain criteria (e.g., patients in medical studies, users in behavioral analysis). Hence, we found out that it is important to perform Cross Validation using GroupKFold, which ensures that samples from the same group (one individual in our case) are kept together in either the training set or the validation set during each fold. This action helped to prevent overfitting. The results from the cross-validation provided a more reliable estimate of the model's performance, yielding slightly more realistic numbers than the initial evaluation. Having established that the RandomForestRegressor provided the highest R2-score out of all the machine learning algorithms using the Hold-out method, we performed 5-fold Cross Validation on the mentioned regressor. The results of the five folds are shown in table II on Page 6 Section IV.

E. Hyperparameter Tuning

After concluding that the RandomForestRegressor provided the highest R2-score, we went on to explore the process called Hyperparameter Tuning. It is well known that in most cases RandomForestRegressor works reasonably well with the default values of the hyperparameters specified in software packages. Nevertheless, tuning the hyperparameters can improve the performance [12]. The RandomForestRegressor algorithm has several hyperparameters that may influence its performance.

- The **number of trees** should be set high: the higher the number of trees, the better the results in terms of performance and precision of variable importances.
- The **nodesize** parameter specifies the minimum number of observations in a terminal node. Setting it lower leads to trees with a larger depth which means that more splits are performed until the terminal nodes [13]. We therefore set the limits at 10 and 50 which helped prevent overfitting and maintaining the model's simplicity.
- The **sample size** parameter determines how many observations are drawn for the training of each tree. Decreasing the sample size leads to more diverse trees and thereby lower correlation between the trees, which has a positive effect on the prediction accuracy when aggregating the trees [12]. Moreover, Martínez-Muñoz and Suárez [14] show that there is no great performance difference between sampling with or without replacement.
- The number of trees in a forest is a parameter that is not tunable in the classical sense but should be set sufficiently high [15]. However, in order to save on time and computational resources we set n_estimators to 100 and 300.

We also performed GridSearch and RandomSearch considering the parameters mentioned above. One of the simplest strategies is grid search, in which all possible combinations of given discrete parameter spaces are evaluated. Continuous parameters have to be discretized beforehand. Random search on the other hand, draws the hyperparameter values randomly (e.g., from a uniform distribution) from a specified hyperparameter space. Bergstra and Bengio [16] show that for neural networks random search is more efficient in searching good hyperparameter specifications than grid search. In our case, after acquiring the results from the two techniques, we got nearly the same R2-score as the defaultly chosen parameters.

F. Feature selection

Random forest is advantageous for handling datasets with many features. However, in practical applications like medical prediction modeling, using a subset of the most important features improves efficiency. Variable selection identifies these crucial features based on statistical metrics, reducing data collection burden and enhancing prediction accuracy, crucial in datasets with numerous potential features [17]. In this study, we decided to use Random Forest feature importance to identify the top 100 significant features from a dataset consisting of 806 features. The selected features were used to train a Random Forest Regressor model, achieving an R2-score of 0.892 on the test set, slightly outperforming the model trained on the entire feature set, which scored 0.887. We also performed feature selection using SelectKBest to extract the top 100 and top 300 features. The results we got were expected. Namely, the top 100 features had a R2-score of 0.884 when fitted with the RanfomForestRegressor, and the top 300 features didn't show much of a difference with the score of 0.882. This depicts the effectiveness of feature selection in enhancing model performance by focusing on the most informative attributes, and also the fact that the model would work properly if it used the whole dataset.

IV. RESULTS

The performance of the proposed methods for chewing rate estimation was tested through a series of experiments and the results are presented below. Subsection IV-A presents the results obtained with the four chosen algorithms using the whole dataset. Section IV-B shows the results of the Cross validation. In Section IV-C, we analyze the importance different feature sets and their influence on the performance of the proposed method.

A. Results of the four machine learning algorithms (Hold-out)

For our regression problem, we used four different machine learning algorithms: RandomForest, SVR, KNN, and DummyRegressor as a baseline model. These models were chosen due to their distinct characteristics and capabilities.

Metric	Dummy	RFE	KNN	SVR
R2	−0.0025	0.88718	0.79729	0.64263
MAE	8.65619	2.34516	3.62205	3.55014
MSE	150.5424	18.15085	30.43871	53.6636
RMSE	12.26957	4.26038	5.51713	7.32554

TABLE I: R2-score, MAE, MSE and RMSE

Among the models tested, the RandomForest regressor outperformed SVM and KNN across all metrics. This superior performance highlighted RandomForest's effectiveness in handling the dataset's complexity and variability.

B. Cross validation results

In this study, we used the GroupKFold cross-validation method to evaluate the performance of a RandomForest model. Our dataset consists of 34 different persons, and it was divided into groups based on PersonID. Using this technique, the dataset was divided into k blocks in a stratified manner with group of subjects [18]. This means that if a subject with a set of records is in block k, the recordings of that person do not occur in block k–1. One of the k blocks is chosen as the validation set, while the remaining k–1 blocks constitute the training set. This process is repeated k times, with k = 5. We evaluated the model's performance using several metrics, including MAE, RMSE, MSE and R2 score. The results of the GroupKFold cross-validation are summarized in Table III.

Metric	Fold 1	Fold 2	Fold 3	Fold 4	Fold 5
RMSE	5.626	6.268	3.234	3.835	5.986
MSE	5.626	6.268	3.234	3.835	5.986
MAE	2.722	3.194	2.072	2.589	3.478
R2	0.847	0.776	0.916	0.901	0.685

TABLE II: Cross Validation results

The RandomForest model demonstrated consistent performance across different folds, with the following average metrics (Table III):

Metric	Value
Average RMSE	4.989713938593206
Average MSE	26.38702901273617
Average MAE	2.810915349820026
Average R2	0.8248522970096509

TABLE III: Average results of the Cross Validation

The RandomForest model achieved a high level of accuracy and robustness, as indicated in Table III. This consistency across the different folds of GroupKFold suggests that the model generalizes well to unseen data. We can also conclude that the use of GroupKFold was critical in ensuring that the evaluation was realistic.

C. Results: Manually selected features

Additionally to using feature_importances and SelectKBest, we decided that it would be beneficial to manually select some of the features we anticipated would give a satisfactory result. For that purpose, we fitted the model on 21 different hand-picked combinations of features, all of them merging various sensor data, based on the sensor data relevance itself. The masseter and temporalis move the mandible when chewing food. The pterygoid muscles move the mandible when the latter needs anteroposterior or lateral and medial adjustment [19]. Therefore, we based the combinations on the following subset of features: Accelerometer, Left Cheek, Right Cheek, Left Temple and Right Temple. The MAE and the R2-score of the best and worst model's performance, whilst fitting the model with RandomForestRegressor is shown in Table IV on page 6 in section IV. We can conclude that the model performs consistently when working with this subset, regardless of the specific combinations, proving the relevance of the selected features.

Metric	RFE
R2 (best)	0.898997
MAE (best)	2.328827
R2 (worst)	0.867227
MAE (worst)	2.595997

TABLE IV: Subset of features results comparison

V. Conclusion

In this study, we presented a novel method for chewing rate estimation using data acquired from the OCOsense smart glasses. The data was collected from a total of 34 subjects during controlled eating protocols. From the sensors incorporated in the the OCOsense smart glasses, we used all the data that they provided, as well as some hand-picked sensor data. We tested four different machine learning algorithms: RandomForestRegressor, SVR, KNeighborsRegressor and DummyRegressor. The RandomForest regressor outperformed the other models. It demonstrated higher-level performance across all metrics.

To ensure robust evaluation, we executed GroupKFold cross-validation, which demonstrated consistent performance across different folds, which meant that the model generalizes well to unseen data. This was critical in ensuring that the evaluation was realistic and not biased by the presence of data from the same subjects in both training and validation sets.

Additionally, we analyzed the importance of different feature sets by manually selecting and testing 21 different combinations of features based on sensor data relevance. The model performed consistently with each subset.

Although the presented work has advantages over existing methods for chewing rate estimation, it is also subject to some limitations. For example, the used dataset contains data collected in a controlled environment, and it remains an open question how well the model will perform in more natural, real-life scenarios. Moreover, the current model might not perform well for subjects with chewing rates outside the range observed during the controlled protocols.

To address these limitations, future work will involve developing and testing models with data recorded in public places, using the new version of OCOsense smart glasses, which have an improved design. Additionally, creating synthetic data that includes diverse levels of chewing activity can help develop more robust models for chewing rate estimation. These steps will help ensure that the proposed method can be effectively used in a variety of real-life scenarios, providing accurate and reliable chewing rate estimation.

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Performance comparison between PPG and ECG based heart rate detection

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Abstract: Heart activity measurement is a key metric when analyzing one's heart health. Two non – invasive methods can be used to obtain it: optical, through photoplethysmography (PPG), and electrical, through electrocardiography (ECG). PPG – based sensors rely on the blood volume reflectivity, while ECG – based sensors rely on the heart's electrical activity. This paper looks at techniques for processing PPG and ECG signals, for batch and real – time processing, as well as a comparison experiment with commercial PPG and ECG based heart rate devices. A system was prototyped for processing ECG and PPG signals, using batch processing, and it was shown that Z-score, or standard score, is a good technique for heart rate detection for real – time systems. It was also shown that commercial PPG sensors struggle when paired with sports that have rough biomechanics, that cause the PPG based heart rate monitor to move and cause moving artifacts in the PPG signal.

Key words: Photoplethysmography; Electrocardiography; Heart Rate; Biomedical Sensors; Digital Signal Processing

I. INTRODUCTION

In the realm of healthcare and fitness, the accurate monitoring of heart rate stands as a fundamental metric for assessing heart health and physical performance. With the advancement of wearable technology, the integration of photoplethysmography (PPG) and electrocardiography (ECG) sensors has revolutionized the precision and accessibility of heart activity monitoring.

PPG[1] makes use of light-emitting diodes (LEDs). When light travels through biological tissues it is absorbed by bones, skin pigments and both venous and arterial blood. Since light is more strongly absorbed by blood than the surrounding tissues, the changes in blood flow can be detected by these sensors as changes in the intensity of light[2]. In terms of placement, PPG sensors can be placed anywhere near a bigger blood vessel[3].

In contrast, ECG[4] operates on the principle that the heart's electrical activity can be detected through the skin. By strategically placing electrodes on the body's surface, typically on the chest, limbs, and torso, ECG captures the electrical signals produced by the heart's depolarization and repolarization during each heartbeat. This system is know as the 12 – lead electrocardiogram. These signals are then amplified, recorded, and interpreted to generate a graphical representation known as an electrocardiogram.

Both signals from PPG and ECG can be used to calculate heart rate and heart activity anomalies. In consumer electronics, both these types of sensors are used, because they can be packed in a small form factor.

PPG sensors are by themselves small in size, thanks to today's electronic advancements, while ECG sensors usually cut down to two (sometimes three) leads, which also cuts down the analog electronics needed to process all of them. In this paper looks at both sensors' output signals, ways to process them and compare their accuracy.

II. SIGNAL WAVEFORMS

A. PPG waveform

The signal that a PPG sensor generates is shown in figure 1. In general, the PPG waveform is derived from two components: pulsatile (AC) component and non – pulsatile (DC) component. The pulsatile component is what interests us, as that component is related to the change in blood flow. It can be used to monitor the heart's activity as it beats, which gives the ability to calculate its beating rate. The non – pulsatile component will be filtered out in later experiments, as it doesn't hold any valuable information for the purpose of this paper. It's usually related to the reflections of other tissues, as well as ambient light and the sensor's electronic design.

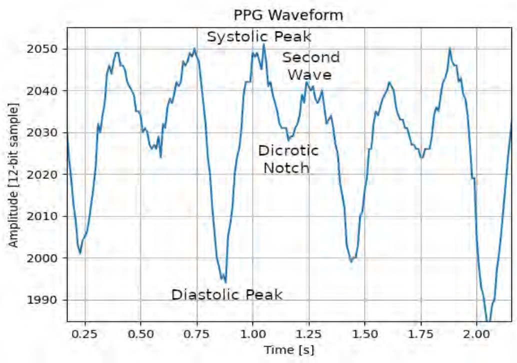

Fig 1. Raw PPG signal

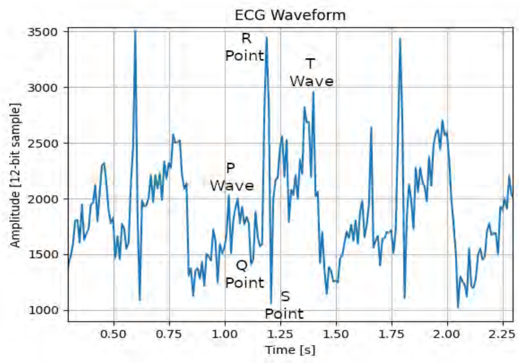

Fig. 2 Raw ECG signal

The waveform itself has four features:

- **Systolic point** – point of maximum amount of blood volume
- **Dicrotic notch** – point of temporary blood volume increase in capillaries due to pressure gradient of blood flow in opposite direction
- **Second wave** – point of return of blood towards the heart
- **Diastolic point –** point of minimal blood volume

The two useful features that can be used to calculate heart rate are the systolic and diastolic points. Using the time between two systolic or two diastolic points, one can calculate the heart's rate of beating in beats per minute (bpm).

B. *ECG waveform*

The signal that an ECG sensor generates is shown in figure 2. It has five features:

- **P wave** – depolarization of Atrias
- **QRS complex –** depolarization of Ventricles
- **T wave –** repolaziration of Ventricles

What interests us is the QRS complex, or more specifically the R point. The R point is the point at which there is maximal Ventricle contraction, and it differentiates itself from the rest of the signal with a very large amplitude. We can easily detect it and find the time between two R peaks – called the RR interval – and use that time to calculate the heart's rate of beating[4]. In the next part, we have made an experiment to compare the differences in these two kinds of sensor.

III. A PROTOTYPE SYSTEM FOR HEART ACTIVITY AND HEART RATE MEASUREMENT

For visualising the difference in PPG and ECG, we have made a small system, consisting of a microcontroller, an analog PPG and an analog ECG sensor. We have gathered data from both sensors and then processed it. Both sensors are analog and were sampled at 100Hz with a 12-bit ADC. The block diagram of the system is shown in figure 3.

The hardware components are the following:

1. STM32F411VETx microcontroller
2. KY-039S PPG sensor
3. OLIMEX SHIELD-EKG-EMG module
4. CP2102 USB to UART birdge

The STM32F411VETx microcontroller is an STM32 microcontroller from the STM32 Dynamic Efficiency™ line. It has a Cortex®-M4 core with a floating point unit, a working clock of up to 100MHz and a rich set of peripherals. We have utilized it's 12 – bit ADC to sample the signals from the sensors, as well as it's UART to send the signals through an USB to UART bridge to be processed on a PC.

The KY-039S is an analog PPG sensor from Joy-IT. It's a simple PPG sensor, with no filtering nor analog or digital processing. It's raw output signal does need a bit of preprocessing to have a better look and to be easier to work with.

The Olimex SHIELD-EKG-EMG module is a shield for the Arduino Uno that utilizes both ECG and EMG (the difference between their usage is just the placement of the electrodes). It's raw signal is also not filtered in any way, so we have filtered it as well.

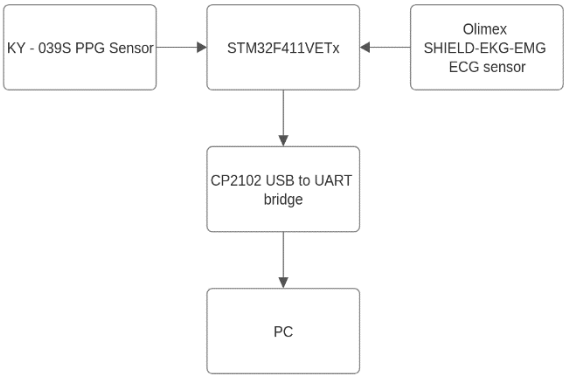

Fig. 3 System block diagram

A. *Preprocessing*

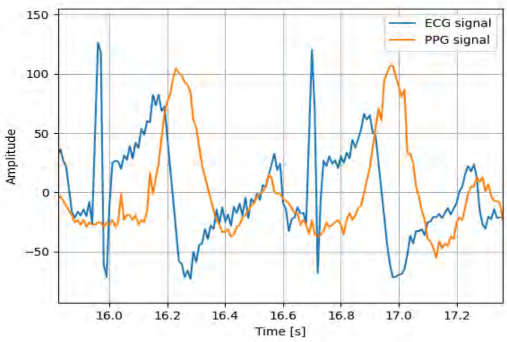

Fig. 4 Raw signals from sensors

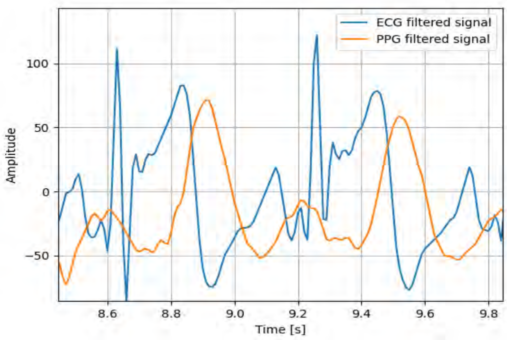

Fig. 5 Filtered signals from sensors

Figure 4 shows us the raw waveform of these two types of sensors, with the DC offset removed. Notice the delay of about 200-250 ms between the two signals. The ECG picks up the heart beat as it beats, while the PPG delays about 200ms, the time needed for the blood to be pumped to the finger, where we are doing the measurements with the PPG sensor.

These signals are already good enough to work with, as there is practically no noise in the ECG R points and the PPG Systolic points, and the maxima can be easily found. Nevertheless, we will be filtering the high frequency noise, just to make the signals a little better. Filtering the signals with a low pass 25 Hz filter, we get a waveform shown in figure 5.

B. *Thresholding and non – maxima suppression*

Looking at the filtered signals in figure 5, we can easily differentiate the peaks from the rest of the signal. Tresholding and non – maxima suppression gives us the peaks in figure 6. What's left is to find the RR – interval in the ECG signal and the distance between the Systolic peaks in the PPG signal.

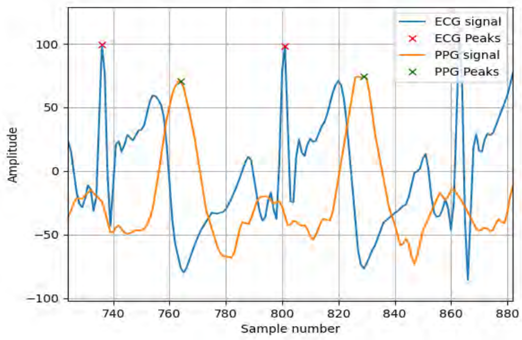

Fig. 6 R peaks in ECG / Systolic peaks in PPG signals

C. *Finding distances between maxima*

The distances between maxima can be easily calculated as the difference in points between them devided by the sampling frequency.

Going through all the peaks in both signals, calculating the distances, the heart reate and putting the results on a single graph, we get figure 7.

The results in figure 7 show us the difference between the two types of sensors. Notice the deviation from zero – error line as the heart rate rises. It is widely known that PPG sensors have a problem with accuracy due too two main problems: moving artifacts[5] and light interference from the environment. In this result, however, it is just an error in the calculating algorithm. Because the algorithm is optimized to be used for both signals at the same time, it favors one signal over the other. The deviation is also not that high, averaging arround 3 bpm. Because the system is a prototype, it was hard to get a good signal with a heart rate above 100 bpm. The heart can reach a maximum frequency of up to arround 3Hz, or 200 bpm, so sampling with 100Hz in this experiment was more than enough to get a good signal.

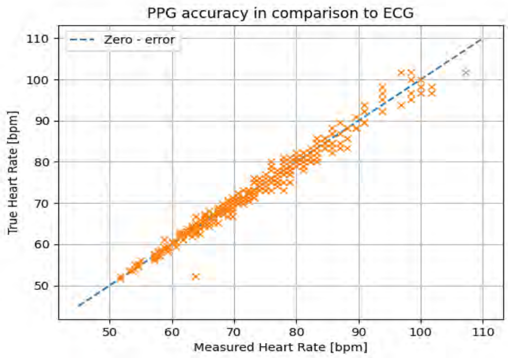

Fig. 7 Heart rate accuracy comparison

IV. PROCESSING PPG AND ECG SIGNALS IN REAL – TIME FOR EMBEDDED APPLICATIONS

With the experiment above, we have shown that, for getting heart rate data, one algorithm is enough for processing both PPG and ECG signals[6]. Taking into account that both signals have a frequency component that comes from the heart, it shouldn't be trivial that signals from both sensors should have the same frequency component of the heart's beating.

When processing data, two approaches can be made: batch processing and real – time processing. The key difference here is that batch processing is done on a cluster of data all at once, while real – time processing is done on a single sample in real time. What's better depends on the resources of the system and what the data will be used for. The previous experiment was done using batch processing, as you can more easily manipulate data that way. For embedded solutions, like oximeters, heart rate chest straps, smart watches and other wearables, a real – time processing algorithm might be more suitable.

A simple algorithm can be made that can process both PPG and ECG signals in real – time[7] with the following steps:

A) Preprocessing

B) Calculating moving average and standard deviation

C) Looking for samples that deviate **n** times from moving average (also known as z – score[8] / standard score)

In the first phase, we have filtered both signals with a Butterworth bandpass filter with a bandwidth of 29.5Hz (from 0.5Hz to 30Hz), to eliminate DC offset and high – frequency noise. 30Hz is a bit too high for a PPG signal, but it will still work without a problem. The problem comes from the ECG signal, as it has higher frequency components in the R peak, and it's hard to distinguish it if we filter out too many high frequencies[9]. In the second phase, we have calculated the signal's moving average and standard deviation. We will be using a 100 samples (or 1 second) moving window to calculate both. A bigger window is better for slower – changing signals, as the short peaks will average out, while the tall peaks will stand out and give a higher z – score. This also means that the first 100 samples that come from the sensors can't be manipulated, as they won't have enough previous samples to calculate the moving average and standard deviation. In the last phase, we have tresholded the z – score, which is a the number of standard deviations a point is above a moving average calculated from previous points, looking for peaks in the signal. The formula for z – score is the following:

$$Z - score = \frac{X - \mu}{\sigma} \quad (1)$$

, with X being the current sample value, μ being the moving average and σ being the standard deviation.

Applying the z – score algorithm gives us figures 8 and 9 for ECG and PPG respectively.

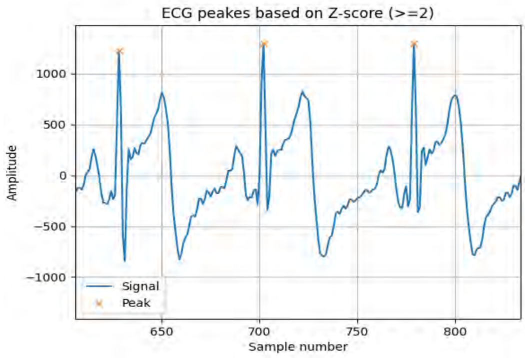

Fig. 8 Peaks in ECG signal based on z – score

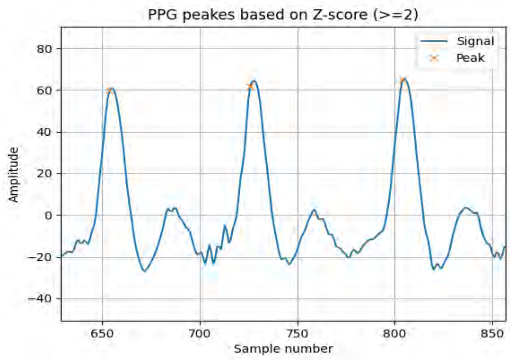

Fig. 9 Peaks in PPG signal based on z – score

From figure 8 and 9, we can definitely say that we can catch peaks in real time with z – score. However, looking a bit more closly, we can see that the z – score algorithm works better for ECG[17] than PPG. Notice the Z score in the ECG signal. The z - score satisfying our treshold (z >= 2) gives us almost always 1 point, sometimes 2 points. The z – score in the PPG signal is almost the width as the Systolic wave, meaning there will be a need for peak suppression. As we can never know which point is highest on the Systolic peak (since the system is real – time), an easy solution is to take the first point which satisfies our threshold, and throw away all the points that are right next to it. Doing that can cause an error of a few samples. We can calculate the error, in bpm, with the following formula:

$$Error = 60 * \frac{\Delta samples}{fs} \quad (2)$$

, with Δsamples being the number of samples between the true peak and choosen peak, and fs being the sampling frequency.

With a sampling frequency of 100Hz, an error of 5 samples gives us an absolute error of 3 bpm and a relative error of 5%, while 10 samples gives us an absolute error of 6bpm and a relative error of 10%. Each sample error with this frequency amounts to 0.6 bpm absolute error and 1% relative error. Figure 10 shows us the new accuracy graph.

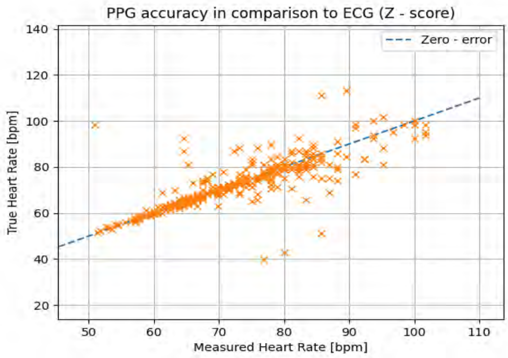

Fig. 10 Heart rate accuracy (Z – score)

Looking at figure 10, compared to figure 7, we get a similar looking graph, only with more points deviating from the center line, meaning more error. Most of the error is due to false peaks. Most of the false peaks come from the ECG signal, as the T wave peaks are also getting caught. That is not the be the case with PPG, where there were no recorded false peaks, becouse the Disystollic peaks are arround 6 times smaller than the Systollic peaks, compared to T wave peaks and R peaks of only arround 0.8 times. Not filtering the ECG signal doesn't help, as the T wave peak is stil only arround 0.7 times smaller than the R peak. This can be a limitation of the ECG sensor, or the nodes themselves. This could also be a reason as to why PPG sensors are used more than ECG sensors in consumer electronics, as needing a better sensor and/or beefy algorithm to proccess it correctly is more expensive. In the last part, we have looked at commercial heart rate monitors, both PPG-based and ECG-based, and compared them in a real world application. We have taken data from our own recorded activities, mainly running on different types of terrains, as well as mountaing biking.

V. ACCURACY OF COMMERCIAL HEART RATE MONITORS – AN EXPERIMENT

Among enthusiasts and professional athletes, heart rate monitors are a greet tool to monitor performance during exercises and keep track of progress in the long term. Companies like Garmin, Coros, Polar, Suunto and many others have perfected the craft of GPS sports watches and chest straps, both of which have a sensor for monitoring heart rate and heart activity. Watches mainly have a PPG sensor, although Garmin has a series in which they have wrist ECG sensors, while chest straps mainly have ECG sensors.

For this experiment, we have used two Garmin smartwatches, the Fenix 6 Pro[10] and the Forerunner 55[11], as the PPG-based heart rate monitor, one Garmin HRM Run[12] chest strap and one GEOID HS500[13] chest strap, as the ECG-based heart rate monitor. We have recorded different types of activities with these devices at the same time and we have visualized the data, in the same way as figure 7 annd figure 10. For better visualization, we have taken data from 3 kinds of activities: trail running, road running and mountain biking (MTB). We have paird the heart rate data from each devices with the same timestamp and have devided them into 3 groups: uphill, downhill and flat. This way, we can see whether the current point is recorded going uphill, downhill or on a flat surface. The results are shown in figure 11, 12 and 13 for MTB rides, trails runs and road runs respectively.

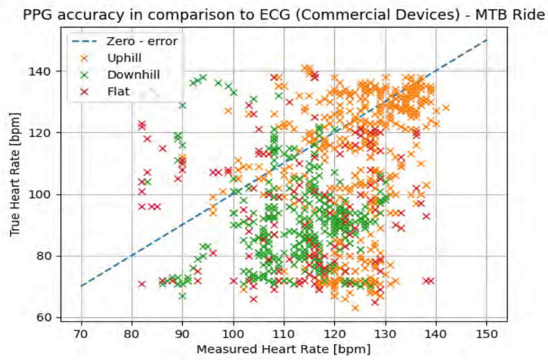

Fig. 11 Heart rate accuracy (commercial devices) from MTB rides

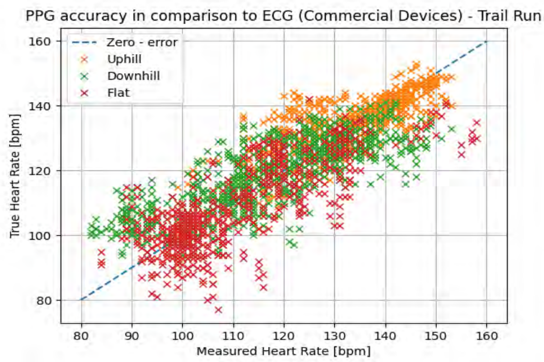

Fig. 12 Heart rate accuracy (commercial devices) from trail runs

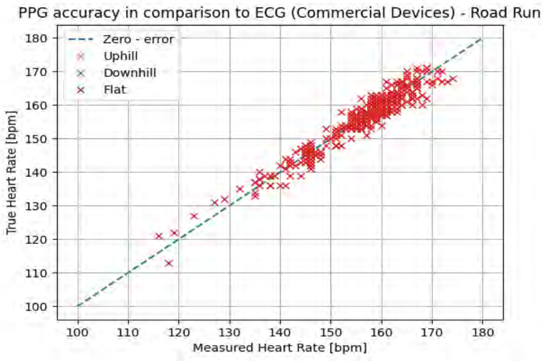

Fig. 13 Heart rate accuracy (commercial devices) from road runs

From these figures, we can see that accuracy scales from most accurate on the road runs, while least accurate on the MTB rides. Also, in each activity, points on uphill and flat terrain have less error than points on downhill terrain. There are a few possibilities as to why this happens, but the most likely one is biomechanics. Running downhill has a really high impact on the body, meaning the sensors move a lot. This is even more visual on the MTB rides, as the body moves a lot, and so do the sensors. For PPG-based sensors this causes moving artifacts as the absorbed light is distorted, while for ECG-based sensors this means the nodes might loose contact with the skin. These activities were recorded with the ECG-based heart rate monitors as the reference, as the ECG-based heart rate monitor is a more robust system than the PPG-based heart rate monitor.

Conclusion

When looking at monitoring heart activity, one of two processes can be choosen, either ECG or PPG. Out of the two, ECG has been around for longer[14] and it is more robust and accurate. However, comparing the price and complexity to PPG, the choice is not always obvious. More work can be done to determine whether commercial PPG-based and ECG-based devices are reliable. As mentioned, PPG-based heart rate sensor have a real problem with moving artifacts, which can even be used to detect, for example, running cadance. On the other hand, ECG-based heart rate sensor rely on good contact with the skin that can be disrupted with more impactfull movement.

In real world applications, even though PPG based heart rate monitors have really robust algorithms, like Garmin's, moving artifacts still cause a lot of trouble. Using PPG heart rate monitors for sports is where most of the problems occur, as some sports, due to the biomechanics, cause a lot of moving artifacts in the PPG signal. This gives the algorithm a tough time with processing the signals, and it makes a lot of errors, as we can see in the last experiment. Overall, non – critical environments can still go use PPG sensors with great success. Critical environments, on the other hand, will probably stick with ECG for the foreseeable future.

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ЗДРУЖЕНИЕ ЗА ЕЛЕКТРОНИКА ТЕЛЕКОМУНИКАЦИИ АВТОМАТИКА И ИНФОРМАТИКА НА РЕПУБЛИКА МАКЕДОНИЈА

SOCIETY FOR ELECTRONIC TELECOMUNICATIONS AUTOMATICS AND INFORMATICS OF THE REPUBLIC OF MACEDONIA

Cyber Security Applications CybSec

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GPU-Accelerated Password Hacking: Analyzing Performance Across Varied Password Lengths

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***Abstract*—With the development of new technologies, the required computational power has also been exponentially increasing. Graphical Processing Units (GPUs) are the latest and best processing units on the market, reaching up to five times the performance benchmarks of the latest Central Processing Units (CPUs). As such, GPUs have been at the forefront of digital image and video processing, various scientific discoveries and research, as well as playing a crucial role in the rise of Artificial Intelligence (AI). Our goal is to analyze GPU performance for brute-force password hacking, which requires iterating all possible variations of passwords which can be formed from a given alphabet of characters. Brute-force attacks require a lot of computational power since the number of possible variations depends on the extensiveness of the password alphabet and increases exponentially based on the number of characters in the password. We define an alphabet of 67 characters, the first ten are the numbers from 0 to 9, the next 52 characters are all the lowercase and uppercase letters from the alphabet, and the last five are special characters. Even though the effectiveness of the algorithm depends on the extensiveness of the alphabet, for our purposes we only focus on five special characters. The experiments in this research have been generated with the NVIDIA Tesla T4 GPU. Our results show that for a password of eight characters, the time required to find the password is more than 28800 seconds.**

Keywords—Graphical Processing Units (GPUs), brute-force attacks, parallel programming, CUDA, performance metrics, password hacking

I. INTRODUCTION

Graphical Processing Units (GPUs) have become almost an essential part of every modern computer system. New technologies are demanding better and higher computational power, thus necessitating the rise of development and production of GPUs in order to support the technological advancements. The GPUs work in concurrence with the more general, task-parallel Central Processing Units (CPUs) in the computer system. Typically, the sequential problems, usually occurring with high regularity and arithmetic intensity, are performed on the CPUs, while the GPUs are mostly used for the compute-intensive problems which need to be performed at a faster rate [1]. Starting of as processing units to enhance graphical processing in computer systems, GPUs today are widely used for any problem which requires high computational power and parallelism, such as digital image and video processing, almost all methods and techniques used in Artificial Intelligence (AI), especially Deep Learning (DL) and Neural Networks (NN), cloud computing, virtualization and network security. The leading development of self-driving cars, robots, and smart cameras is also powered by GPUs [2].

The first GPU was the GeForce 256, introduced by NVIDIA in 1999, which contained a 32-bit floating-point vertex transform and lighting processor, and a configurable integer pixel-fragment pipeline, programmed with OpenGL and Microsoft Direct X7 APIs. With programmable shaders emerging, NVIDIA's GeForce 3 introduced the first programmable vertex processor which executed vertex shared programs [3]. The GeForce 8800 marked the introduction of NVIDIA's Tesla unified architecture, which made programming GPUs directly possible using specific APIs. NVIDIA also developed the CUDA (Compute Unified Device Architecture) programming model and software environment, which let programmers write scalable parallel programs using a straightforward extension of the C/C++ languages [4].

The initial GPU development was modeled after the concept of a graphics pipeline where the pipeline simply transforms coordinates from 3D space into 2D pixel space on the screen (see Fig. 1). The pipeline is divided into two stages, geometry and rendering. The early iterations of what we now know as GPUs only implemented the rendering stage in hardware, and still relied on the CPU to provide some of the required calculations. The first GPU to implement the entire graphics pipeline was the GeForce 256, which consisted of 23 million transistors, 32 MB of 128-bit DRAM (Dynamic Random Access Memory) and a core clock cycle of 120 MHz [5]. The limited reuse of the available generated data within the pipeline combined with other resource limitations (registers, textures, instructions per shader), prompted the development of the unified pipeline architecture and the unified shader model. The GeForce 8800 was the first to introduce both of these concepts, implementing scalar stream processors (SP) in order to perform the shader operations. The stream processors are grouped into 8 clusters, making it 16 SPs per cluster. The stream processors in the same cluster share parts of the registers, memory and first level cache in order to fasten their communication, and introduce SIMD (Single Instruction Multiple Data) [6]. In comparison to the GeForce 256, the first GeForce 8 had 681 million transistors, 768 MB of 384-bit GDDR3 DRAM, and the core clock cycle of 600 MHz. The sudden rise of AI has directly contributed to new innovations in the GPU architectures, with NVIDIA leading the way. The latest NVIDIA GPUs offer a massive increase in the performance from their predecessors, especially when performing ML/DL computations or when focusing on HPC (High Performance Computing). Hopper, the most recent NVIDIA GPU architecture, offers a set of novel attributes, including new tensor cores and distributed shared memory, which should greatly facilitate software optimization and modelling efforts for GPU architectures [7].

If a comparison is made between GPU and other hardware, for an example FPGA (Field-Programmable Gate Array), we can simply notice the difference, emphasizing that FPGA is very powerful solution providing many potential benefits such as flexibility, low latency, and reduced power consumption. Even so, GPUs offer higher throughput, easier programmability, and a more mature development environment as compared to other parallel processing units, which make them ideal for use in complex deep learning-based and high performance computing applications that require large-scale data parallelism [19].

In the sphere of information technology, cybersecurity has been one of the most referenced topics in the last decade and has seen vast improvements and progress [9]. The digitalization of the world and development of smart technologies has greatly increased the rate and severity of cybercrime. It is estimated that cybercrime accounted for just under one trillion USD in damages in 2020, depicting the importance of cybersecurity that much more [10]. Cybersecurity threats have been evolving with the vast rise of cybersecurity as well. Among these threats, brute-force attacks stand as a prevalent and persistent menace, and can be particularly damaging due to their simplicity and effectiveness [11]. These attacks involve the systematic and repetitive guessing of login credentials, such as usernames and passwords, to gain unauthorized access to systems and accounts. By employing automated scripts or dedicated tools,

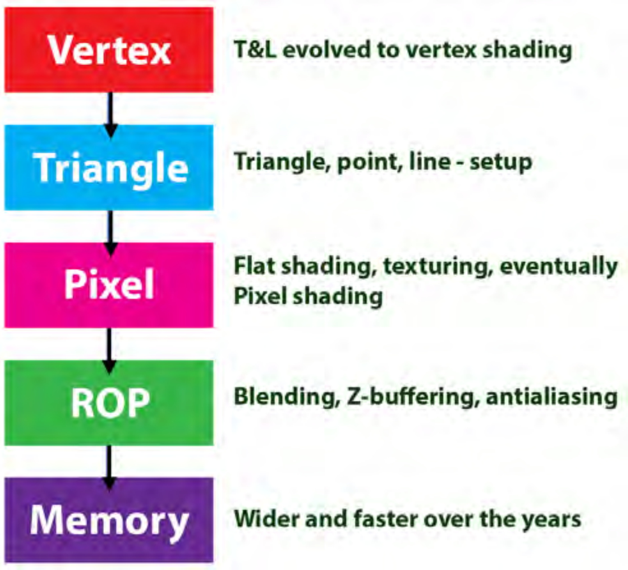

Fig. 1. A classic graphics pipeline [8]

attackers can generate a vast number of combinations, overwhelming security defenses and potentially breaching the systems [12]. Considering the possibilities of using a type of attack in the password guessing algorithm, one of the options is to use Dictionary Attack. This type of attack is relatively faster than brute force attack. The dictionary attack tires to match the password with most occurring words or words of daily life usage. The attacker makes the dictionary of most commonly used words that might have been used as a password, for example, names of birds, familiar places or famous actors' name. The attacker then applies all these words to break the password. Although the dictionary attack is faster than brute force attack, it has some limitations too, for example, it contains limited words and sometimes it is unable to crack the password because it remains a possibility that password may not be present in the dictionary itself [20]. Brute-force attacks are usually very time-consuming, causing the attackers to look for new solutions and implementations which will greatly increase their speed. The computational power and effectiveness of GPUs offer a major increase in the rate of which the repetitive guesses are generated when performing these attacks. The most common method of authentication and protection against intrusion in a computer system is to use alphanumeric usernames and at least 12 character long passwords in combination with facial recognition, fingerprint, digital certificate or other combination of factors [13]. What this usually means is that there is a set number of rules which the user has to follow in order to generate a strong password, as well as the limited number of alphanumeric characters available at their disposal. The required time for the brute-force attack to generate a guess is reliant on the aforementioned set of rules and the number of possible alphanumeric characters which the password is generated from, i.e. the alphabet of the password.

As cybercriminals continuously adapt their tactics to circumvent traditional security measures, organizations are compelled to adopt a proactive stance towards cybersecurity. This involves implementing robust security protocols, conducting regular risk assessments, and fostering a culture of security awareness among employees. Additionally, advancements in encryption technologies and secure authentication methods, such as biometrics and token-based authentication, are essential in mitigating the risks posed by brute-force attacks.

This paper focuses on discovering the limits of available GPUs for the purpose of generating brute-force credential attacks based on a limited set of rules. The subsequent segments delve into the technical aspects of executing these attacks, alongside the methodology used and the findings obtained during both the development and experimental stages. In section II, we explain the impact of password length and character variability on the potency of brute-force credential attacks. We also give an insight into the development of our GPU-accelerated solution and the importance of GPU architecture. Section III focuses on the experimental results, whilst showing a visual correlation between the key factors which have a massive effect on the total execution time. The importance and effect of code complexity is the main topic in section IV, while section V summarizes the paper and gives an insight on the future of GPU development.

II. METHODOLOGY

Password length and character variability are the two most important factors when generating brute-force credential attacks. These two parameters directly affect the total number of possible guesses which need to be generated, drastically increasing the required time of completion as these parameters also increase. The direct correlation between these two parameters is enclosed with (1), where c represents the total combinations, n represents the number of characters and l the password length.

$$c = n^l \tag{1}$$

For the purposes of this paper, the maximum available password length is set at eight characters. The full range of alphanumeric characters, with the addition of five other characters (!@%^*), are used as the available characters, i.e. the alphabet for password guessing, making the total number of available characters at 67. In order to truly test the power of Graphical Processing Units, more specifically, the one we are using, the code is written using the CUDA API and the C/C++ standards.

Usually, it is agreed within the CUDA developers' community that at the beginning of the code, a special macro function is written in order to retrieve the errors occurring when calling the functions from the CUDA API. Furthermore, before the main functions of the code are explained, it is required to define three helper functions which will be used throughout the processes of password generation and guessing. Each method designed to run on the GPU should always be marked with the *__device__* keyword before the function declaration, which will let the compiler know that the sequence of code should be run on the GPU. Two of the three aforementioned helper methods are a reimplementation of the standard C methods for comparing and copying arrays of characters. These separate methods had to be rewritten in order to exploit the capabilities of parallel computing using GPUs. The third helper function generates the password guess from all the possible available combinations, based on the index of the thread currently executing the function. CUDA GPU architectures split the device into a three-part hierarchical structure (see Fig. 2). Each GPU is internally divided into grids, blocks and threads. Every single available thread running on the same kernel is a grid. In order to increase the efficiency and parallelism GPUs offer, each grid is comprised of multiple blocks. A block is a logical unit containing a set number of threads, and a certain amount of shared memory. Each block in the grid is identified by a specific block index, and GPUs usually consist of 65,535 blocks [14]. Threads are last in the

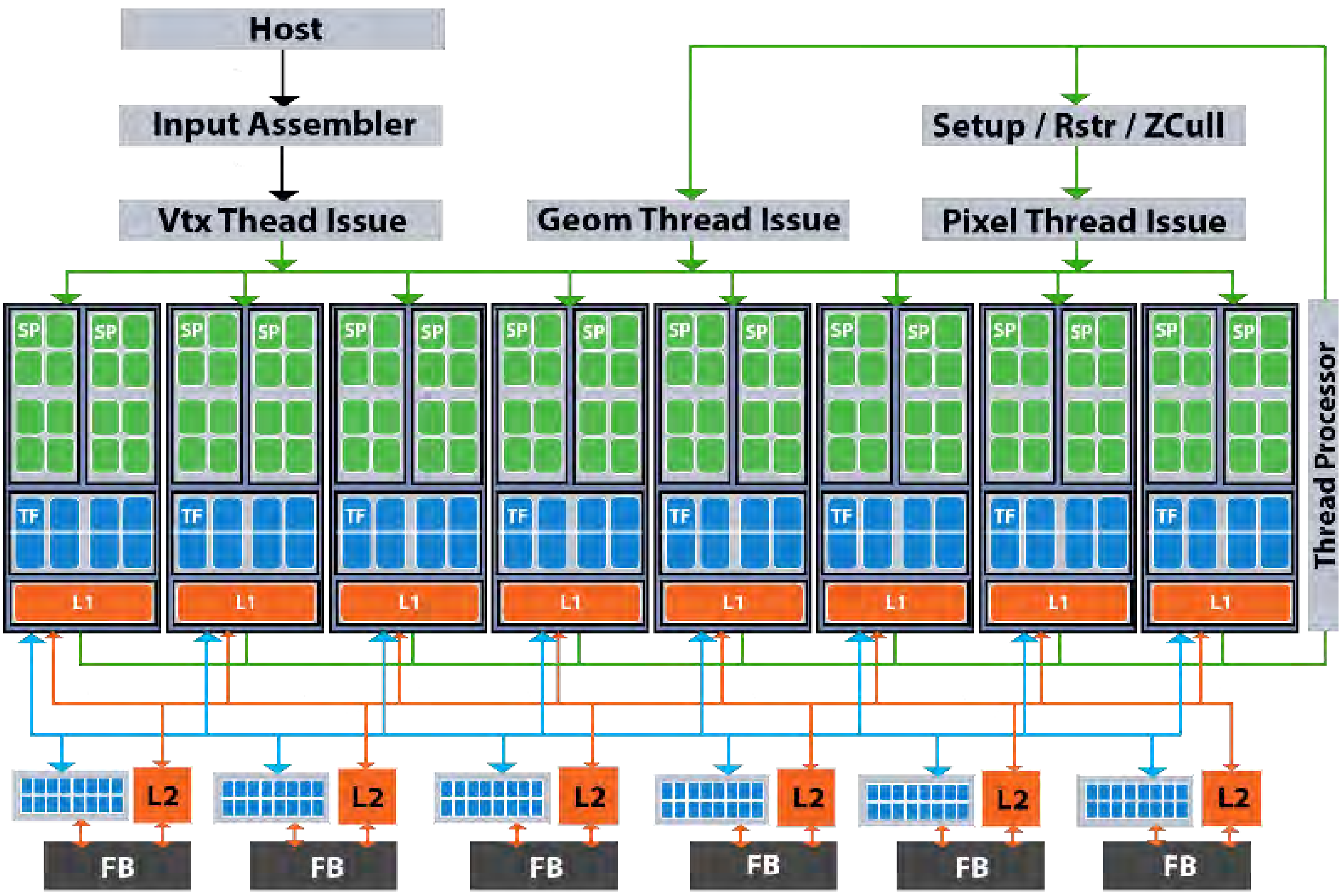

Fig. 2. NVIDIA GeForce 8800 GTX architecture [8]

GPU architecture hierarchy, and all blocks are composed of threads. Similarly to blocks, each thread has its own thread index which is related to the block that thread is running in. Usually, there are between 512 and 1024 threads in each block. The method for generating a guess uses the thread's index in order to retrieve characters from the available, and each character is concatenated to the previous array of characters, thus generating the password guess.

GPUs and the CUDA software model allow software developers the opportunity to develop parallel computing solutions which offer great computing speed and processing prowess. When developing highly parallel computing solutions, it is of great importance to distinguish between host and kernel functions (details in Fig. 3). Host functions are functions which are designed to run on the device's CPU. These functions have to be lightweight, and do not require major processing power in order to generate the required result. On the contrary, when performing parallel computing on GPUs, the kernel function is the main function which will be executed on the GPU. In CUDA, the kernel function is directly responsible for the allocation of memory and threads on the GPU, and it handles the multithreading automatically. The call to a CUDA kernel function can explicitly be distinguished from any other regular C/C++ function call by the definition of the additional parameters required to start a parallel region, which are the available number of blocks and the available number of threads for that region (2). The declaration of the kernel function in code is also always preceded by the *__global__* keyword, which will let the compiler know that the following sequence of code is the GPU kernel function. In order to start the kernel function with the correct GPU arguments for that parallel region, CUDA offers developers specific API calls which retrieve device specific information, i.e. the maximum number of blocks on that GPU, as well as the maximum number of threads per block.

$$kernel_{function} < \ll \ldots \gg > (function_{arguments}) \quad (2)$$

As previously stated, the kernel function is responsible for allocating the required memory, starting the parallel execution and controlling the threads and their result. Because each GPU has a limit on the number of blocks and threads that can be started by the kernel, in cases where higher processing demand is required, it is up to the developer to account for that overhead. Because of the nature of brute force attacks and the need to test every possible character combination in order to find the password, the number of threads which are required to run simultaneously on the GPU is equal to the total number of combinations. If the GPU can satisfy the required number of threads that need to be run, the function which generates the password guess is called by each thread exactly once. However, if an overhead on the number of threads occurred, i.e. the total number of required threads exceeded the limits of the GPU, each thread inside the kernel function will execute the function for password generation as many times as the factor of overhead that occurred. Regardless of whether an overhead in the number of threads occurred or not, the result of the kernel function is to extract the correctly guessed password and save it, along with the index of the thread responsible for finding the password.

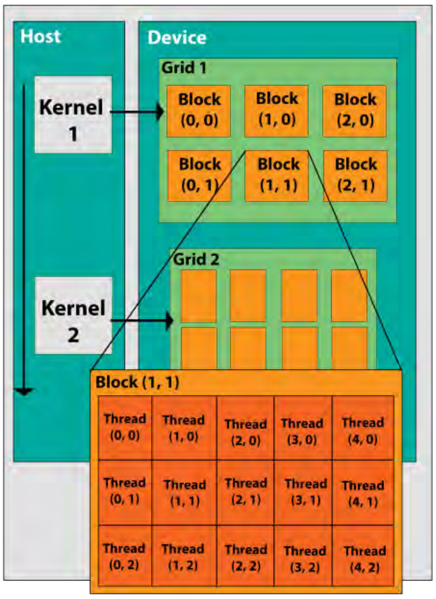

Fig. 3. CUDA GPU architecture [15]

Multithreaded parallel processing requires the threads to be a part of the same memory address space, which in the world of parallel programming is known as the shared memory concept. Each thread has access to the same global variables shared in that address space, which makes memory sharing and synchronization of threads a much more simplified process. Threads also share their process state between each other, making threads lightweight and relatively inexpensive to manage [16]. Before starting the parallel region with the kernel function, every developer must allocate the global variables which will be used by the threads throughout their execution. Because these threads will be run on the GPU, the allocated memory must first be transferred to the GPU before starting the kernel. CUDA offers specific API calls which transfer all of the variables from the host (CPU) to the device (GPU). Once all of the required variables have been allocated and transferred to the GPU, the kernel function is started. Each thread in the parallel region has a different execution time from the others, making thread synchronization one of the most important security measures to be taken in order to ensure correct execution of the program. Fortunately for developers, CUDA offers methods which take care of the thread synchronization before continuing the execution of the code. Once all of the threads finish, the guessed password and the index of the thread which found the password are transferred back from the memory of the GPU into the local memory of the CPU. As a result of this execution, the user receives feedback of whether the correct password was found and which thread was responsible for finding it. At the end, it is always good practice to deallocate all of the previously allocated memory for the required variables.

It is important to note that at the beginning of the program, the user is prompted to enter a password, which is required to be a maximum of 8 characters long, otherwise the program will fail its execution and notify the user of the error. If the entered password is within the possible password combinations based on the password length and defined set of characters, the program will find it and print out the correct password, otherwise, it will notify the user that it was unable to find the required password.

III. Experimental Results

Our goal was to test the limits and power of GPUs when performing tasks which require large amounts of parallel processing and high-performance computing. In order to better understand the processing power and speed of brute-force password hacking using GPUs, in addition to the global variables required to generate the guesses, two other variables were defined to track the execution time of the program based on the password length. The calculation of the execution time is also done with the help of the available CUDA API, which calculates the total amount of elapsed time, in milliseconds, from the start of the kernel until the end of the kernel. Table I shows a visual representation of the experimental results and execution time of the program. Although the results are clear and simple, they are important for future research in the field of cybersecurity. There are different types of brute-force attacks, but the difference is in the design of the algorithm, in the uniqueness of the defined alphabet, code and machine.

TABLE I. Visual representation of the experimental results, tested on the NVIDIA Tesla T4 GPU

Password length	Potential password combinations	Execution time (s)
1	67	0.00048
2	4,489	0.0005
3	300,763	0.00055
4	20,151,121	0.00248
5	1,350,125,107	0.15373
6	90,458,382,169	7.94912
7	6,060,711,605,323	761.85494
8	406,067,677,556,641	28,800+

IV. Discussion

The experimental results show that the execution time significantly increases with the increase of the number of characters in the password. The exponential increase in the required execution time is directly proportional to the exponential increase in the total number of combinations, calculated using the formula from Section II. The performance of the tool was tested on the NVIDIA Tesla T4 GPU, managing to show great results for passwords with length between one and seven characters.

When talking about performance metrics in relation to the program code and used algorithms, there is no better performance metric than the Big O notation. The Big O notation, also known as the Bachmann-Landau notation [17], is the most prevalent metric for judging computational complexity of algorithms. Each algorithm can be assessed using the Big O notation based on the number of operations performed by each algorithm, especially for larger input sizes [18]. The code complexity of brute-force attacks can vary, but it is always dependent on the number of possible outcomes that the brute-force attack should go through. As previously stated, the number of threads that need to be executed is the same as the total number of combinations based on the password length and the set of available characters. If the total number of threads is within the maximum range of the GPU, then one thread performs exactly one guess of the password, meaning that the Big O notation of this algorithm is *O(n)*, which means a linear complexity based on the number of threads being executed. The complexity of the algorithm rises when the number of threads exceeds the maximum range of available threads of the GPU. The following equation demonstrates that the overhead of the number of threads o is directly proportional to the total number of combinations c and inversely proportional to the product of the total number of blocks b and the threads per blocks t.

$$o = \frac{c}{b * t} \tag{3}$$

In these cases, each thread will have to execute the function as many times as the factor of overhead that occurred in the number of threads. Based on these factors and the given overhead (3), the code complexity of the algorithm can be represented as $O(o*n^2)$, or to simplify, $O(n^2)$, meaning that the complexity changed from linear to quadratic. Because the total number of combinations is very large, this change in complexity can impact the execution time of the program at a very high rate, which is very noticeable in the transition from passwords with a length of seven characters to passwords with a length of eight characters.

The possibility of improving the performance of the algorithm is seen in increasing the number of pre-defined alphanumeric characters, adding additional 27 characters. This increases the number of available characters to 94, which is actually the total number of printable characters from the keyboard, excluding the delete and space characters.

One of the ways this algorithm can be used is in ethical hacking. Ethical hackers, with the approval of the owner, use their knowledge and skills to detect security vulnerabilities, analyze and fix problems to protect the system from malicious hackers. Ethical hacking aims to increase security by detecting system vulnerabilities before attackers and it is legal and should not be associated with a crime [21]. In case of using our algorithm for those purposes, the possibility of harming other users is avoided.

V. Conclusion

GPUs produce great results in high performance computing and parallel programming problems, and with the rise of AI and data science, as well as the importance of data itself, GPUs will continue to gain popularity in the computing world. Our research proves that GPUs are perfectly capable of handling very large amounts of calculations, which are required when performing brute-force attacks. Even though security systems and cybersecurity has been clamping down on such attacks in the last few years, given the right amount of time, it is still possible to breach these systems even with simple brute-force solutions and algorithms. The performance limitations of the NVIDIA Tesla T4 GPU are visibly represented in the massive increase in execution time for passwords with a length of 8 characters, however, with the massive rise of GPU development, these is no telling how high computational power may rise in the future.

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Web Application for Web Attack Detection Through Network Traffic Analysis

Identifying Suspicious Patterns in Packet Data

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***Abstract* — In response to the escalating complexity of cyber threats, this paper explores the detection of web attacks using network traffic analysis techniques. By using powerful tools capable of dissecting packet-level data, this paper examines packet headers and payloads to identify potential attack vectors. We have developed application which analyzes packets based on predefined criteria. This application provides immediate insights into any anomalous network behavior. Through real-time packet inspection and analysis, this approach aims to safeguard networks from emerging cyber threats effectively.**

Keywords: web attack, network traffic, packet data, web application, Wireshark

I. Introduction

In cybersecurity, detecting and preventing web attacks is crucial for safeguarding networks and systems. Analyzing network traffic provides valuable insights into data behavior, which can help in attack prevention. This study explores the efficacy of network analysis tools, focusing on their ability to monitor traffic and identify open ports, used protocols, packet payloads and IP addresses. Wireshark stands out for its robust features and popularity, making it the tool of choice. By utilizing Wiresharks's capabilities, this research aims to detect attack patterns and anomalies in network traffic, contributing to better defense strategies against web-based threats. Through empirical analysis, this study seeks to offer insights for improving network security in a dynamic threat landscape.

Many researches have been done on the data that Wireshark monitors and detects, in order to detect attacks and prevent them. In [1], the authors are defining the drawbacks of using Machine Learning (ML) techniques against a direct approach, since ML is designed to detect specific threat and has to be retrained to detect additional (new) threats. Additionally, in [2] the authors are presenting the improvements and characteristics of using a lightweight packet to detect ransomware, in order to create faster algorithm to detect and shorten the time to react to the threat.

Furthermore, [3] presents the necessity of Wireshark to detect packets and create a way to prevent syn packets to flood the network and the end users, whereas, in [4], the authors are using Deep Learning techniques on top of the dataset to detect several predefined attacks. The authors in [5] are focusing on the data itself by using brain signal images and analyzing the network vulnerabilities using nmap and Wireshark. By doing so, they are analyzing and preventing data leakage of important medical data.

Additionally, the authors in [6] and [7] are using Wireshark data to make network and forensic analysis, where in [6], the authors are combining SNORT with Wireshark, where data detected with SNORT is sent to Wireshark for further analysis. The authors in [7] are using BitTorrent data to forensically examine this type of traffic and detect threats.

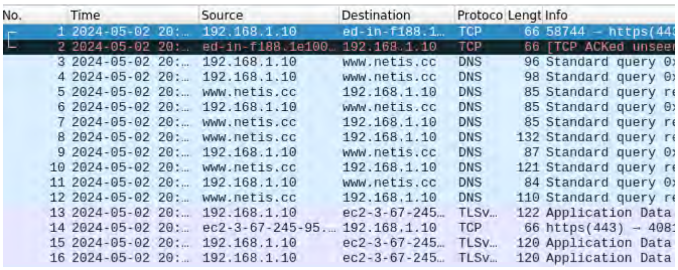
In this paper, we are analyzing data from Wireshark and creating a wrapper application to further analyze the packets and determine threats and anomalous network behavior. Section II presents the Wireshark tool and packet analysis. Section III presents the wrapper application and threat detection with detailed analysis in Section IV. Section V presents the wrapper application and Section VI concludes the paper and gives overview of further research possibilities.

II. Wireshark & Tshark

Wireshark and Tshark are powerful network packet analyzers widely used by network administrators, security professionals, and developers to examine and troubleshoot network traffic.

A. Wireshark

Wireshark, a graphical user interface (GUI) tool that provides an intuitive environment for capturing, analyzing and visualizing network packets in real-time. It offers a comprehensive set of features, including packet filtering, protocol dissection and deep inspection capabilities, making it an indispensable tool for network diagnostics and protocol development. One of the outputs of Wireshark is presented in Figure 1.



No.	Time	Source	Destination	Protoco	Lengt	Info
1	2024-05-02 20:…	192.168.1.10	ed-in-f188.1…	TCP	66	58744 → https(44
2	2024-05-02 20:…	ed-in-f188.1e100…	192.168.1.10	TCP	66	[TCP ACKed unseen
3	2024-05-02 20:…	192.168.1.10	www.netis.cc	DNS	96	Standard query 0x
4	2024-05-02 20:…	192.168.1.10	www.netis.cc	DNS	98	Standard query 0x
5	2024-05-02 20:…	www.netis.cc	192.168.1.10	DNS	85	Standard query re
6	2024-05-02 20:…	192.168.1.10	www.netis.cc	DNS	85	Standard query 0x
7	2024-05-02 20:…	www.netis.cc	192.168.1.10	DNS	85	Standard query re
8	2024-05-02 20:…	www.netis.cc	192.168.1.10	DNS	132	Standard query re
9	2024-05-02 20:…	192.168.1.10	www.netis.cc	DNS	87	Standard query 0x
10	2024-05-02 20:…	www.netis.cc	192.168.1.10	DNS	121	Standard query re
11	2024-05-02 20:…	192.168.1.10	www.netis.cc	DNS	84	Standard query 0x
12	2024-05-02 20:…	www.netis.cc	192.168.1.10	DNS	110	Standard query re
13	2024-05-02 20:…	192.168.1.10	ec2-3-67-245…	TLSv…	122	Application Data
14	2024-05-02 20:…	ec2-3-67-245-95.…	192.168.1.10	TCP	66	https(443) → 408
15	2024-05-02 20:…	192.168.1.10	ec2-3-67-245…	TLSv…	120	Application Data
16	2024-05-02 20:…	192.168.1.10	ec2-3-67-245…	TLSv…	120	Application Data

Figure 1. Output of packets captured with Wireshark

Packet fields captured with Wireshark:

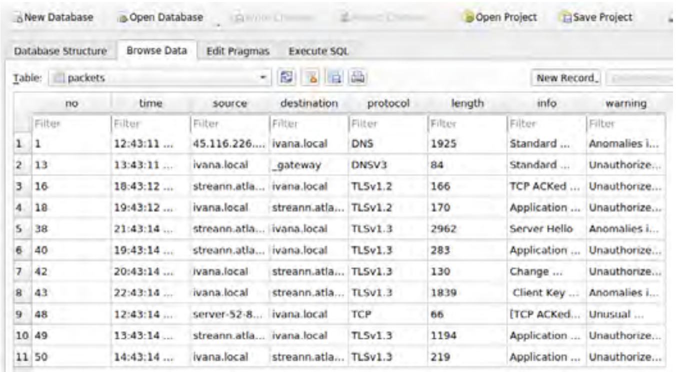
- *Time* – represents a specific moment in time within a packet capture recorded. Timestamps indicate when each packet was captured or observed on the network.
- *Source Address* – the network address of the device that initiated the communication or sent the packet. It identifies the sender of the packet.
- *Destination Address* – the network address of the device to which the communication is directed or where the packet is intended to be delivered. It identifies the receiver of the packet.
- *Protocol* – refers to the network protocol being used by the captured packet. It indicated the type of communication protocol used at the network layer of the OSI (Open Systems Interconnection) model. Knowing the protocol of a packet is crucial for understanding how the data is structured and how it is intended to be processed by the devices involved in the communication.
- *Length* – indicates the size of the captured packet. It represents the length of the packet's payload, including any encapsulated data and headers. The length value is typically measured in bytes. The length field provides insights into the amount of data transmitted in a single packet. Analyzing the packet lengths can help identify patterns in network traffic, detect anomalies, and optimize network performance.
- *Information* – refers to a summary of the packet contents, usually based on the packet's headers and any available payload data. Typically provides a concise summary of the key details from the packet headers, making it easier for analysts to quickly understand the nature of the captured packets.

B. *Tshark*

Tshark, is a command-line interface (CLI) equivalent to Wireshark, designed for headless environments and automation tasks. It operates in a similar manner to Wireshark but without the graphical interface, making it more lightweight and suitable for batch processing and scripted analysis. Tshark can capture live traffic or read captured packet files, extract specific fields or protocol information, and generate output in various formats, in this project we use CSV format, but also available as JSON or XML. Its versatility and scripting capabilities make it a preferred choice for integrating packet analysis.

III. Dynamic Application

On top of the data provided by Wireshark and TShark, a dynamic wrapper application is created using Angular and TypeScript to build dynamic user experiences. On the backend, Node.js is used to connect to the data and facilitate the algorithm for anomaly detection. Moreover, SQLite is used as a lightweight yet robust database engine to efficiently store and retrieve application data with SQL querying prowess. The data stored in SQLite is shown in Figure 2.



	no	time	source	destination	protocol	length	info	warning
1	1	12:43:11 ...	45.116.226....	ivana.local	DNS	1925	Standard ...	Anomalies i...
2	13	13:43:11 ...	ivana.local	_gateway	DNSV3	84	Standard ...	Unauthorize...
3	16	18:43:12 ...	streann.atla...	ivana.local	TLSv1.2	166	TCP ACKed ...	Unauthorize...
4	18	19:43:12 ...	ivana.local	streann.atla...	TLSv1.2	170	Application ...	Unauthorize...
5	38	21:43:14 ...	streann.atla...	ivana.local	TLSv1.3	2962	Server Hello	Anomalies i...
6	40	19:43:14 ...	streann.atla...	ivana.local	TLSv1.3	283	Application ...	Unauthorize...
7	42	20:43:14 ...	ivana.local	streann.atla...	TLSv1.3	130	Change ...	Unauthorize...
8	43	22:43:14 ...	ivana.local	streann.atla...	TLSv1.3	1839	Client Key ...	Anomalies i...
9	48	12:43:14 ...	server-52-8...	ivana.local	TCP	66	[TCP ACKed...	Unusual ...
10	49	13:43:14 ...	streann.atla...	ivana.local	TLSv1.3	1194	Application ...	Unauthorize...
11	50	14:43:14 ...	ivana.local	streann.atla...	TLSv1.3	219	Application ...	Unauthorize...

Figure 2 Data dump from Wireshark in SQLite

A custom Bash script is used to execute Tshark commands, capturing network packets in real-time. This script is designed to filter packets based on predefined conditions, flagging those with potential warnings. Upon detection, relevant packet data is extracted and written into the SQLite database. This streamed approach ensures prompt identification of suspicious network activity, facilitating rapid response measures. These tools form a cohesive tech stack, enabling the application to be responsive and feature-rich with a blend of fast and informative user interface and backend robustness.

IV. Potential Warnings

Analyzing packet captures in Wireshark can reveal potential security risks by examining various aspects of the network traffic.

A. *Unusual Traffic Patterns, Behavior Analysis*

These are unusual spikes in traffic or patterns that deviate from the norm. This could indicate a potential security threat such as DDoS (Distributed Denial-of-Service) attack or unauthorized data exfiltration. Also patterns of behavior that deviate from normal network activity. Includes spikes in traffic during off-hours or unusual communication patterns between network hosts.

B. *Protocol Anomalies, Vulnerable Ports, Abnormal Port Usage*

These are anomalies in protocol usage. For example, HTTP traffic on a port typically associated with a different protocol, it could indicate someone attempting to bypass security measures. Also, identifying traffic on non-standard ports or ports typically associated with specific protocol. This could indicate attempts to evade detection or exploit vulnerabilities.

Ports that are more likely to be targeted because they often have weak credentials and defenses.

Utilizing the data presented in Table I, we are able to conduct an examination of both the protocol and information fields extracted from the packet. In instances where a protocol does not align with its typical port association, indicating protocol anomalies, vulnerable ports or abnormal port usage, we prompt a warning.

TABLE I. PROTOCOLS ASSOCIATED WITH PORT

Protocol	Protocol	Port
HTTP/HTTPS	Hypertext Transfer Protocol/ HTTP Secure	80, 443, 8080, 8443
FTP	File Transfer Protocol	20, 21
SSH	Secure Shell	22
DNS	Domain Name System	53
Telnet	Telecommunication Network	23
SMTP	Simple Mail Transfer Protocol	25
RDP	Remote Desktop Protocol	3389

C. Authentication Failures, Fatal Messages

These are failed authentication attempts or unauthorized login attempts. These could indicate Brute Force attacks or attempts to gain unauthorized access to systems. We scrutinize the message field extracted from the packet to detect specific indicators such as ‘Client Key Exchange Failed’, ‘Encrypted Handshake Message Fail’ or ‘Server Key Exchange Failed’. These indicators prompt a warning for authentication failures.

Our analysis involves identifying suspicious messages, particularly those related to key exchange failures, to trigger timely warnings. An example of these suspicious messages is shown in Figure 3. Additionally, other messages we get in the information field from Wireshark that may be fatal and we can trigger a warning for are:

- *Unexpected message* – An inappropriate message was received. This alert is always fatal and should never be observed in communication between proper implementations.
- *Bad record mac* – This alert is returned if a record is received with an incorrect MAC. This message is always fatal and should never be observed in communication between proper implementations.
- *Decryption failed* – This alert was used in some earlier versions of TLS, and may have permitted certain attacks against the CBC mode.
- *Handshake failure* – Reception of a handshake failure message indicates that the sender was unable to negotiate an acceptable set of security parameters given the options available. This is a fatal error.
- *No certificate* – This alert was used in SSLv3 but not any versions of TLS.
- *Bad certificate* – A certificate was corrupt, contained signatures that did not verify correctly.
- *Unsupported certificate* – A certificate was of an unsupported type.
- *Certificate revoked* – A certificate was revoked by its signer.
- *Certificate expired* – A certificate has expired or is not currently valid.
- *Illegal parameter* – A field in the handshake was out of range or inconsistent with other fields. This message is always fatal.
- *Unknown ca* – A valid certificate chain or partial chain was received, but the certificate was not accepted because the CA certificate could not be located or couldn’t be matched with a known, trusted CA. This message is always fatal.
- *Access denied* – A valid certificate was received, but when access control was applied, the sender decided not to proceed with negotiation. This message is always fatal.
- *Decode error* – A message could not be decoded because some field was out of the specified range or the length of the message was incorrect.
- *Decrypt error* – A handshake cryptographic operation failed, including being unable to correctly verify a signature or validate a Finished message. This message is always fatal.
- *Insufficient security* – Returned instead of handshake failure when a negotiation has failed specifically because the server requires ciphers more secure than those supported by the client. This message is always fatal.
- *User canceled* – This handshake is being canceled for some reason unrelated to a protocol failure. If the user cancels an operation after the handshake is complete, just closing the connection by sending a close notify is more appropriate. This alert should be followed by a close notify. And this message is generally a warning.
- *Unsupported extension* – Sent by clients that receive an extended server hello containing an extension that they did not put in the corresponding client hello. This message is always fatal.

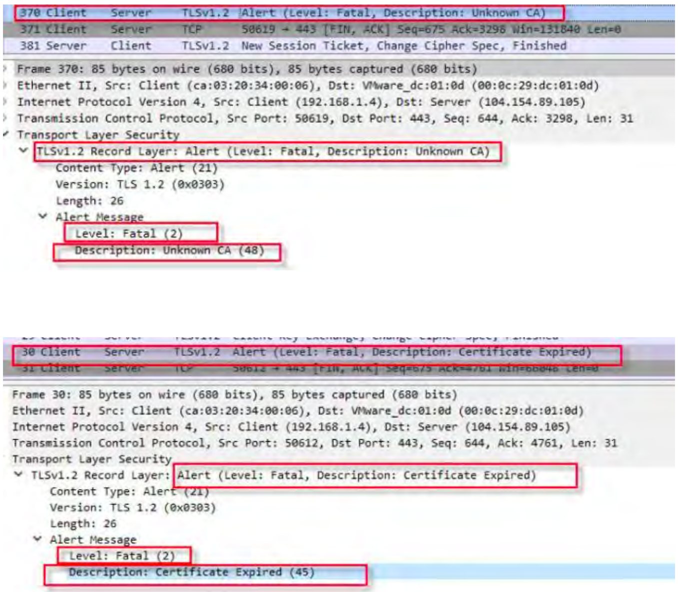
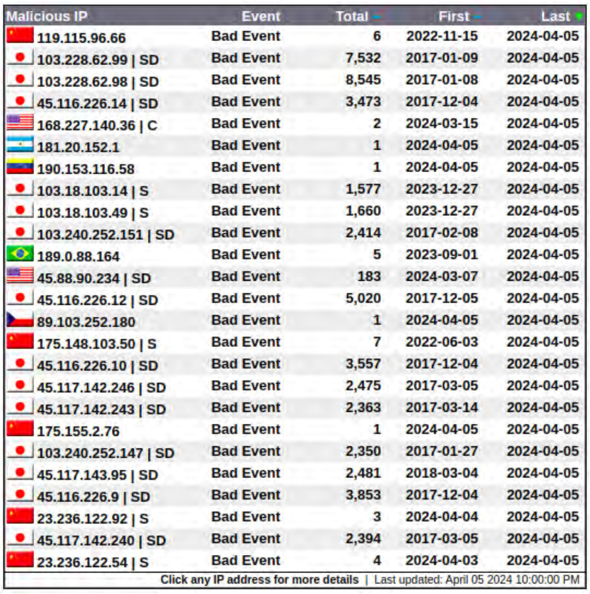


Figure 3 Example of detected suspicious messages

D. Traffic to Blacklisted Sites, Unauthorized Connections

This refers to traffic to known malicious or blacklisted sites occurred. More so, connections to unauthorized or suspicious IP addresses. Connections to known malicious IP addresses or domains. An example list of these IP addresses is shown in Figure 4.

We cross-reference the source and destination addresses extracted from the Wireshark packet against a database of known malicious IP addresses. If a match is found, indication to blacklisted sites or unauthorized connections, a warning is promptly issued.



Malicious IP	Event	Total	First	Last
119.115.96.66	Bad Event	6	2022-11-15	2024-04-05
103.228.62.99 | SD	Bad Event	7,532	2017-01-09	2024-04-05
103.228.62.98 | SD	Bad Event	8,545	2017-01-08	2024-04-05
45.116.226.14 | SD	Bad Event	3,473	2017-12-04	2024-04-05
168.227.140.36 | C	Bad Event	2	2024-03-15	2024-04-05
181.20.152.1	Bad Event	1	2024-04-05	2024-04-05
190.153.116.58	Bad Event	1	2024-04-05	2024-04-05
103.18.103.14 | S	Bad Event	1,577	2023-12-27	2024-04-05
103.18.103.49 | S	Bad Event	1,660	2023-12-27	2024-04-05
103.240.252.151 | SD	Bad Event	2,414	2017-02-08	2024-04-05
189.0.88.164	Bad Event	5	2023-09-01	2024-04-05
45.88.90.234 | SD	Bad Event	183	2024-03-07	2024-04-05
45.116.226.12 | SD	Bad Event	5,020	2017-12-05	2024-04-05
89.103.252.180	Bad Event	1	2024-04-05	2024-04-05
175.148.103.50 | S	Bad Event	7	2022-06-03	2024-04-05
45.116.226.10 | SD	Bad Event	3,557	2017-12-04	2024-04-05
45.117.142.246 | SD	Bad Event	2,475	2017-03-05	2024-04-05
45.117.142.243 | SD	Bad Event	2,363	2017-03-14	2024-04-05
175.155.2.76	Bad Event	1	2024-04-05	2024-04-05
103.240.252.147 | SD	Bad Event	2,350	2017-01-27	2024-04-05
45.117.143.95 | SD	Bad Event	2,481	2018-03-04	2024-04-05
45.116.226.9 | SD	Bad Event	3,853	2017-12-04	2024-04-05
23.236.122.92 | S	Bad Event	3	2024-04-04	2024-04-05
45.117.142.240 | SD	Bad Event	2,394	2017-03-05	2024-04-05
23.236.122.54 | S	Bad Event	4	2024-04-03	2024-04-05

Click any IP address for more details | Last updated: April 05 2024 10:00:00 PM

Figure 4 List of known suspicious IP addresses

E. Unauthorized Protocols, Suspicious Payloads

Indicates use of unauthorized protocols or applications on the network. This could indicate shadow IT or potentially malicious activity. Furthermore, payload of packets with suspicious content. This includes unexpected file transfers, unusual file types, or encrypted data sent over non-secure protocols.

We maintain a registry of sanctioned protocols along with their corresponding ports. Upon scrutinizing the protocol field extracted from the packet, any protocol not found in the list triggers a warning denoting unauthorized protocol usage.

List of Authorized Protocols

TABLE II. LIST OF AUTHORIZED PROTOCOLS

Protocol	Protocol	Port
HTTP	Hypertext Transfer Protocol	80
HTTPS	HTTP Secure	443
FTP	File Transfer Protocol	21
SSH	Secure Shell	22
SMTP	Simple Mail Transfer Protocol	143
IMAP	Internet Message Access Protocol	143
POP3	Post Office Protocol version 3	110
DNS	Domain Name System	53
NTP	Network Time Protocol	123
LDAP	Lightweight Directory Access Protocol	389
SNMP	Simple Network Management Protocol	161
SMB	Server Message Block	445
RDP	Remote Desktop Protocol	3389
AFP	Apple Filing Protocol	548
ICMP	Internet Control Message Protocol	/
Telnet	Telecommunication Network	23
Syslog	System Logging Protocol	514
DHCP	Dynamic Host Configuration Protocol	67 – server 68 – client
SFTP	SSH File Transfer Protocol	22
DoT	DNS over TLS	853

F. Anomalies in Network Flows

Analyzes network flows for anomalies such as unusually large or small packet sizes, abnormal packet timing, or unexpected patterns in communication. Packets larger than 1500 bytes (for Ethernet Maximum Transmission Unit) are considered as large and packets smaller than 64 bytes (for minimum Ethernet frame size) as small. We assess the length field retrieved from the packet, flagging instances where the length falls below 64 bytes or exceeds 1500 bytes, signaling potential anomalies in network flows.

G. Geolocation Analysis Warning

Wireshark's GeoIP feature identifies the geographical location of IP addresses involved in network traffic. Identifies suspicious connections originating from unexpected locations.

Utilizing Wireshark's GeoIP feature in conjunction with data on the origins of known malicious IP addresses, we can generate geolocation analysis warnings (Figure 5).

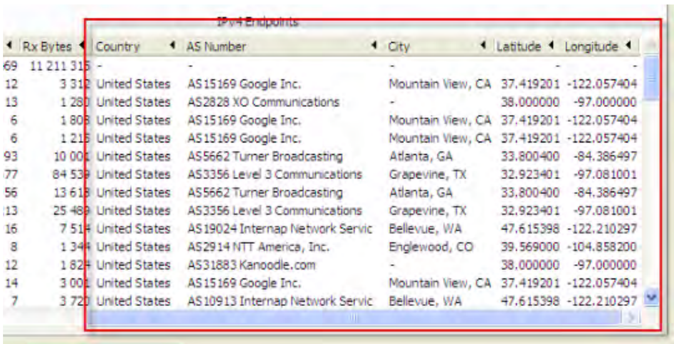


Figure 5 GeoIP feature of Wireshark

V. Packet Analyzer application

The final product is the wrapper application that runs in real-time, seamlessly integrating the tools described earlier. Leveraging Tshark for packet capture and a custom Bash script for packet analysis, this application continuously monitors network traffic. Detected packets that meet predefined warning criteria are promptly saved to an SQLite database using Node.js backend. In parallel, the Angular frontend dynamically retrieves and displays this data in a user-friendly table format, providing real-time insights into any network anomalies.

Figure 6 Packet analyzer wrapper application

Each warning is accompanied by an explanatory description detailing its significance and potential implications, enabling swift and informed decision-making to mitigate any potential harm effectively (Figure 6).

VI. Conclusion

The focus of this research is to create an efficient way to alert users of potential risks by analyzing packets from Wireshark and Tshark. The additional outcome is a database of known threats that can be used in Machine Learning to create even more accurate analysis and detection. Future research is to gather more data using the wrapper application from other users and create a threat prediction machine learning model and analyze accuracy and speed of prediction.

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Analysis of models for detection of cyberattacks in computer systems and networks

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Abstract— **The fields of machine learning and cybersecurity have become so popular in the last decade, that we are now seeing the culmination of the intersection of intelligent protection systems that use machine learning to consciously analyze behavior within the system they are responsible for protecting. These systems have to decide what makes the difference between the safety or danger for our data. We look at different types of machine learning algorithms that we use, their advantages and disadvantages, effectiveness and application in systems to successfully detect different types of cyberattacks. As these models for intrusion protection systems evolve, we hope that our systems will be secured with each new attack that has been suffered.**

Keywords*— *cybersecurity; intrusion detection; machine learning; data protection;

I. Introduction

In today's digital world, where we store vast amounts of data and have many transactions with that data, one key factor is protecting the systems and networks that make it all possible. In the field of cybersecurity, there are intrusion detection systems and intrusion prevention systems whose main task is to detect and sometimes prevent potential cyber-attacks and threats made against our systems and networks. These systems employ different intrusion detection methodologies, signature-based, anomaly-based, or hybrid approaches [1]. Anomaly-based detection uses statistical and machine learning models to establish a baseline of normal behavior of network traffic and data in the system, and then identifies any deviations from this norm as potential attacks or threats. Although it is a good approach for detecting unknown attacks, it sometimes allows false positives and negatives.

Machine learning algorithms are used in cyber security for their ability to analyze complex cyber-attack patterns where there are a huge number of data parameters and attack vectors. Based on those parameters they should use their predictive power to manage the prevention of the attacks by dropping or blocking of malicious traffic. It is important to understand threat patterns by observing the behavior of attackers and their intrusion attempts, and system behavior to construct a good machine learning-based detection security tool. Machine learning offers supervised learning algorithms (such as SVM, LR, KNN, Random Forest) and unsupervised learning algorithms (Fuzzy C, K-means clustering) for classification based on training data [2].

In general, the classification can be binary, where the target variable is labeled as "attack" or "normal", or multiclass classification, where "normal" or one of several already known types of attack is defined. Supervised learning provides a precise decision by mapping input data with an output label for a specific attack, while unsupervised learning looks for similarities in the data where attacks are detected and groups them. Unsupervised learning is good when dealing with an attack that has not been seen or analyzed before, but shows some similarity to existing attacks. The figure below summarizes the options for machine learning-based intrusion detection techniques [3].

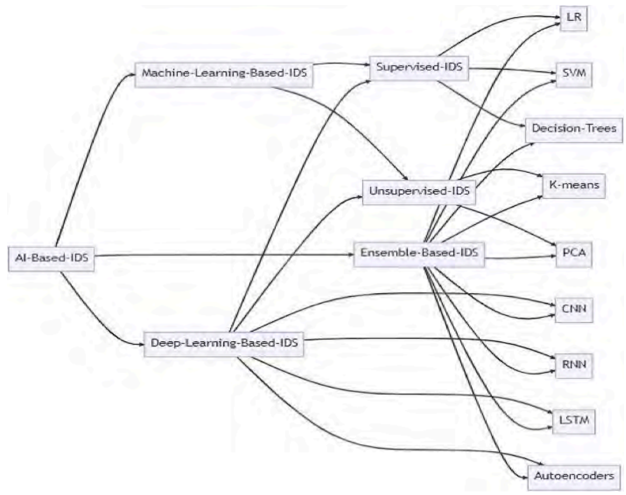

Fig 1. Different types of AI-based intrusion detection techniques and algorithms

In our analysis, we focused mainly on supervised learning algorithms which are discussed in detail later in this text.

II. Data

The data we used to analyze the algorithms is from the CICIDS2017 dataset, collected and formatted by the Canadian Institute for Cybersecurity, or CIC (Canadian Institute for Cybersecurity) [4]. The dataset itself has so-called benign (normal) and most recent attack data, which is similar to real-world data from captured packets (PCAPs). Additionally, there is information about labeled data streams such as time, source and destination IP address along with ports, protocols and attacks in CSV files. This data is obtained from analyzed network traffic using their CICFlowMeter tool.

CICFlowMeter is a tool for obtaining data flows from network traffic that generates 84 features for the traffic [5]. It reads the pcap file and generates a graphical report of the extracted features, and additionally provides a csv file for the same report. We used some of these csv data and features to train and test machine learning models.

The data set was collected over the course of one working week, from 9:00 AM on Monday, July 3, 2017, to 5:00 PM on Friday, July 7, 2017. On Monday, it turned out that there were mostly benign attacks, i.e. normal behavior in traffic. During the following days (Tuesday, Wednesday, Thursday and Friday), various cyber-attacks were implemented on the system such as Brute Force FTP, Brute Force SSH, DoS, Heartbleed, Web attacks, infiltrations, botnets and DDoS in various forms.

In the CICIDS2017 full file, the csv files were split by individual days. We took the dataset files from all the days and analyzed them separately. Each model was trained and tested on the data (the data was split, train-test) of every day separately, with results obtained for each day. We did this to test the models separately for each set of attacks by day, and to see if each model, if retrained for each day, could conclude that an attack had occurred, regardless of previous days and experiences. Each day has a different data subset where the number of instances varies, because the traffic also varies from day to day. However, there is also dirty data in them, data that has NaN or NULL values for some parameters, which cannot be used when training the models, so additional cleaning was done by discarding these values.

In the dataset 84 features were generated by the tool. From all of the features 79 are used as valid, because the remaining 5 are features that represent specific information about the machine being analyzed, not the traffic itself. From the features themselves, information can be extracted about the destination port, the number of packets in both directions of traffic, packet lengths, frame lengths, information about packet headers and message format, information about packet-specific flags, sending and receiving speed, duration of active sending periods and passive periods where the network is less loaded and other statistically derived parameters that are important for system and network behavior.

Below is an image of the correlation matrix with the most mutually correlated features. Most of them did not show any high correlation, or in other words, a large number of features introduce a moment of uniqueness, and those that are highly correlated are directly derived from each other (for example, the number of packets in a stream, with a flow rate of packages). One of the challenges from this dataset is the low correlation between the target variable and the features.

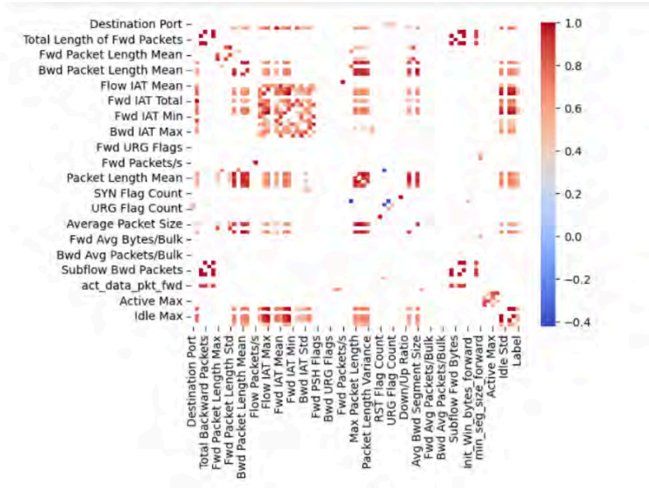

Fig 2. Correlation matrix of the features used and the target variable

As mentioned before, the supervised learning algorithms use labels for defining normal behavior or some type of attack. The dataset uses multiclass labeling, where besides the normal behavior label BENIGN, we have a list of labels mapped with every type of attack that was performed on the system. For the label of the target variable that would signify some type of attack, we have the following attack types:

- FTP - Patator
- SSH - Patator
- DoS Goldeneye
- DoS Hulk
- DoS Slowhttptest
- DoS slowloris
- Heartbleed
- Web Attack - Brute Force
- Web Attack - SQL Injection
- Web Attack - XSS
- Bot
- PortScan

Every one of these attacks has its own characteristic behaviors and impacts on the network traffic, which can be predicted using the help of machine learning models.

III. Methodology

For the development of the intrusion detection models and data preprocessing, we used the Python library scikit-learn, which provides various and useful functionalities, models, functions, and visualizations for working out the problem [6].

In the data preprocessing, we encountered two problems that needed to be addressed. The first was the measured data values that were approaching infinity and were larger than the maximum value of float numbers. All those instances that had this issue, had the values substituted with the maximum float 32 value. The second issue was dealing with the NaN or NULL values, where in some cases we had to substitute some of those values with the average value for that feature, or remove those instances entirely to achieve higher accuracy and better performance.

Before we establish the models, and train them to have some sort of predictive power or ability, we divide the dataset into a training set which includes 80% of the entire dataset, and a test set which includes the rest 20% of the data. In addition, we used stratification when dividing the dataset, so that there is an equal distribution of the classes of the training and test set. Given that most of the analyzed data were benign attacks (no attack), this prevents additional mistakes if a real attack instance was somehow not included in one of the train or test sets. We chose a few models for training and testing intrusion detection, and we kept the choices to only the most widely used classifiers which give a higher certainty in the decisions. We trained the Decision Tree Classifier, Random Forest Classifier[7], KNN Classifier [8] (k=5) and XGBoost Classifier [9]. Some algorithms such as SVM require a lot of resources for working through large datasets such as this one, and because of that they are inefficient for training and there is no result even after long training periods (because of the feature vector size). Our goal was to analyze efficient algorithms only, so these types of algorithms were not considered.

It is important to mention that every one of these models was trained separately and anew for every single day, so there is a specific distribution of predictions of the different types of attacks that happened during those days, and so we can see which model can best predict which types of attacks. For measuring the performance of each of the algorithms for every day, we took the accuracy as a metric, and the confusion matrices. The accuracy, despite being very high for almost all of the models, gives a numeric measure of how the models perform in comparison to the others, while the confusion matrices give a representation where each of the models make mistakes or misclassified any of the attacks.

IV. Results

After training the models, they were tested on their corresponding test sets, where the accuracies for each of the prediction algorithms were measured on different days.

TABLE I. ALGORITHM ACCURACIES PER DAY

Day	Random Forest Accuracy	XGBoost Accuracy	KNN Accuracy	Decision Tree Accuracy
Monday	1.0	1.0	1.0	1.0
Tuesday	0.9999663	0.9999887	0.9990801	0.9999887
Wednesday	0.9995084	0.9997253	0.9950048	0.9994650
Thursday (morning)	0.9957148	0.9964485	0.9953919	0.9954213
Thursday (afternoon)	0.9999653	0.9999480	0.9998960	0.9999480
Friday (morning)	0.9994502	0.9998429	0.9960992	0.9997120
Friday (afternoon)	0.9998952	0.9999301	0.9983418	0.9998603

We can see that the traditional machine learning algorithms have good performances when a dataset has enough instances of an attack, and the type of attack is singled out or is in a combination with other types of attacks of similar nature. (many web attacks at once, or many brute-force attacks at once). In this case, the models train relatively quickly and give test results with a fairly high accuracy. The analysis using confusion matrix comparisons is represented for every day separately, for all algorithms, because every day has different types of attacks and it is important to show where there is a gap or a mistake in the decision of each of the classifiers for every type of attack. In a table format it is defined how each of the algorithms classified each of the attacks.

A. Monday (no attacks)

On Monday, there are no attacks, and all of the instances are with normal behavior, the only class that is detected from all the models is BENIGN.

B. Tuesday (brute-force patator attacks)

On Tuesday, FTP-based and SSH-based brute-force attacks had occurred using tools known as patators. Here the models had classified part of the instances as attacks, where XGBoost and Decision Tree had shown the best detection accuracy, while the KNN detection model had made the most mistakes.

TABLE II. CONFUSION MATRIX RESULTS OF THE MODELS WHEN DETECTING BRUTE FORCE ATTACKS

Random Forest

	BENIGN	FTP-Patator	SSH-Patator
BENIGN	86378	0	0
FTP-Patator	1	1587	0
SSH-Patator	2	0	1177

XGBoost

	BENIGN	FTP-Patator	SSH-Patator
BENIGN	86378	1	0
FTP-Patator	0	1587	0
SSH-Patator	0	0	1179

KNN

	BENIGN	FTP-Patator	SSH-Patator
BENIGN	86330	7	41
FTP-Patator	5	1581	2
SSH-Patator	25	2	1152

Decision Tree

	BENIGN	FTP-Patator	SSH-Patator
BENIGN	86378	0	0
FTP-Patator	1	1587	0
SSH-Patator	0	0	1179

C. Wednesday (denial-of-service attacks and heartbleed)

Wednesday covers different types of DoS attacks, which use different strategies to disable the target system by wasting its resources. Generally, XGBoost again was the best classifier for this type of attack. However, an interesting conclusion is that all of the models make a certain mistake when classifying the DoS Hulk (DoS HTTP Unbearable Load King) attack, which generates a large volume of HTTP GET requests to overwhelm a server. Additionally, none of the algorithms made a mistake when detecting a Heartbleed attack, which is considered to be a rarer type of attack, seeing how the vulnerability that causes it is already fixed and implemented in most systems.

TABLE III. CONFUSION MATRIX RESULTS OF THE MODELS WHEN DETECTING DENIAL OF SERVICE AND HEARTBLEED ATTACKS

Random Forest	BENIGN	DoS Goldeneye	DoS Hulk	DoS Slowhttptest	DoS slowloris	Heartbleed
BENIGN	87959	1	37	3	1	0
DoS Goldeneye	3	2051	5	0	0	0
DoS Hulk	19	4	46192	0	0	0
DoS Slowhttptest	1	0	0	1095	4	0
DoS slowloris	0	0	0	1	1158	0
Heartbleed	0	0	0	0	0	2

XGBoost	BENIGN	DoS Goldeneye	DoS Hulk	DoS Slowhttptest	DoS slowloris	Heartbleed
BENIGN	87985	0	14	2	0	0
DoS Goldeneye	2	2051	6	0	0	0
DoS Hulk	1	6	46108	0	0	0
DoS Slowhttptest	1	0	0	1096	3	0
DoS slowloris	1	0	0	1	1157	0
Heartbleed	0	0	0	0	0	2

KNN	BENIGN	DoS Goldeneye	DoS Hulk	DoS Slowhttptest	DoS slowloris	Heartbleed
BENIGN	87514	22	417	24	24	0
DoS Goldeneye	20	2033	5	1	0	0
DoS Hulk	136	3	46076	0	0	0
DoS Slowhttptest	19	0	0	1077	4	0
DoS slowloris	12	1	0	3	1143	0
Heartbleed	0	0	0	0	0	2

Decision Tree	BENIGN	DoS Goldeneye	DoS Hulk	DoS Slowhttptest	DoS slowloris	Heartbleed
BENIGN	87969	1	22	4	5	0
DoS Goldeneye	1	2053	5	0	0	0
DoS Hulk	13	5	45994	1	0	0
DoS Slowhttptest	4	3	0	1086	7	0
DoS slowloris	0	0	0	3	1156	0
Heartbleed	0	0	0	0	0	2

D. Thursday (web attacks and infiltration)

On Thursday we have two attack periods, one in the morning and one in the afternoon, with different types of attacks.

TABLE IV. CONFUSION MATRIX RESULTS OF THE MODELS WHEN DETECTING WEB ATTACKS

Random Forest	BENIGN	Web Attack – Brute Force	Web Attack – SQL Injection	Web Attack – XSS
BENIGN	33635	0	0	0
Web Attack – Brute Force	5	243	1	53
Web Attack – SQL Injection	1	1	2	0
Web Attack – XSS	4	81	0	45

XGBoost	BENIGN	Web Attack – Brute Force	Web Attack – SQL Injection	Web Attack – XSS
BENIGN	33635	0	0	0
Web Attack – Brute Force	2	259	0	41
Web Attack – SQL Injection	1	0	3	0
Web Attack – XSS	3	74	0	53

KNN	BENIGN	Web Attack – Brute Force	Web Attack – SQL Injection	Web Attack – XSS
BENIGN	33625	9	0	1
Web Attack – Brute Force	9	248	0	45
Web Attack – SQL Injection	1	2	1	0
Web Attack – XSS	3	87	0	52

Decision Tree	BENIGN	Web Attack – Brute Force	Web Attack – SQL Injection	Web Attack – XSS
BENIGN	33634	1	0	0
Web Attack – Brute Force	3	226	3	70
Web Attack – SQL Injection	0	0	3	1
Web Attack – XSS	2	76	0	52

One type of attacks are the web attacks, which exploit some vulnerabilities in web applications, where some of the more frequent ones are SQL injections, and sometimes in badly constructed application mechanisms, XSS (Cross-site scripting) attacks are possible. With this type of attack, all algorithms showed some level of confusion in distinguishing between XSS attacks and SQL injection attacks.

This makes sense to a certain degree, given that both types of attacks are similar in the way that they inject explicit data or program code (scripts) into the system, and the distinction between what is data and what is attack code is a more complex problem.

Thursday afternoon showed the infiltration attacks, which means that someone got unauthorized access to our system, and perhaps tried to do something with the system afterwards.

TABLE V. CONFUSION MATRIX RESULTS OF THE MODELS WHEN DETECTING INFRILTRATION ATTACKS

Random Forest

	BENIGN	Infiltration
BENIGN	57710	0
Infiltration	2	5

XGBoost

	BENIGN	Infiltration
BENIGN	57710	0
Infiltration	3	4

KNN

	BENIGN	Infiltration
BENIGN	57710	0
Infiltration	6	1

Decision Tree

	BENIGN	Infiltration
BENIGN	57709	1
Infiltration	2	5

Even though there were fewer instances of these attacks, the models still sometimes misclassified the attack as BENIGN, which indicates that passive infiltration can be confused with some normal system behavior.

E. Friday (bot attacks and port scanning)

On Friday there were two attack periods as well, morning and afternoon, namely bot (or botnet) attacks and port scanning attacks.

TABLE VI. CONFUSION MATRIX RESULTS OF THE MODELS WHEN DETECTING BOT AND BOTNET ATTACKS

Random Forest

	BENIGN	Bot
BENIGN	37804	1
Bot	20	373

XGBoost

	BENIGN	Bot
BENIGN	37801	4
Bot	2	391

KNN

	BENIGN	Bot
BENIGN	37739	66
Bot	83	310

Decision Tree

	BENIGN	Bot
BENIGN	37801	4
Bot	7	386

With the bot attacks, the Random Forest and KNN models sometimes made misclassifications of BENIGN behavior, to be classified as some bot attack.

TABLE VII. RESULTS OF THE MODELS WHEN DETECTING PORT SCANNING ATTACKS

Random Forest

	BENIGN	PortScan
BENIGN	25505	1
PortScan	5	31781

XGBoost

	BENIGN	PortScan
BENIGN	25506	0
PortScan	4	31782

KNN

	BENIGN	PortScan
BENIGN	25457	49
PortScan	46	31740

Decision Tree

	BENIGN	PortScan
BENIGN	25503	3
PortScan	5	31781

For the end of the attacks on Friday, a few port scanning attacks were performed, where the attacker aims to find an open network port in the system, through which they could access data or system resources, or disable communication through that port. In this type of attack, similarly to the bot networks, sometimes BENIGN behavior is misclassified as a port scan attack. The KNN model made more mistakes than the rest, even sometimes recognizing a port scanning attack as normal behavior, when it isn't.

V. Conclusion

When developing an intrusion detection system using traditional machine learning, we would have to make a decision whether one model would be used for all types of attacks, or we would group the attacks by models, and set separate models for a certain type of attack which would work in parallel on the inference, meaning one packet or flow would be tested by more than one model at once. We tried to train one model for all the days at once. If we want to use one model for all types of attacks, we have to consider the following:

- XGBoost does not offer sufficient performance because of the required limit of choosing the number of classes. This must be made despite using the objective='multi: softmax', because it does not count the classes automatically. After manually setting the number of classes, we have an issue with not knowing the specified type of attack. This means that serial training concurrently is not a possibility with this algorithm and it is not flexible for possible future changes in the system.

- On the other hand, the Random Forest classifier offers serial training, but we can see it fails to keep a consistent accuracy when there is a change in the attack pattern (from brute-force attacks to DoS attacks). The KNN algorithm makes the same mistakes as the Random Forest algorithm - during drastic changes in the attack type, and additionally the training time is significantly longer because of the feature vector size.

In conclusion, with the use or inference is that if we use the traditional machine learning algorithms, we have to be careful with two things. One is that the attacks in the datasets have to be carefully isolated and grouped so that the models can be trained well on the data, a large number of attacks at once (in one day or in any different/other unit) can lead to poor performance of the model. The other is that inference should be made by many models at once (one for brute-force, one for web attacks, one for infiltration etc.) and not just one model for all types of attacks because the parameters are very dynamic regarding the type of cyberattack.

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Binary Classification of VPN Proxy IP Address

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***Abstract*— This paper introduces a binary classification model to determine whether an IP address is associated with a VPN or Proxy service, using anonymized data from CrowdSec's cybersecurity platform, which integrates attack alerts and additional features. Given the dataset's significant imbalance—only 5% of records represent VPN or Proxy usage—this poses challenges for standard classification techniques. Our approach involves exhaustive data investigation and processing, advanced feature engineering to extract relevant patterns from time-series data, and the deployment of diverse machine learning models. Balancing techniques are implemented to improve classification performance on imbalanced data. The proposed model achieved an accuracy of 97% and an F1-score of 0.55, demonstrating its effectiveness in detecting anonymized malicious activities. These results suggest that while our model significantly improves threat detection, further enhancements in precision and recall are necessary to strengthen CrowdSec's ability to protect individual users and businesses against anonymous cyber threats.**

Keywords— VPN, Proxy, machine learning techniques

I. INTRODUCTION

In the domain of cyber security, recognizing malicious activities and their sources is of greatest importance for defending digital assets. **CrowdSec**, a cyber-security corporation, leverages crowd sourced collaborative intelligence to recognize threats and malicious activities. Their freely-available software, the **CrowdSec** Security Engine, constantly collects malicious activities, including the attacker's IP address and a timestamp. Specifies the critical part of VPNs and proxies in recognizing attacker's identities, precisely classifying IP addresses as either VPN/proxy or not is a significant task.

This paper works towards constructing a predictive classification model to classify IP addresses based on even if they are related with VPN or Proxy services. Taking advantage of an anonymous dataset containing attack records, this project will implement diverse machine learning techniques to develop a powerful classification model. The dataset provides notable challenges, such as its imbalanced nature, with only 5% of the records recognized as VPNs or proxies, involving highly developed feature engineering and model balancing approaches.

The paper gives a comprehensive overview of various approaches, beginning with data investigation and processing, followed by feature engineering to extract significant understandings from the time-series data. Various machine learning models will be trained and estimated their performances, with the most accurate performance model being chosen determined on its performance on an unseen test set. The greatest goal is to enhance CrowdSec's malicious detection capabilities, developing a secure digital environment.

The rest of the paper is organized as follows: Section II summarizes the related work, Section III explains the experimental setup, and Section IV presents and elaborates the results, while Section V concludes the paper.

II. RELATED WORK

The rise in VPN and proxy use for anonymizing online activities challenges organizations in distinguishing legitimate users from those bypassing security measures. Accurate classification of such traffic is crucial for preventing unauthorized access and safeguarding data. Prior research has applied machine learning to improve detection and strengthen cybersecurity.

This study [1] discovers by providing a thorough summary of the challenges and techniques involved in identifying anonymizing web proxies, which are frequently used by individuals for concealing their identities. With an accuracy of 94.6%, the authors' neural network-based model effectively classifies network traffic, identifying between regular and anonymized proxy traffic. The study emphasizes the importance of this approach to enhance network security, particularly in circumstances where identity masking and illegal access are threats. Despite the encouraging consequences, the scientists believe that more research is necessary to further develop the model's accuracy and lower the number of false positives and negatives. This involves investigating larger datasets as well as additional machine learning techniques. This approach provides an excellent platform for future breakthroughs in proxy detection.

This thesis [2] offers a thorough description of machine learning-based approaches for identifying proxies and Virtual Private Networks (VPNs). The difficulty in recognizing illegal users that use these identity-masking techniques is investigated by the author, as it creates serious security risks for internet companies such as Facebook and Netflix. The research provides computational models based on multi-layered neural networks which are intended to classify network traffic as being generated by a user's device either directly or indirectly (via the use of proxies or VPNs). In this paper, two OpenVPN protocol configurations and models for traffic detection from concealing proxies are developed and tested. The results indicate that these algorithms are capable of accurately categorizing this type of traffic, showing great promise for improving the safety measures that online services use to identify unwanted access.

III. EXPERIMENTAL SETUP

A. Dataset Analysis for Cyber Attack Classification

The dataset comprises 61,629,685 instances of network attacks, with an emphasis on various attributes related to both the defender and the attacker. Each network attack record is described by the following attributes:

attribute	type	description
attack_time	datetime	Timestamp when the attack was recorded.
watcher country	category	Country where the entity observing the attack is located. Indication of the geographical location of the observer.
watcher_as_num	float	Autonomous System Number (ASN) of the watcher.
watcher_as_name	category	Name associated with the watcher's ASN;
attacker country	category	Country of the attacker
attacker_as_num	float	Autonomous System Number (ASN) of the attacker.
attacker_as_name	category	Name associated with the attacker's ASN
attack_type	category	This categorizes the nature of the malicious activity.
watcher_uuid_enum	Int	An encoded identifier for the watcher. This is a unique identifier for the watcher entity, often used for anonymization or indexing purposes.
attacker_ip_enum	Int	An encoded identifier for the attacker's IP address. Similar to the watcher UUID, this provides a unique identifier for the attacker's IP, aiding in analysis while preserving privacy.
label	category	A label indicating the classification of the attack.

(*)ASNs are unique identifiers assigned to networks on the internet, which help in routing traffic.

Fig. 1 Dataset Analysis for Cyber Attack Classification

(*)ASNs are unique identifiers assigned to networks on the internet, which help in routing traffic.

B. Visualization for Cyber Attack Classification

In this paper, we perform a comprehensive overview of a dataset focused on cyber classification tasks. The primary goal is to make a complete exploration of the data distribution, identify patterns and understand the relationship between different key features to aim in the implementation of classification models. This section will represent visual interpretations to provide a comprehensive overview of the dataset. Understanding the relationship and distribution of key features is crucial for visualizing it and it is the primary step before further processing and analysis in the following sections.

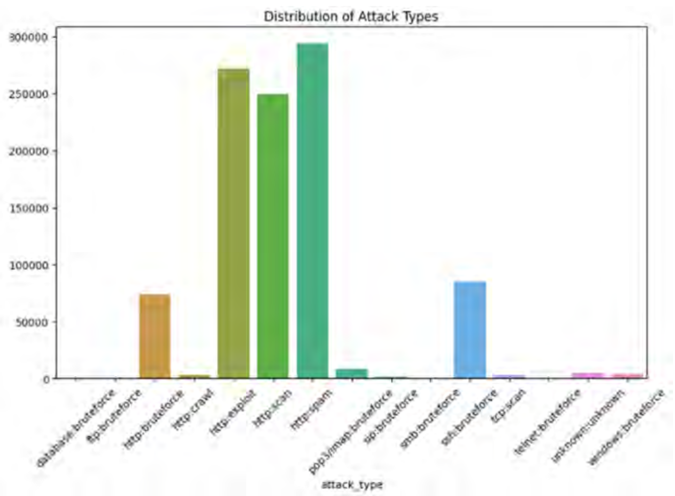

Fig. 2 Distribution of attack type

The first visualization diagram in Fig. 2 demonstrates the distribution of various attack types in the dataset to illustrate the frequency of each type of attack. Three attack types are the most frequently encountered attack types: **http:exploit**, **http:bruteforce**, and **http:spam**. Attack types such as **windows:bruteforce** and telnet:bruteforce are much less common, which indicates that they are rare events. The main insight is that the dataset is unbalanced on account of a variety of attack types. We can utilize a variety of techniques to overcome unbalanced distribution of attack types such as resampling to create a more balanced feature set. Our primary goal is to develop a good classification model that generalizes effectively to all attack types while filtering and selecting data based on higher frequency.

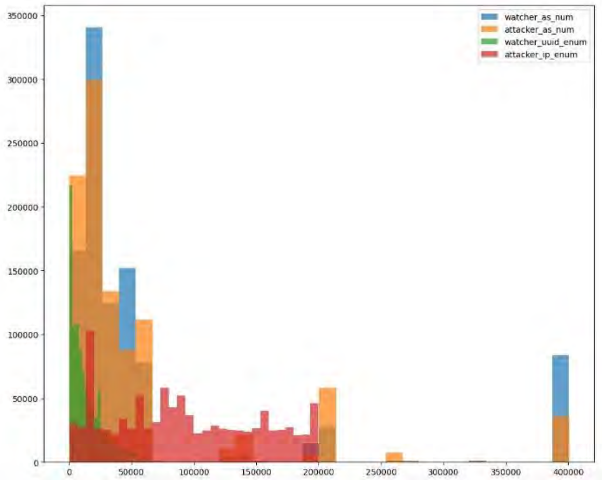

Fig. 3 Numerical feature distribution

In the following part of this section, we will present interpretations of numerical feature distribution in order to gain a better knowledge of the dataset. From Fig. 3, the conclusion is that both features **watcher_as_num** and **attacker_as_num** demonstrate a right-skew distribution. This suggests that the majority of ASNs are in the lower numerical range, with fewer ASNs in the upper range. Leading to the conclusion that the network activity is concentrated in specific ASNs. Furthermore, the **watcher_uuid_enum** and **attacker_ip_enum** show a more uniform distribution, indicating a greater range of unique IDs and IP addresses within the dataset. Understanding these distributions is crucial for preprocessing steps such as normalization and transformation which increase machine learning model performance.

The comprehensive comparison of the boxplots for **watcher_as_num** and **attacker_as_num** by attack type in gives useful information for improving cyber security machine learning classification models. Fig. 4 displays the distribution of **watcher_as_num** values for different attack types, emphasizing the spread and outlier in each category. Attack type **http:bruteforce** shows a wide range of **watcher_as_num** values. This indicates that these attacks are being detected by a variety of ASNs. On the other hand, attack types such as

http:explot and **http:spam** are tracked by a more specific set of ASNs.

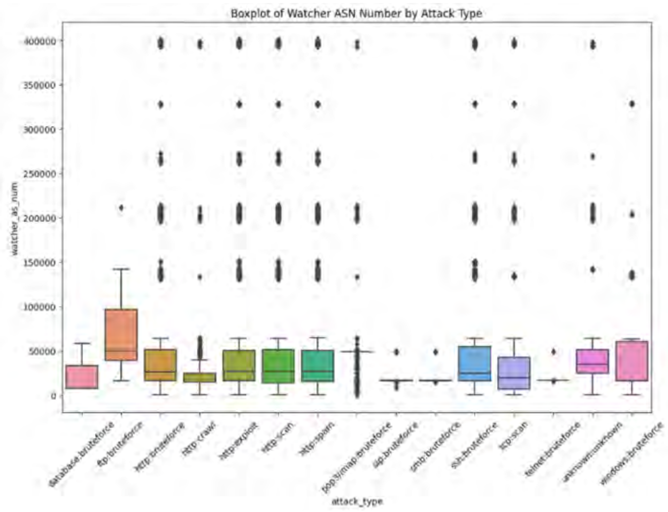

Fig. 4 Boxplot for watcher ASN number by attack type

The attack type labeled "unknown" includes a relatively wide range of **attacker_as_num** values, indicating that unknown-type attackers have spread across a broad spectrum of networks, suggesting a diversified set of ASNs participating in these attacks. Attack categories such as **http:exploit**, **http:scan**, and **http:spam**, in contrast, show a slightly uniform spread of ASN numbers, indicating that these attacks are concentrated in specific ASNs. The presence of anomalies in a large number of attack types indicates that certain attacks come from ASNs that are not often linked to certain categories of attacks. Furthermore, the variety of ASN values for techniques of attack such as **windows:bruteforce** and **tcp:scan** is smaller, demonstrating that these attacks are more concentrated and limited.

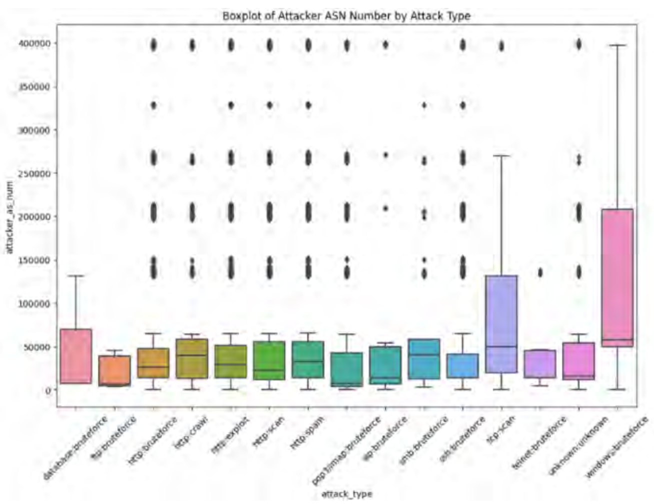

Fig. 5 Boxplot for attacker ASN number by attack type

C. Feature Engineering

The most important phase in this process is feature engineering, which transforms unprocessed data into useful features that improve the ability to forecast the results of the model. This paper generates features that determine the temporal, category, and frequency-based properties of the data by utilizing a number of advanced techniques.

Initially, the primary approach for generating a feature is based on time-based features, which calculates the number, standard deviation, and range of attack times correlated to each attacker (identified by **attacker_ip_enum**). These attributes can be particularly helpful in identifying patterns in attack time, such as whether an attacker becomes more active during certain periods or has a constant attack frequency. The standard deviation helps in recognizing the variability in attack timings, which can be related to various attack behaviors, while the time span is tracked in seconds to provide granularity.

Next, using the **one_hot_features_attack** method, the program processes the attack types using one-hot encoding. Attack types are classified as "type" and "service," and binary vectors are utilized to encode these categories. The model can understand categorical input using one-hot encoding by converting each category into a distinct feature that can have a value of 0 or 1, expressing the presence or absence of that category. Since it enables the model to learn patterns relevant to many different combinations of these features, this step is necessary for addressing the diversity of attack types and services. Furthermore, the normalization of the encoding attack types is done by dividing by the total number of occurrences, ensuring that the features accurately represent the proportional distribution of attack types for every attacker.

Additionally, frequency-based details about the attackers' ASN and nation are generated by the program. In order to demonstrate how common specific ASNs or nations belong to attackers, the frequency of each **attacker_as_name** (Autonomous System Number) and **attacker_country** in the dataset is taken into account. By calculating statistics that include the mean, maximum, and minimum frequency for each attacker, these features are improved even more. Target encoding (TE) is additionally utilized to the **attacker_country** feature, where each country's mean label—that is, the probability that an IP address is a VPN proxy—is calculated. Target encoding is especially helpful when instances when the category feature has predicted associations with the target variable, enabling the model to capture this connection more directly than one-hot encoding.

Finally, these generated features are put together and combined to produce a complete dataset which includes several data dimensions. By using a comprehensive approach to feature engineering, the model may better categorize VPN Proxy IP addresses by taking into account both the fundamental characteristics of the data and the connections between various features.

D. Model Training and Evaluation

The model development and evaluation method in this pipeline provides a comprehensive approach to evaluate the performance of six different classifiers: **RandomForest, GradientBoosting, LogisticRegression, DecisionTree, KNeighbors**, and **GaussianNB**. The dataset is methodically split utilizing **KFold** cross-validation with five splits to ensure that each model is trained and verified on distinct subsets, minimizing the possibility of over fitting while providing a more precise estimation of model performance. The pipeline utilizes a **SimpleImputer** to fill in values that are missing with the mean in order to handle missing data. Following that, it uses a **StandardScaler** for scaling features, which is necessary for maximizing the efficiency of many machine learning methods.

Threshold adjustment is an essential phase in this process, if the script iteratively adjusts the forecasting threshold to maximize the F1-score while maintaining an equitable balance between recall and precision. To guarantee integrity in the evaluation process, predictions are made on the test data after it has been processed and transformed in an approach similar to that of the training data. For the purpose of providing insights into the effectiveness of models and prediction confidence, performance measures including accuracy, precision, recall, and F1-score are taken into account for each fold, and visualizations such as confusion matrices and histograms of shown probabilities are provided.

IV. RESULTS

This section will present the measurements results from the experimental setup described in Section III.

In this study, several machine learning models, such as **RandomForest (**Fig. *6***)**, **GradientBoosting (**Fig. *7***)**, **LogisticRegression (**Fig. 8**)**, **DecisionTree (**Fig. 9**)**, **KNeighbors (**Fig. 10**)**, and **GaussianNB (**Fig. 11**)** are developed and tested using an entire approach involving cross-validation, feature engineering, and exact threshold adjustment. As previously stated, the dataset is analyzed to identify significant features such as time-based features, one-hot encoded attack types, and frequency-based features, leading to a wide variety of inputs for the models. Several metrics are employed to evaluate the performance of each model, including precision, recall, precision, accuracy, and F1-score. These measurements offer various perspectives on the model's effectiveness.

The confusion matrix data for each model provide an extensive overview of their performance. For example, the **RandomForest** model achieved a final accuracy of around 0.9817, indicating that it accurately predicted approximately 98.17% of the instances. However, accuracy alone can be misleading, especially with imbalanced datasets like this one, where the majority class may alter the results. Precision, which for **RandomForest** had a value of 0.5272, suggests that 52.72% of the cases displayed as positives turned out to be true positives, minimizing false positives. However, depending only on precision may result in missing false negatives, which is why recall is essential. The recall for **RandomForest** was roughly 0.5974, indicating that the model correctly identified 59.74% of the real positives but missed some, leading to false negatives. **RandomForest** obtained an F1-score of approximately 0.5604, indicating a decent trade-off between precision and recall.

Cross-validation was used to ensure that the models are strong and can generalize well to new data. Using numerous folds, each model's performance was validated across distinct data splits, lowering the risk of over fitting. The confusion matrices for further models, such as **GradientBoosting**, **DecisionTree**, and **LogisticRegression**, show similar patterns but with different metrics. For example, the **DecisionTree** model showed below average precision and recall, leading to a lower F1-score of 0.4372, indicating that it was less effective at balancing false positives and false negatives than **RandomForest**. The **GaussianNB** model generated acceptable recall (approximately 0.9881), but had lower precision, leading to a lower F1-score of 0.0463, suggesting that it generated more false positives.

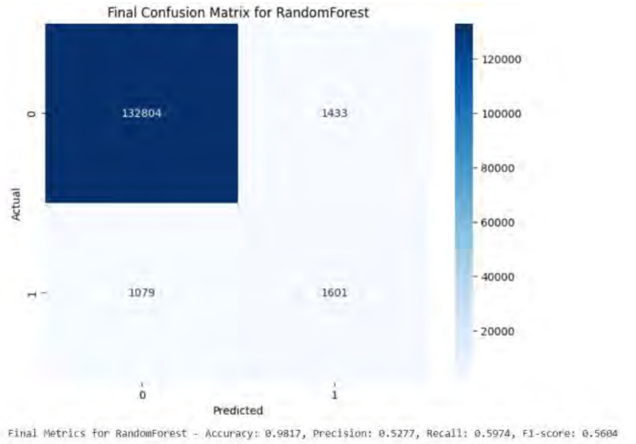

Fig. 6 Final confusion matrix and metrics for RandomForest,

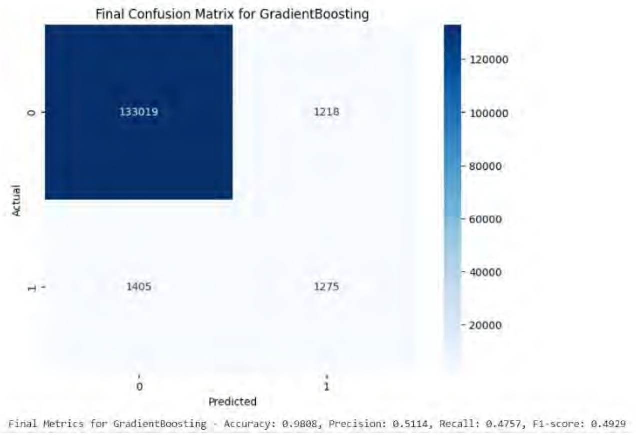

Fig. 7 Final confusion matrix and metrics for Gradient Boosting

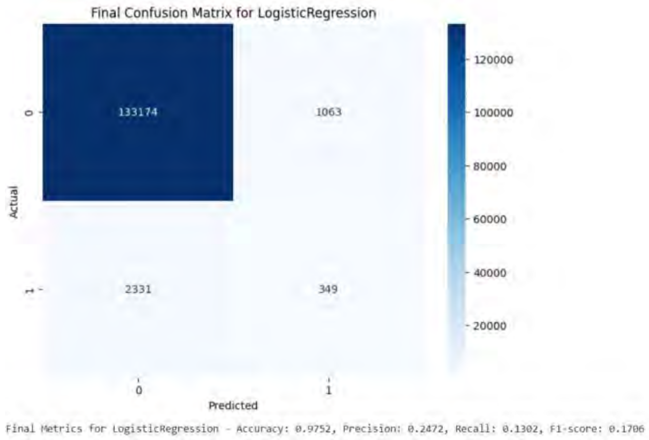

Fig. 8 Final confusion matrix and metrics for Logistic Regression

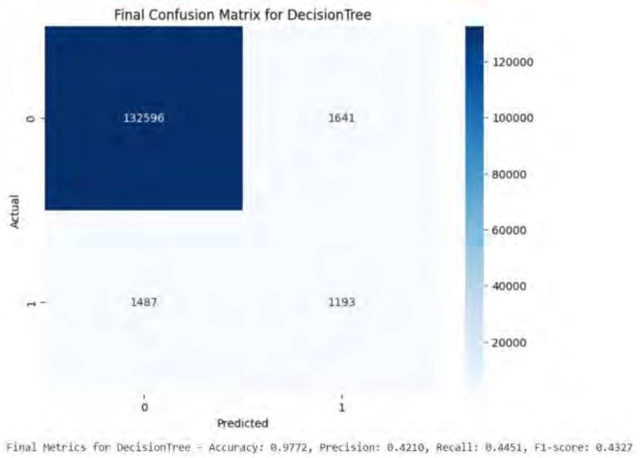

Fig. 9 Final confusion matrix and metrics for Decision Tree

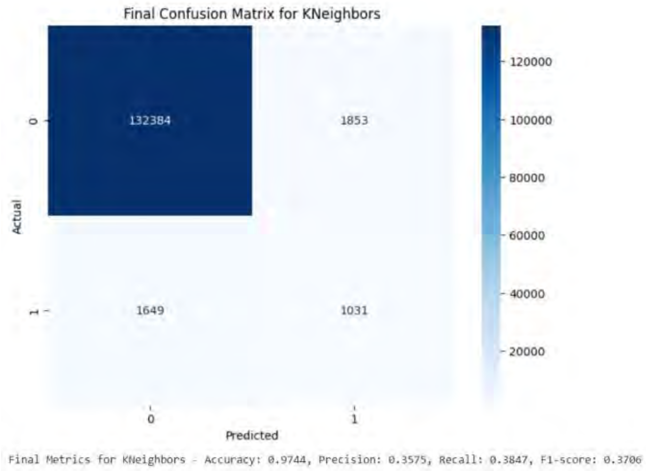

Fig. 10 Final confusion matrix and metrics for KNeighbors

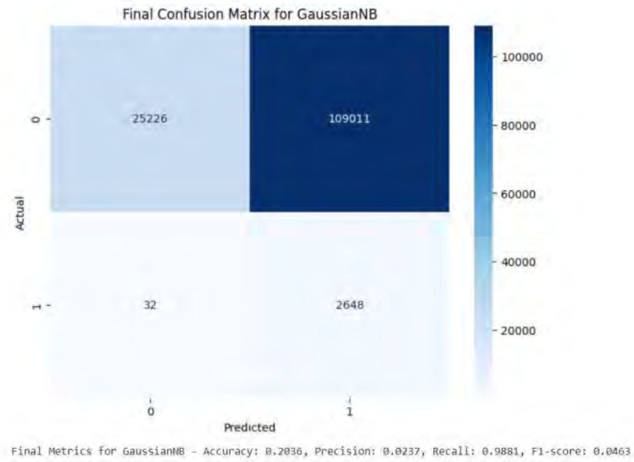

Fig. 11 Final confusion matrix and metrics for GaussianNB

The confusion matrices (Figures 6-11) show how effectively each model performs classification, especially in this skewed dataset. However, a more comprehensive review necessitates taking into account additional metrics that provide deeper understanding into model performance.

- Accuracy

Accuracy is the fraction of correctly classified instances among all instances. Although accuracy is frequently employed as the primary evaluation metric, it might be misleading when applied to imbalanced datasets in which the majority class dominates. The confusion matrices reveal that the majority of models are highly accurate: **RandomForest: 0.9817, GradientBoosting: 0.9808, LogisticRegression: 0.9752, DecisionTree: 0.9772, KNeighbors: 0.9744 and GaussianNB: 0.2036.**

Considering the great accuracy, it is obvious that this statistic does not fully represent the models' performance, particularly when class imbalance is present. For example, while the **RandomForest** model is 98.17% accurate, it misclassifies a substantial percentage of negative cases (as shown in the **RandomForest** confusion matrix).

- Precision

Precision measures the fraction of real positive predictions, demonstrating the model's ability to prevent false positives. Precision is especially critical when the consequences of a false positive are substantial. Precision was high for models like **RandomForest and LogisticRegression.** Our research results are **RandomForest: 0.5277, GradientBoosting: 0.5114, LogisticRegression: 0.2472, DecisionTree: 0.4210, KNeighbors: 0.3575 and GaussianNB: 0.0237.**

The **GaussianNB** model has the lowest precision, given to its tendency to forecast the positive class inaccurately (as evidenced by the large number of false positives). **RandomForest** had the maximum precision, with relatively few false positives.

- Recall

Recall measures how well the model detects real positive cases. A high recall is required when the cost of missing a positive (false negative) is large. Our research results are: **RandomForest: 0.5974, GradientBoosting: 0.4757, LogisticRegression: 0.1302, DecisionTree: 0.4451, KNeighbors: 0.3847 and GaussianNB: 0.9881.**

GaussianNB and **GradientBoosting** have competitive recall scores, indicating that these models could be beneficial in situations where false negatives must be minimized. However, the low precision of GaussianNB demonstrates that strong recall comes at the expense of increased false positives.

- F1 score

The F1-score balances precision and recall by computing their harmonic mean. It is an effective metric when both false positives and false negatives are significant. The F1-score provides a comprehensive perspective of a model's performance, particularly on imbalanced datasets. Our research results are: **Random forest: 0.5604, Gradient Boosting: 0.4929, Logistic regression: 0.1706, DecisionTree: 0.4327, KNeighbors: 0.3706 and GaussianNB: 0.0463**.

As expected, **RandomForest** had the greatest F1-score, indicating a strong mix of precision and recall. DecisionTree and **GradientBoosting** both performed well, with F1-scores above 0.4929, indicating that they can handle false positives and false negatives quite effectively.

These variations demonstrate the importance of considering various measurements instead of depending solely on one. Depending on an individual's application, a model that has greater recall may be selected if the cost of missing a positive is huge, while a model with greater accuracy may be chosen if false positives are more costly. By combining the confusion matrices with those indicators, we can better comprehend each model's advantages and drawbacks and select the most suitable one for deployment.

V. CONCLUSION

This study effectively develops a binary classification model for determining whether an IP address is associated with a VPN or proxy service, thus addressing an important cyber security concern. The study enhances the identification of threats by accurately separating anonymous malicious actions using anonymous data from **CrowdSec's** cyber security system, including attack warnings and other features. Because of the dataset's significant imbalance—just 5% of records suggested the use of a VPN or proxy—conventional classification techniques encountered a significant obstacle. However, the study overcame this imbalance through comprehensive data analysis, sophisticated feature engineering, and the use of different machine learning algorithms. The implementation of balancing techniques significantly enhanced model performance, making it suitable for imbalanced datasets. The model's investigation revealed that by carefully selecting features from time-series analysis and using a variety of machine learning techniques, it is possible to significantly enhance the classification of VPN and proxy IP addresses. This improvement adds immediately to CrowdSec's cyber security efforts, thus safeguarding individuals and organizations against anonymous attacks via the internet. The study highlights the importance of using an integrated strategy that includes data processing, feature engineering, and model evaluation to accomplish high-performance metrics in challenging, imbalanced datasets.

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A Review on Machine Learning Based Intrusion Detection System: Techniques, Public Datasets and Challenges

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Dedicated to Prof. Mile J. Stankovski on his anniversary

***Abstract*—This review paper focuses on the machine learning techniques used by the research community for detecting anomalies in network traffic in order to show intrusion activities. The paper states some of the state-of-the-art machine learning techniques used in anomaly detection. Furthermore, the paper briefly describes the evolution of training datasets, highlights the main representatives, and points out some of the shortcomings that should be taken into consideration while addressing the issues of anomaly detection with intrusion detection systems in modern IT network environments. The review emphasizes the perspectives for future work on this subject by presenting the challenges of training machine learning models for anomaly detection in intrusion detection systems.**

***Keywords*—key anomaly detection, intrusion detection systems, machine learning, IDS datasets**

I. Introduction

Detecting anomalies in network traffic is a method that can significantly improve network security[1]. The intrusion detection system's (IDS's) ability to distinguish between the normal (benign) traffic and abnormal (malicious) traffic increases the confidence in its deployment and helps in mitigating the operational malfunctions and security vulnerabilities.

The research community continuously searches for ways to ensure efficient security and quality of service in large-scale networks. The growth of new communication technologies and services, coupled with the rising number of web users, applications, interconnected network devices, and services, makes computer networks large and increasingly complex.

The term "anomaly" has various interpretations. Barnett and Lewis define an anomaly in a data set as an "observation (or a subset of observations) which appears to be inconsistent with the remainder of that set of data" [2]. Chandola et al. describe it as "patterns in data not conforming to a well-defined notion of normal behavior"[3]. According to Lakhina et al., "anomalies are unusual and significant changes in a network's traffic levels, which can often span multiple links"[4]. Hoque et al. define it as "non-conforming interesting patterns compared to the well-defined notion of normal behavior". These definitions highlight the role of anomalies in generated datasets and the importance of understanding the concept of normality in developing solutions to detect network anomalies.

Although it may seem straightforward, defining a region that denotes normal behavior and identifying anomalies that deviate from this pattern is quite challenging. The primary goals in this field are faster diagnosis, reduced complexity, and appropriate correction of causes.

This ability of machine learning (ML) models to detect anomalies by distinguishing normal from abnormal, can be included in intrusion detection systems (IDS) and enhance the security of IT networks. Achieving precise anomaly detection in IDS requires that a solid baseline of normal data points, structured in a dataset, must be established. Datasets consist of different features and measurements created by collecting data points from external activities and internal activities of the network hosts [5]. Data points collected from external activities represent the packet flows, while the internal activities are represented by system logs, host statistics etc., generated from the various processes and services running on the hosts. In the field of IT network security, ML models for anomaly detection can be trained with two different approaches: first by using data points from one data source and second by using data points from a combination of data sources.

The potential impact of this research effort is immense, it should inspire development of numerous models, algorithms, and mechanisms to ensure the security and health of increasingly large and complex network systems. As in [6],[7], the focus is primarily on the most popular techniques but also this paper is reviewing other important topics such as datasets, challenges and recommendations.

II. Related Work

In this part, we are going to review and synthesize existing research on anomaly detection in intrusion detection systems. The last 20 years have been clearly marked by many proposals for ML implementation in anomaly detection. This was stated by the authors of [8], where they emphasize that "ML is suitable for implementing IDS solutions in real time with no (or little) human supervision." This means that machine learning IDSs, by detecting anomalies in generated IT network data, can effectively detect known and unknown intrusions. IDS powered by machine learning algorithms can deliver robust protective measures against network intrusions and enable swift detection of security vulnerabilities, allowing for swift corrective actions to minimize potential harm.

The authors of [9] conducted a systematic review of data mining in big data for intrusion detection and concluded that the most used data mining techniques are Decision Tree (DT), Bayesian Networks (BN), k-Means, Artificial Neural Network (ANN), and Support Vector Machine (SVM). In the work of [10], the researchers presented various research papers that show the importance of ML in intrusion detection systems, particularly by implementing different classifiers for intrusion detection. The authors conclude that ensemble and hybrid classifiers have shown better performance than single classifier models. This is similar to the results of the work in [11], where the authors reviewed various studies and concluded that ensemble and hybrid classifiers demonstrated the highest predictive accuracy and detection rate, outperforming their single-classifier counterparts.

The authors of [12] focus on studying big data classification for intrusion detection. The approach with big data classification can help optimize the process of intrusion detection. Their work led them to the conclusion that the techniques and technologies used should be expanded toward verdict solutions to overcome big data classification difficulties. Some of the optimization techniques were addressed in [13], where the authors conducted a study that reviewed several optimization algorithms proposed in the past decade, providing researchers with insights into various intrusion detection approaches and highlighting the limitations and opportunities for designing improved algorithms. Each algorithm has its own strengths and weaknesses, which often need to be combined with other techniques for better performance.

The pattern matching relevant to network intrusion detection is addressed in this 2023 review [14], where the authors have outlined the widely adopted research and methods. The review assessed advancements in signature-based systems' pattern matching techniques, using both fixed strings and regular expressions, for handling large-data volumes in line with modern trends. The review discusses how machine learning techniques are increasingly important for analyzing malicious network traffic and strengthening defense against network intrusions, with the need to correlate large volumes of data from multiple network endpoints and security applications collected and analyzed by Security Event and Incident Management (SIEM) systems.

From the perspective of training ML models with data points collected from external host activities, numerous review papers were published specifically on working with packet flow data points. The authors of [15] have been working on synthesizing broadly published research papers regarding datasets in the field of Intrusion Detection Systems used for performance evaluation of ML-based IDS. The authors conclude that there is a need for updating contemporary datasets since they do not reflect new trends of attacks that include different processes and technologies. Additionally, the patterns in the datasets don't reflect realistic network scenarios. Similar results were presented in [16], where a study on various techniques for intrusion detection was conducted and shows that there might be a problem with updating the information for new attacks, resulting in high false alarms or poor accuracy. The study reviewed popular datasets, stating that there should be more new datasets with broader malware activities. In 2022, the authors of [17] used four popular datasets—KDD'99, NSL-KDD, CICIDS2017, and UNSW-NB15—to create a summarization and offer taxonomy. They state that feature selection is critical and almost always required for improving performance. Additionally, they address the issue of data imbalance as a problem that can be overcome with a sampling approach. Regarding the process of selecting dataset features for better results, the authors of [18] demonstrated the use of Feature Elimination and Principal Component Analysis (PCA) over various classification algorithms such as Decision Tree, Naïve Bayes, and Support Vector Machine, with the Decision Tree showing the best results. Working on a similar issue, the authors of [19] provided a comprehensive overview of various ML techniques for IDS, concluding that 58.33% of the research papers include the KDD-NSL dataset. The authors suggest using more modern datasets in future research and note that ensemble and hybrid classifiers have outperformed their single-classifier equivalents.

Although most of the work is done using datasets with external data points, there are studies that utilize data points from internal host activities [20], [21], [22]. However, this is not reflected in many review studies, and the overall approach is missing. Some recent reviews address the importance of combining external and internal data points in the so-called Predictive IDS approach [23]. Additionally, the authors of [24] focused on reviewing deep learning techniques for IDS by analyzing data points from network flow and system logs, although they do not emphasize the importance of datasets in developing IDS. One of the most comprehensive reviews was done in 2023 by the authors of [25], where they present internal data points as part of modern security architectures and devices responsible for securing the IT network perimeter.

The authors of [26], besides providing an extended overview of the taxonomy of network attacks, their tools, the most relevant features to detect them, data sources of IDSs, data types in datasets, the architecture of the IDSs, and the detection modes, are also addressing the challenges for future investigation. The authors point out that future challenges will be in defining what constitutes an anomaly and what does not. They also emphasize the tasks required for preprocessing data, as the datasets are enormous, and proper feature selection represents a significant challenge.

III. Machine Learning Techniques For IDS

As stated in the previous section, ML algorithms are widely used in conducting research studies on anomaly detection for IDS. These research studies have defined several state-of-the-art methods that can be used as benchmarks for future reference. Broadly, ML algorithms can be divided into two categories: Supervised ML and Unsupervised ML. The former uses labeled data for ML model development, while the latter uses unlabeled data.

The development of ML models includes the use of algorithms like k-Nearest Neighbor (kNN), Decision Tree (DT), Naïve Bayes (NB), and Support Vector Machine (SVM) for supervised ML, and K-means and Self-Organizing Map (SOM) for unsupervised ML model development. The application of all the mentioned ML algorithms in the field of anomaly detection, even outside of IDS in IT networks, defines them as representatives of state-of-the-art ML algorithms.

IV. Overview Of The Public Datasets

Anomaly detection for IDS is an important and hot topic for many researchers in the field of cybersecurity. They implement it in all aspects of IT network security, especially when processing security-related data to detect malicious activities. This requires quality IT network datasets that can help in setting the baseline for developing new systems and applications and setting benchmarks for future system evaluation.

Fortunately, the research community continuously develops network-related datasets that can be used for conducting research in the field of anomaly detection in IT network traffic. Although these datasets are not universally applicable to all systems, they can help in defining the core aspects of anomaly detection in intrusion detection systems.

In the next sections, we will present some of the most common publicly available network datasets. We will review two representatives of the datasets in three distinctive periods of development, which we have named: Initial Dataset Collections, Progressive Dataset Collections, and Advanced Dataset Collections. This selection of datasets reflects the historical aspect of dataset development, their usage by the research community, the diversity of attacks covered by the dataset, and the volume and quality of data.

A. Initial Dataset Collections

This collection of datasets was built in the period from the mid-90s until the mid-2000s and represents IT network datasets that are missing records of data extracted from modern network protocols. Additionally, these datasets usually contain inconsistent and duplicate data points in the records[27]. Some of the representatives include KDD Cup 1999 and NSL-KDD Dataset, which are described in the following paragraphs.

- KDD Cup 1999 Dataset

Developed by DARPA, KDD CUP 99 is a dataset that doesn't belong to packet capture or flow capture formats. This dataset consists of features collected from TCP connections and failed logins. In this dataset, there is no IP address. With more than 5 million data points, this dataset includes 20 different types of attacks. The KDD CUP 99 has been broadly used over the last 25 years by the research community in building and evaluating systems for anomaly detection. Since it was created in 1998, its biggest disadvantage is that the protocols used are old and don't reflect the current networking environment[27].

- NSL-KDD Dataset

NSL-KDD supersedes the KDD CUP 99. Various implementations and reviews have shown that KDD CUP 99 has a problem with a large number of duplicates in the dataset. This led to the development of NSL-KDD. This dataset contains 150,000 data points and is divided into training and testing subsets designed for intrusion detection. In terms of similarity to KDD CUP 99, NSL-KDD has the same features, and the traffic is dated from 1998. This means that the network traffic represented in this dataset is old and doesn't represent new IT network environments [28].

B. Progressive Dataset Collections

This collection includes datasets developed from the early 2010s to the mid-2010s. The need for the development of this collection arose from the disadvantages seen in datasets like KDD Cup 1999 and NSL-KDD. Some of the datasets from this period are shown in the following paragraphs.

- CTU-13 Dataset

Developed in 2011 by CTU University, Czech Republic, the CTU-13 dataset encompasses IT network traffic data points in three formats: packet, unidirectional flow, and bidirectional flow. This dataset represents network data from botnet attacks in 13 different scenarios. The traffic is labeled in three ways: one set is labeled as benign network traffic, another set is labeled as malicious network traffic, and the rest is labeled as background network traffic. This means that the background traffic can be either malicious or benign, and it is up to the user to divide the dataset into training and testing subsets.

- UNSW-NB15 Dataset

Created in 2015, the UNSW-NB15 Dataset represents IT network traffic captured in packet-based format. This dataset contains malicious and benign network traffic generated with the IXIA Perfect Storm tool over a period of 31 hours. Malicious traffic includes 9 different families of attacks such as DoS, exploits, fuzzers, backdoor, etc. The dataset can also be used in flow-based format, and it has additional features included. UNSW-NB15 is divided into two subsets: one for training and one for testing purposes. In comparison to the KDD datasets, this UNSW-NB15 has 45 distinct IP addresses.

C. Advanced Dataset Collections

The advanced datasets collection represents datasets with the most sophisticated collection of data points. Here, the research community has invested heavily in developing these datasets, and they are built with a diverse range of IT network protocols at various levels of the OSI model. Additionally, the datasets include records of data points representing various attacks, developed following different attack methodologies. Some of the representatives are shown in the following paragraphs.

- CICIDS 2017

One of the most advanced datasets for training intrusion detection systems is CICIDS 2017. Developed by the Canadian Institute for Cybersecurity, this dataset encompasses network traffic in bidirectional flow-based format and packet-based format. It consists of more than 80 network traffic features, and the researchers have extracted additional metadata about the attacks in the dataset and the IP addresses used. The dataset includes data points collected for normal user behavior generated with scripts. CICIDS 2017 contains various attacks such as Heartbleed, DoS, DDoS, SSH brute force, web attacks, and infiltration attacks.

- CUPID

With more than 50GB of data, the CUPID dataset represents one of the most robust datasets developed for training and evaluating IDS systems. This dataset has 179 unique hosts and generated network traffic that contains 75% TCP-based and 7.5% UDP-based protocols. This dataset includes network traffic that uses Internet Hypertext Transfer Protocol (HTTP), Simple Mail Transfer Protocol (SMTP), Internet Control Message Protocol (ICMP), Lightweight Directory Access Protocol (LDAP), Kerberos, Distributed Computing Environment (DCE) / Remote Procedure Call (RPC), Server Message Block (SMB), and Network Basic Input/Output System (NetBIOS). The rich variety of protocols included in this dataset is possible because of the different services involved in the traffic generation process, such as email, DNS lookups, or active directory accesses. Additionally, the dataset was created by considering the attacker's perspective and following the stages within the cyber kill chain attack strategy.

The presented datasets are just a small sample of the developed datasets used by the research community in developing ML models for anomaly detection in IDS. A more in-depth analysis of the various data points and dataset features was done by the authors of [29], where they analyze the strengths, weaknesses, limitations, and use concerns of different IDS datasets in their 2024 review paper. Their work makes it clear that each dataset has distinct attributes and compromises. Additionally, they suggest creating a unified approach to building datasets that encompass different dataset features and data points collected from different data sources. This is particularly interesting since, out of the 37 analyzed datasets, only two, MACCDC2012 and CICIDS-CRIME2018, consider data points from internal hosts like system logs and events. This means that a large number of research efforts in anomaly detection for IDS have been conducted without considering the information that can be extracted from internal data points.

Overall, the datasets used for anomaly detection in intrusion detection systems are focused on parameters collected or extracted from IT network traffic. This is clearly represented by the authors in [30], who collected data about 34 datasets used for training IDS in anomaly detection. By examining their findings, we can conclude that, although there are datasets with various approaches and collected features, these datasets lack syslog data points, which can be crucial in detecting anomalies in the network.

V. FEATURE CHALLENGES

When we take into consideration already proven ML algorithms for anomaly detection in IDS, we can conclude that the algorithms mentioned in the second part of these papers are some of the state-of-the-art ML algorithms for detecting anomalies in IT networks. This means they can determine intrusion with a very high probability. However, this doesn’t come without some considerations that need to be addressed. These considerations should mostly apply to the datasets used for the training and testing of ML models.

A. Unified Dataset

Current datasets used by the research community for developing IDS have unique qualities that should be thoroughly evaluated before use[29]. This evaluation should include an analysis of the attack types, the accuracy of the network traffic patterns, the size and complexity of the data, and whether the data is labeled or not. All of this should be done to ensure the selected dataset is appropriate for conducting the research. This means the process of selecting appropriate datasets is inefficient since researchers must spend more time evaluating the dataset. Dedicating one unified dataset for broader, or possibly all, future developments of IDS would optimize the process of developing anomaly detection systems based on ML.

B. Future Evolution

The continuous advancement of technology produces new and unforeseen threats to IT network environments. This is a challenging aspect for the future development of IDS based on anomaly detection. These systems, built on data points collected from previous periods, will not have the new threat patterns incorporated into the ML models. Therefore, a mechanism for continuous monitoring and updating should be introduced to help ML models evolve. How this will be introduced without affecting the current running process is one of the tasks for future research.

C. Multi-Data Source Approach

Since IT network environments today are complex structures with various security devices, IDS should be able to follow the baseline structure of the IT network, including all generated security data points, regardless of the data source from which they are extracted. In that sense, a multi-data source approach should be established. Data points should be extracted from both external and internal sources and encompassed in a reliable dataset that can be used to train ML models for anomaly detection. In the previous section, we noted that a recent study evaluated 37 datasets, but only two of them had data points extracted from internal data sources. This is a very low number of datasets that can offer a multi-data source approach, limiting the possibilities and objectives for future research.

D. Adversarial Attacks and Data Poisoning

Adversarial attacks, which involve the manipulation of input data to evade detection, and data poisoning, where attackers inject malicious samples into the training data, represent significant issues in developing ML models for anomaly detection with IDS[31]. These attacks can compromise the integrity and effectiveness of ML models. Prospective research should develop techniques for creating new generations of datasets resilient to these types of attacks and mitigate the effects of adversarial attacks and data poisoning. The approach should involve adversarial training, data sanitization, and robust learning algorithms[33][34].

E. *Imbalance in Dataset Classes*

The balance between benign and malicious data points in a dataset influences the performance of ML models. If there is an imbalance between these two classes, the model's performance will suffer significantly[35]. This can lead to biased models that perform poorly in detecting anomalies. Efforts to overcome these issues should include developing advanced techniques to address class imbalances. These techniques should involve building robust models with improved sampling methods, data augmentation, and the utilization of synthetic data [36][37].

F. *Data Anonymization*

Data anonymization is a process that can help secure personal and sensitive information embedded in the dataset by incorporating various modifications and exclusions, which leads to developing ML models with datasets that have modified or excluded private and sensitive information. This is an important issue since the manipulation of significant information in the dataset can lead to an irrelevant dataset. Irrelevance comes from the loss of essential features necessary for detecting intrusions[38][39]. The challenge is to preserve the performance of the model while anonymizing private or sensitive data. This should be done by introducing advanced techniques[40] for data anonymization while preserving the utility of the data and restricting access to private or sensitive information.

VI. CONCLUSION

In the previous sections, it was stated that detecting anomalies in IT network data can significantly help in denying and mitigating potential security and operational threats. The state-of-the-art ML algorithms for anomaly detection are available and can support us in developing ML models with reliable and efficient performance. Supervised ML algorithms have performed much better than unsupervised ML algorithms. Evaluations on advanced datasets have shown that the performance of the models is highly dependent on the type of ML algorithm and the dataset used in the training and testing phases.

In this paper, we presented that, although some algorithms have shown remarkable results, there are still challenges that need to be addressed when discussing intrusion detection in IT networks. In the future, the research community can significantly improve intrusion detection by addressing these challenges, which are mostly identified in the domain of datasets used for training and testing ML models. The diversity of information that datasets can hold by collecting data points from the network makes this area exciting, promising, and challenging for investigation. Making a breakthrough by resolving the presented challenges will foster the development of new generations of IDS based on detecting anomalies in datasets created from internal and external data sources.

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An IoT System for Detection and Displaying of PM Particles Concentrations in the Air

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***Abstract*—Main health issues with air pollution and insufficient local information on air pollution are discussed. A partial solution for the problem with a simple IoT system intended for PM particles detection and displaying is presented. Principles of operation and main components of the system are explained. Some of the challenges during the system design and implementation are discussed, particularly the method of establishing reliable PM particle information by sensor testing and calibration. The system consists of three parts: the detector, the display and the Cloud server. It is primarily intended for installation at schools. The main idea behind the display is to provide local information to the students, to instruct them about the actions they can take to protect themselves, and to raise their awareness of the pollution and the need to tackle it.**

***Keywords*—PM particles; IoT system; electronic design; sensor; Cloud server**

I. The Pollution Problem

Air pollution can be natural or produced by humans. During hot seasons wildfires and sand storms are typical natural sources of air pollution. Human activities in construction and in traffic are also regular sources of air pollution. Combustion and various gases present in industrial areas, as well as combustion for electricity production and heating, are sources of pollution in vicinity or within residential areas. Combustion for heating in some areas is especially present during cold season where atmospheric inversion episodes act as amplifier to the problem. The latest is very common in the basin of Skopje.

There are health risks with high concentrations of particulate matter (PM particles) in the air, which is a known fact, but people rarely know how they affect the health depending on their size. There are three typical sizes of particles that attack the body at different levels [1]. Particles between 5um and 10 um accumulate in the upper respiratory tract and the lungs and can be excreted relatively easy. As the size goes down so the penetration of the particles goes deeper. At 2.5um they accumulate in the alveoli and they become substantially harder to excrete. There they can cause infections and other respiratory problems. At sizes of 1um and below they pass the alveoli wall and get into the bloodstream. From there they can accumulate in any organ and slowly degrade it's function causing diseases from "unknown cause" even 10 to 20 years later. To get a better understanding of the particle sizes we can compare them with a human hair as depicted in Fig.1 [2].

In 2013 the World Health Organization classified the air pollution as a human carcinogen [2]. Prenatal exposure to high levels of PM2.5 particles may impair child's mental development. Children exposed to high levels of particulate matter can develop bronchitis at adulthood and suffer from lung damage. Unfortunately, besides throat discomfort, eye irritation or asthmatic reactions, people usually do not know the other consequences and do not pay attention to the pollution that is not detectable with our senses.

The PM particles information from official measuring stations is accurate but scarce. The situation at certain points away from the measuring station can sometimes differ significantly. This has inspired the citizens to take action in an attempt to fill the information gap. One such initiative is "Moj vozduh" where citizens participate with their own sensors and computers to send data to the server. An App is designed and made available free of charge for browsing the data at the available locations.

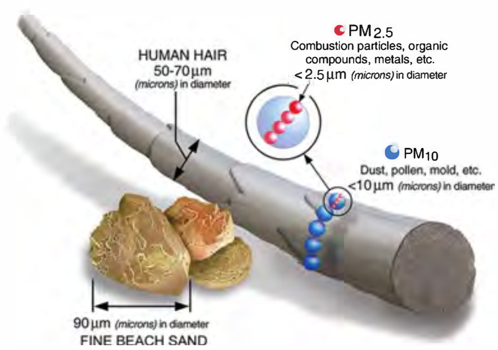

Image courtesy of EPA

Fig. 1. Particles compared to human hair

Material expenses for this work are covered by an EPICS in IEEE Grant.

The main problem with this approach is the reliability of the data because sensors are sometimes managed by inexperienced and/or incompetent people. Our approach is similar but we will apply careful sensor selection, testing and calibration. Additional difference in our approach is the added data presentation at the location of measurement.

II. The System Design

The initial idea for the local sensing device is presented in Fig. 2, while the idea of the system in the Cloud is presented in Fig. 3. Each device (local sensing unit) detects the PM particles concentrations and sends the data to the display and the ThingSpeak Server in the Cloud. Users can either see the current PM particles concentrations on the display locally or access the server through any Web browser and watch the data evolution in time.

Tight connection of the sensing unit and the display may appear as an obstacle. If it was wire connection, than it would require special cable drivers and protection circuits. Since the processors already have built-in wireless connectivity, the wireless connection was selected. The display could connect to a server running on the sensing unit but this has limited range and requires additional server software on the sensing unit. On the other hand we have server in the cloud where any device can connect, so we decided to get the data for the display from the ThingSpeak server. Now the sensing unit and the display are independent and can be connected through any access point. This even allows more displays to connect to a single sensing point – Fig. 4.

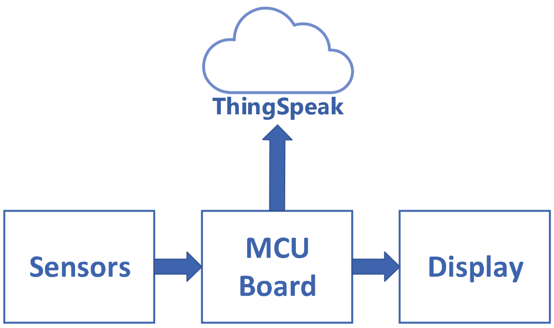

Fig. 2. Local PM detection, display and connection to the Server

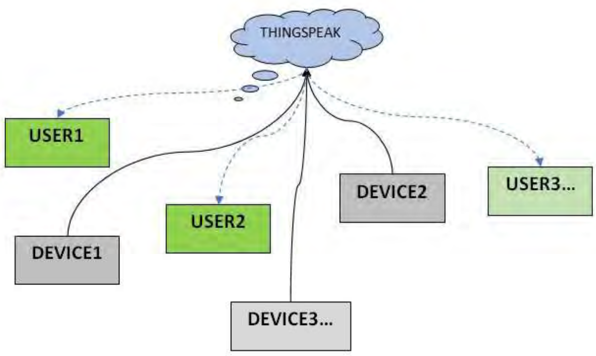

Fig. 3. Devices (Local units) and Users interaction in the Cloud

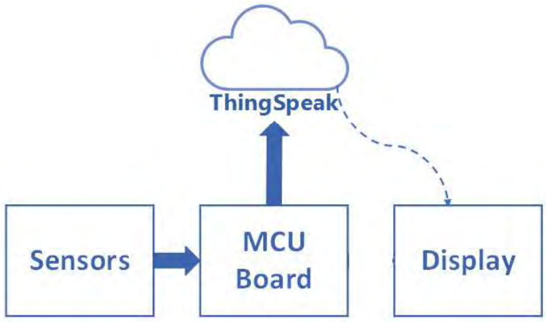

Fig. 4. Display obtaining data through the Cloud

III. Hardware Design

The sensing part is straight-forward: it consists of a power supply, PM particles sensor and Microcontroller with wireless connectivity, as presented in Fig. 5. The display similarly consists of a high current power supply, microcontroller with wireless connectivity and a LED matrix as depicted in Fig. 6. One of the main constraints in the component selection was the cost of the system since the main idea in the project is to allow as many as possible users to access local PM concentrations information and thus achieve high impact.

The power supply is 5V for both, the sensing unit and the display but the current requirements are different. The sensing unit may need up to 400mA [6] (with RF transmitting) but we applied a low cost industrial PSU that provides ten times higher current. This allows for addition of other components in the unit, such as a 2G modem, if the WiFi connection is not an option.

There were two options of good visibility display available. The first display consists of two rows of eight characters each. Each character can be up to 8x8 dots in red color and up to 3cm high. The other display is an RGB display with 32x8 LEDs matrix. Each LED is individually addressable. The characters (7x5 dots) are 6cm high and are visible at up to 40m distance [7]. The color can be used to encode the PM level severity.

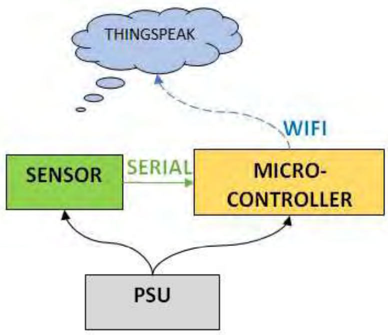

Fig. 5. Sensing unit block-diagram

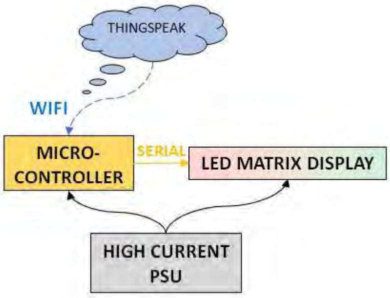

Fig. 6. Display block-diagram

The visibility and the color were the main reasons for selecting the RGB matrix. Now a single display may pull up to 256*3*20mA=15A if every dot is at maximum intensity and white color. Luckily the maximum fill factor appears at the character-8 and equals to (7+7+3*3)/(6*8)=0.48, so the maximum power requirement may be 7.5A, (if all characters were white numbers 8 at full intensity). Anyway, it is good to have high margin so a 15A industrial supply was chosen. It may even allow for using two displays, if more convenient.

The housing of the sensing unit is a standard IP65 plastic cabinet which appeared as the best price/performance choise at $10 per cabinet. The housing of the display is also a standard IP65 cabinet but with a transparent door. The shape of this cabinet is not the best fit for the display and this has to be redesigned. The physical realization of the system hardware is presented in Fig. 7.

IV. Firmware Design

Espressif offers their development environment Platform IO which is a standard development environment with reach libraries. On the other hand they also support the Arduino IDE making all those libraries available to Arduino-like coders. This coding approach is known for quickly achieving basic functionality of the microcontroller system and nothing motivates designers better than fast results. Therefore Arduino IDE was chosen for the development environment augmented with plethora of sophisticated libraries and community contributions. It also doesn't limit the developers to go deeper and explore multitasking programming in the background firmware which is the Free RTOS operating system [8]. It executes the Arduino sketch in a single task. The block-diagram of the sensing unit sketch is presented in Fig. 8 and for the display in Fig. 9.

Fig. 7. Hardware physical realization

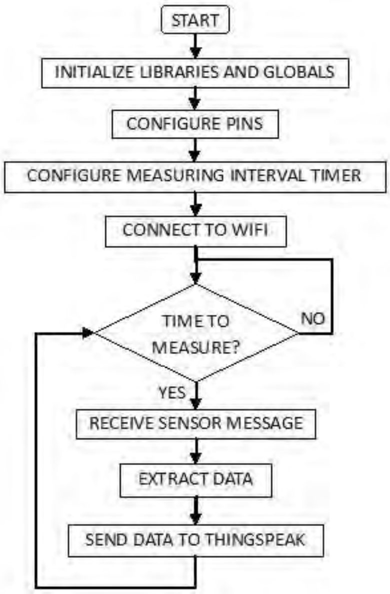

Fig. 8. Sensing unit sketch block-diagram

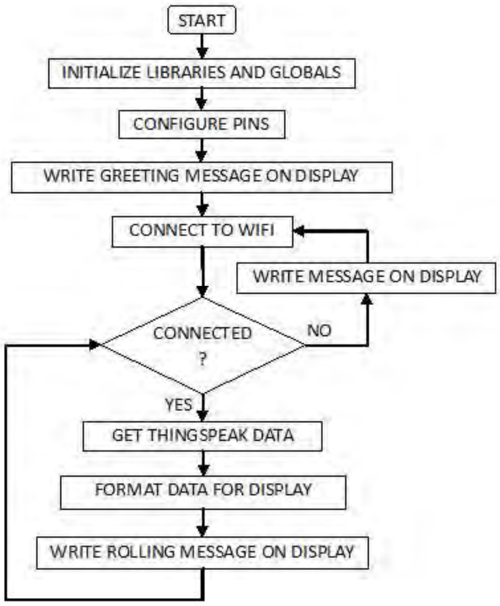

Fig. 9. Display sketch block-diagram

These are basic operating diagrams and contain hard-coded data for connectivity. They need improvement in allowing the user to enter connectivity parameters and also ThingSpeak channel parameters. The sensing unit could contain two sensors for increased reliability which has to be supported in the firmware. The sensors also do not need to operate continuously if the detected PM values don't change, which would extend sensor's operating life. If a GPRS modem is needed, than it would also need an appropriate firmware support. Measuring of ambient light to control the intensity could be implemented at the display. And certainly, if double display appears to be a better option, the firmware has to support it. All these tasks remain for the next version of the device.

Data presentation in ThingSpeak is performed through a Matlab script for plotting. There are many possibilities that can be added for data processing and presentation, such as presenting the location of the device on a map and/or integrating the data from more channels, but the first one to be implemented is filtering the outliers (erroneously received data) which appear as spikes in the plots. Also one hour averaging would provide data suitable for comparison with the government measuring stations. Fig. 10 are some recently collected data.

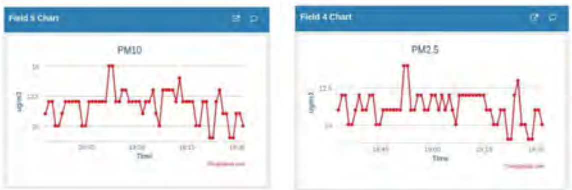

Fig. 10. ThingSpeak graphs of detected PM levels

V. DISSEMINATION

The device has been presented to the participants of the ROBOMAC YUNIOR 2024 competition, and later at the TECH4YOU competition to high school students and to their professors. Some of the schools present at TECH4YOU were also participants in the application for the EPICS in IEEE project "What we breathe?" and contributed for the application acceptance. The project expenses are covered by EPIC in IEEE Grant and the funds are available through the Macedonia IEEE Section account. Students started working in February and by September are expected to produce at least ten devices. The devices will be installed at the participating schools but also at other schools that express interest. Fig. 11 shows students at work, while Fig. 12 depicts a moment from the device demonstration.

Fig. 11. Students at work on the device assembly and programming

Fig. 12. Demonstration of the IoT system

VI. CONCLUSION

This paper presents the achievements of the first phase of the EPICS in IEEE project "What we breathe?" A prototype of a PM particles detecting and display system with data collection and presentation through the cloud server ThingSpeak was successfully designed and realized. Complex functionality that includes WiFi connection to a server was programed through mastering and exploring the reach set of libraries available for the Arduino IDE. A fully functional IoT application was successfully designed.

Many obstacles in physical realization were resolved but also many ideas for further development and improvement of the sensing module and the display were discussed. Possible additions for Matlab data processing in ThingSpeak were also suggested. Sensor calibration will be applied through the developed calibration chamber in the next phase of the project.

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Ethical Aspects in Building a Short-Range Object Detection Radar System with Arduino Mega 2560

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***Abstract* — The advancement of technology has led to the widespread development of innovative radar systems for various applications, including short-range object detection. The use of open-source platforms, such as Arduino Mega 2560, has made it easier for hobbyists and researchers to build different radar systems. However, this convenience raises ethical concerns that must be addressed. This paper examines the ethical aspects of constructing a short-range object detection radar system using Arduino Mega 2560. It delves into the potential implications of such systems on privacy, safety, and potential misuse. The aim of this research is to promote a comprehensive understanding of the ethical challenges associated with radar systems and to foster responsible development and usage practices.**

***Keywords* — Technology, radar systems, applications, open-source platforms, Arduino Mega 2560, ethical challenges.**

I. Introduction

In the ever-evolving landscape of technology, radar systems have emerged as indispensable tools with diverse applications across industries. From monitoring weather patterns to enabling air traffic control and bolstering automotive safety, radar technology has revolutionized the way we interact with the world around us. Advancements in radar technology have traditionally been confined to specialized research institutions and corporations due to the complex and costly nature of their development. However, with the advent of open-source platforms like Arduino Mega 2560, the barriers to entry have significantly lowered, democratizing radar system development and making it accessible to a broader audience of hobbyists, students, and researchers.

The Arduino Mega 2560, a widely popular open-source microcontroller board, boasts an extensive set of features, including many input and output pins, sufficient memory, and computational power, making it well-suited for various projects, including radar systems. This increased accessibility and flexibility has enabled enthusiasts to experiment with radar technology, harness its potential, and customize its applications to meet their unique requirements.

While the democratization of radar system development is a laudable advancement, it is essential to recognize that with newfound opportunities come ethical responsibilities. The rapid proliferation of radar systems, especially those built on open-source platforms, brings to the forefront a host of ethical concerns that demand careful consideration. As these radar systems become more prevalent and find their way into various domains, such as smart cities, autonomous vehicles, and surveillance applications, it is crucial to examine and address the ethical implications that accompany their construction and deployment.

The primary objective of this scientific paper is to conduct an in-depth exploration of the ethical aspects associated with building a short-range object detection radar system using the Arduino Mega 2560 platform. By comprehensively analyzing the potential implications and risks, we aim to foster a greater understanding of the ethical challenges and promote responsible practices in radar system development and usage.

The following sections will delve into various ethical aspects and considerations, including privacy, safety, and potential misuse, associated with the construction and implementation of short-range object detection radar systems. Additionally, we will discuss the ethical frameworks that can guide developers and policymakers in ensuring that radar technology is deployed in a manner that aligns with societal values and priorities [1 – 8].

As technology continues to shape the world, we are presented with both unprecedented opportunities and challenges. The responsible integration of radar systems, driven by open-source platforms like Arduino Mega 2560, demands a proactive approach to address the ethical implications and strike a balance between innovation and ethical considerations. By critically examining the ethical aspects of short-range object detection radar systems, this paper seeks to contribute to a well-rounded understanding of the broader implications of radar technology and encourage the adoption of ethical practices within the community of radar developers and users.

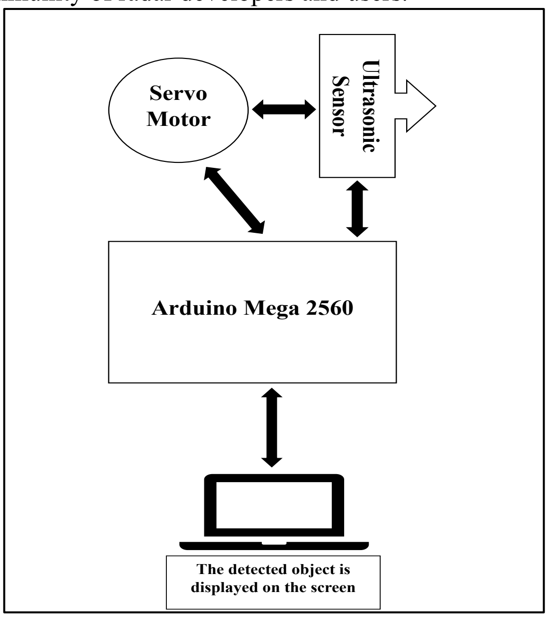

Fig. 1. *The integration of Arduino Mega 2560 with other digital components for radar system development*

II. Ethical Concerns in Short-Range Object Detection Radar Systems

As the accessibility and popularity of short-range object detection radar systems grows, it becomes imperative to critically examine the ethical implications associated with their construction and deployment. This section delves into the ethical concerns arising from the use of radar systems, particularly those built using the Arduino Mega 2560 platform, focusing on three key aspects: privacy implications, safety risks, and potential misuse [1 – 4].

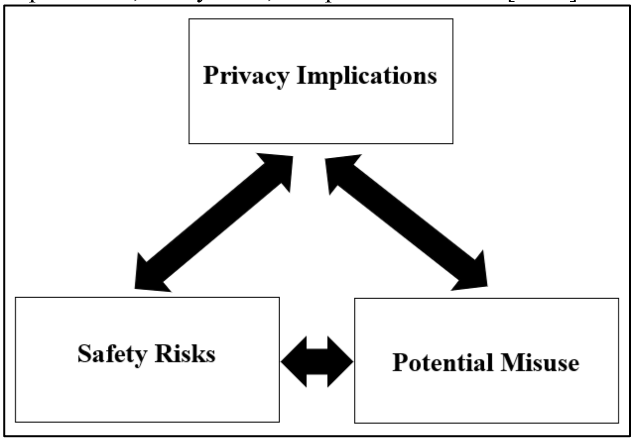

Fig. 2. *Three key aspects of ethical concerns arising from the use of radar systems.*

➢ Privacy Implications

Radar systems designed for object detection, such as proximity sensors in vehicles or smart city infrastructure, collect and process vast amounts of data about the surrounding environment. This data may include information about individuals, vehicles, and other objects within the radar's range. As radar systems become increasingly integrated into various aspects of daily life, the potential for privacy invasion escalates.

a. Data Collection: Radar systems, by design, capture data about objects and their movements within the radar's detection range. Depending on the system's application, this data may include information about individuals, their activities, and patterns of movement. The unintentional collection of personally identifiable information (PII) raises ethical concerns about the potential infringement on individuals' right to privacy.
b. Data Retention: Another ethical dilemma arises from the retention of collected radar data. Storing this data for extended periods may lead to potential misuse or unauthorized access, further compromising privacy. Ethical considerations demand a balance between the need for data retention for system optimization and the preservation of individual privacy rights.
c. Informed Consent: Ethical radar system development requires transparent communication with users about data collection and usage. Obtaining informed consent from individuals whose data may be collected ensures that users understand and agree to the potential implications of the system on their privacy [1 – 4].

➢ Safety Risks

Short-range object detection radar systems are increasingly being used in safety-critical applications, such as collision avoidance in vehicles or industrial settings. Ensuring the safety of individuals and property is paramount, and ethical considerations play a vital role in minimizing potential risks.

a. Collision Avoidance: Radar systems integrated into vehicles for collision avoidance must be designed with the utmost attention to safety. Any system failure, false positives, or inaccurate readings may lead to accidents, posing ethical challenges regarding the technology's reliability and potential consequences for human lives.
b. Radiation Exposure: Radar systems emit electromagnetic waves to detect objects, which raises concerns about potential health risks associated with prolonged exposure. Ethical radar system development requires adhering to established safety standards and ensuring that emissions remain within acceptable limits to safeguard human health [1 – 4].

➢ Potential Misuse

Radar technology, when deployed without ethical oversight, has the potential for misuse, leading to social, political, and security ramifications.

a. Surveillance: One significant ethical concern is the misuse of radar systems for unauthorized surveillance. If radar data is exploited for intrusive surveillance purposes without consent or legal authorization, it infringes upon individuals' right to privacy and autonomy.
b. Autonomous Weapons: The integration of radar technology into autonomous weapons raises profound ethical questions. The deployment of such weapons may lead to the loss of human control and accountability, potentially leading to unintended consequences and ethical dilemmas in warfare and security contexts [1 – 8].

➢ Addressing Ethical Concerns:

To mitigate the ethical concerns surrounding short-range object detection radar systems, developers, policymakers, and stakeholders must proactively implement various strategies:

➢ Privacy Protection:

- Anonymization: Implement data anonymization techniques to protect the privacy of individuals within the radar's detection range.
- Encryption: Ensure that radar data is securely encrypted during transmission and storage to prevent unauthorized access.

- Safety Measures:
  - Fail-Safe Mechanisms: Design radar systems with robust fail-safe mechanisms to minimize the risk of accidents and system failures.
  - Regulatory Compliance: Adhere to safety standards and regulations governing the use of radar technology in safety-critical applications.

- Responsible Use:
  - Industry Guidelines: Collaborate with industry associations and regulatory bodies to establish guidelines for ethical radar system development and usage.
  - Public Awareness: Raise public awareness about radar technology, its capabilities, and potential ethical implications to promote responsible usage and informed decision-making [1 – 8].

A. Ethical Frameworks for Radar System Development

Developing radar systems with a robust ethical framework is crucial to ensure that the technology aligns with societal values, respects individual rights, and addresses potential risks responsibly. This section presents several ethical frameworks and principles that can guide radar system developers using Arduino Mega 2560 or any other platform, fostering the integration of radar technology in a manner that benefits society and adheres to moral principles [9 – 12].

- Principle of Privacy by Design

The principle of Privacy by Design emphasizes the proactive integration of privacy measures into the design and development of technologies. For radar systems, this means implementing privacy-enhancing techniques from the outset to minimize data collection, use, and retention without compromising system functionality.

Adhering to this principle, developers can employ techniques such as data anonymization, minimizing the resolution of collected data, and limiting the scope of data collection to strictly necessary information. By incorporating Privacy by Design, radar system developers can demonstrate their commitment to respecting user privacy and safeguarding data from potential misuse [9 – 12].

- The Fair Information Practice Principles (FIPPs)

The Fair Information Practice Principles form a set of privacy guidelines that have been widely adopted in various contexts, including data protection regulations. The FIPPs consist of principles such as transparency, purpose limitation, data minimization, and user access to information.

When applied to radar system development, these principles advocate for clear communication with users about data collection purposes and usage, obtaining informed consent, and limiting data retention to the required timeframe. Integrating the FIPPs into radar system design ensures that user data is handled ethically and in compliance with privacy regulations [9 – 12].

- Ethical Considerations in Safety-Critical Applications

In safety-critical applications, such as collision avoidance systems in autonomous vehicles or industrial environments, ethical radar system development necessitates a strong focus on safety and reliability. Adopting an ethics of care approach, developers should prioritize the well-being of individuals who interact with radar-equipped systems.

This involves rigorous testing, validation, and continuous monitoring of radar system performance to minimize the risk of accidents and system failures. Developers should also establish clear fail-safe mechanisms and backup systems to ensure the technology operates safely, protecting human lives and property [9 – 12].

- Responsible AI and Transparency

As radar systems become more sophisticated, AI and machine learning algorithms play an essential role in processing radar data and extracting meaningful information. Ethical radar system development requires the adoption of Responsible AI principles, including fairness, accountability, transparency, and explain ability.

Developers should strive to make AI algorithms transparent and interpretable, allowing users to understand how the radar system arrives at its decisions. Moreover, algorithms should be regularly audited for bias and fairness, ensuring that the radar system's output does not discriminate against certain individuals or groups [9 – 12].

- Ethical Impact Assessment

Integrating an ethical impact assessment into radar system development can help identify potential ethical concerns and their potential effects on individuals and society at large. Conducting such assessments allows developers to anticipate and address ethical challenges before deployment.

Ethical impact assessments should consider not only privacy and safety aspects but also potential social and political ramifications of radar system usage. This holistic approach enables developers to make informed decisions about system design, data handling practices, and potential restrictions to prevent misuse [9 – 12].

- Collaboration and Public Engagement

Developers should actively engage with relevant stakeholders, including users, communities, and regulatory authorities, to foster a broader understanding of radar technology's potential and its ethical implications.

Public engagement and collaboration can help developers gain insights into different perspectives, receive feedback, and build trust. This inclusive approach to radar system development ensures that the technology aligns with societal needs, addresses concerns, and incorporates diverse viewpoints [9 – 12], [13].

B. Mitigating Ethical Concerns in Short-Range Object Detection Radar Systems

Ethical concerns in short-range object detection radar systems, especially those built with Arduino Mega 2560, can be addressed through proactive measures and responsible practices. This section outlines key strategies to mitigate ethical concerns and promote the ethical development and deployment of radar technology [14].

- Privacy Protection
  a. Data Minimization: Implement data minimization techniques to collect only essential data required for radar system functionality. Minimizing the resolution and granularity of data can reduce the risk of capturing personally identifiable information (PII).
  b. Anonymization: Apply data anonymization methods to protect the privacy of individuals within the radar's detection range. By converting PII into anonymous data, developers can significantly reduce privacy risks.
  c. Secure Data Storage: Store radar data securely with strong encryption to prevent unauthorized access or data breaches. Employing secure data storage protocols ensures that sensitive information remains protected.
  d. Informed Consent: Obtain informed consent from users whose data might be collected by the radar system. Transparently inform users about the purpose of data collection, how it will be used, and their rights regarding data privacy [9 – 12], [14].

- Safety and Reliability
  a. Rigorous Testing: Conduct extensive testing and validation of radar systems, especially in safety-critical applications. Rigorous testing helps identify and rectify potential errors, false positives, or system failures that may compromise safety.
  b. Fail-Safe Mechanisms: Design radar systems with robust fail-safe mechanisms that can override or disable the system in the event of a critical error. Fail-safe measures ensure that the radar system operates safely, even in unforeseen circumstances.
  c. Redundancy: Introduce redundancy in critical components and sensors to enhance system reliability. Redundant systems can serve as backups in case of primary system failure.
  d. Continuous Monitoring: Implement real-time monitoring of radar system performance to detect anomalies and potential safety risks. Continuous monitoring helps ensure that the system operates within safe parameters [9 – 12].

- Responsible AI and Bias Mitigation
  a. Transparent Algorithms: Use explainable AI algorithms that provide clear insights into how the radar system processes data and makes decisions. Transparent algorithms enhance user trust and allow for scrutiny of decision-making processes.
  b. Bias Assessment: Regularly assess AI algorithms for biases, especially when dealing with demographic or situational variables. Address and mitigate biases to avoid discriminatory outcomes and ensure fairness.
  c. Fair Data Sampling: Use diverse and representative datasets during the development phase to avoid skewed or biased training data. Fair data sampling reduces the risk of perpetuating biases in the radar system's performance [9 – 12].

- Ethical Impact Assessment
  a. Ethical Impact Evaluation: Conduct thorough ethical impact assessments before deploying radar systems in various applications. This evaluation should consider potential social, political, and human rights implications.
  b. Stakeholder Consultation: Involve relevant stakeholders, including users, communities, privacy advocates, and experts, in the ethical impact assessment process. Stakeholder consultations bring diverse perspectives and insights to light [9 – 12].

- Ethical Guidelines and Standards
  a. Industry Collaboration: Collaborate with industry associations, regulatory bodies, and standard-setting organizations to develop ethical guidelines for radar system development and deployment.
  b. Compliance with Regulations: Ensure compliance with relevant data protection and safety regulations. Following established guidelines helps ensure that radar systems meet ethical standards and legal requirements [9 – 12].
- Responsible Use and Policy Frameworks:
  a. Policy Development: Participate in the development of policies and regulations related to radar system deployment, privacy, and safety. Policy frameworks provide a structure for ethical radar system integration.
  b. Educate Users: Educate users and the public about radar technology, its benefits, potential risks, and privacy implications. Informed users are better equipped to make responsible decisions regarding radar system usage [9 – 12].

III. Conclusion

In the pursuit of technological advancement and democratization of radar system development with platforms like Arduino Mega 2560, ethical considerations play a pivotal role in shaping the future landscape of short-range object detection radar systems. This scientific paper aimed to explore the ethical aspects and challenges associated with building such radar systems, providing insights into the responsible integration of radar technology into various applications.

Throughout the paper, we examined the fundamental principles of radar technology, the suitability of Arduino Mega 2560 as a radar platform, and the design considerations for short-range object detection radar systems. We also delved into the ethical concerns arising from the deployment of radar systems, emphasizing three core aspects: privacy implications, safety risks, and potential misuse. These concerns highlight the need for a holistic ethical framework that addresses the complex interplay between technological innovation and societal values.

The democratization of radar technology brings forth unprecedented opportunities for innovation and creative applications. However, as radar systems become more prevalent in smart cities, autonomous vehicles, and surveillance settings, we must be vigilant in safeguarding individual privacy and data protection. Striking a balance between data collection for system optimization and preserving individual privacy rights is essential to maintain public trust in radar technology.

Moreover, the safety of radar systems, particularly in safety-critical applications like collision avoidance in vehicles, must be prioritized. Adhering to safety standards, implementing fail-safe mechanisms, and continuously monitoring system performance can help minimize potential risks and ensure the technology's responsible deployment.

The potential misuse of radar technology, whether for unauthorized surveillance or in autonomous weapons, necessitates comprehensive ethical guidelines and legal frameworks. Collaboration between developers, policymakers, and experts is vital to create responsible guidelines that govern radar system development, usage, and potential restrictions to prevent misuse and maintain accountability.

To address these ethical concerns effectively, it is imperative to foster public awareness and understanding of radar technology and its implications. Transparent communication with users, informed consent procedures, and education on the benefits and risks of radar systems will empower individuals to make informed decisions about their engagement with these technologies.

In conclusion, the responsible integration of short-range object detection radar systems using Arduino Mega 2560 demands an ethical approach. By adhering to ethical principles, developers can navigate the complex terrain of technological innovation while prioritizing privacy, safety, and societal well-being. As we continue to advance radar technology, we must remain committed to building a future where innovation is complemented by ethical considerations and human values, ensuring that radar systems serve as tools for progress, empowerment, and social good.

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The use of Digital development board for development of ultrasonic radar system for short distance detection in a 360-degree

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***Abstract* — This scientific paper discusses the application of single-board computers in performing various projects focusing on the practical development of an ultrasonic radar system for detecting objects at short distances in a 360-degree radius using the digital development electronic board Arduino Mega 2560. This platform contributes to the development of electronic technology, microcomputers and microprocessors and their application for educational purposes. The development of the ultrasonic radar system for the detection of objects at short distances in a 360-degree radius was carried out by programming the ultrasonic radar system using the tools Arduino IDE and Processing PDE.**

***Keywords* — Ultrasonic Radar System, 360-degree radius, digital development electronic board, Arduino Mega 2560, Arduino IDE, Processing PDE**

I. INTRODUCTION

The topic of this scientific paper has a wide application in the field of digital electronics, information of communication technologies (ICT) and Integrated Control and Monitoring System (ICMS) as important scientific branches in the digital world. At the same time within the framework of programming and the use of algorithms which are key elements in the course of the development of the practical part within the scientific paper, i.e. the creation of an ultrasonic radar system for the detection of objects at short distances in a 360-degree radius using the Arduino Mega 2560 digital development electronic board. The scientific paper shows the importance of the application of single-board computers in various educational processes and areas that are key factors for development and scientific advancements in technology today. Through the practical development of the Ultrasonic Radar System for the detection of objects at short Distances in a 360-degree radius (furthermore: URSAD), in this paper is showed the way to successfully connect the Arduino Mega 2560 digital development electronic board (programmed with the Arduino IDE tool) with a personal computer using a program made with the Processing PDE software. It allows to finally display on the computer screen the presence of a certain object detected by the short-range object detection ultrasonic radar system in a 360-degree radius. The ability to program and display on a computer screen is made possible by the integration of the Arduino Mega 2560 digital development electronic board with the digital electronic platform, specifically the Arduino IDE and Processing PDE.

II. SINGLE BOARD COMPUTERS

A single-board computer is a device or digital component that contains only the most necessary circuitry needed to operate as a machine. These boards, or single-board computers, are often shipped without cases and other accessories to keep the selling price low. A single-board computer is also called a digital development electronic board or a development board because they can be programmed and connected to various digital electronic platforms that allow the construction of various systems or devices that develop the scientific branch itself as a scientific discipline in today's digital science. The most important component, the heart of a single-board computer, is the microprocessor. A microprocessor is a unit that has several General-Purpose Input/Output (GPIO) ports that can be used for different digital applications, platforms, and can be programmed to work in a certain way. There are many manufacturers of microprocessors available in the market and each manufacturer and brand has its own main purpose and purpose with which they differ in selling price, capabilities, features that offer users opportunities to use them for making and experimenting with various projects and scientific experiments from different disciplines and fields [6-9], and [15].

Today's single-board computers are supported by a large Internet community around the world, where hobbyists and professionals share projects, scientific experiments, scientific journals and papers, and help each other solve various problems encountered during their construction, projects or scientific experiments. The large community is also an important factor when it comes to educational purposes. Information and data are easy and most likely someone has already done a similar thing, which can be a source of inspiration. Very often source code is provided (open source), which makes it easy for anyone interested to start a project or a particular experiment.

Depending on the application, different board specifications are required. Some boards, or digital development boards, are designed as multimedia players and therefore need a microprocessor that can handle video and audio acceleration. Another popular single board computer is the Arduino digital development board [13]. It was started as a school project with the main goal of developing a cheap solution that could be learning programming and electronics. This approach was quickly liked by amateurs and researchers who found large areas of use, which contributed to the development of the community around the platform. The Arduino digital development electronic board is designed to be programmed within their own integrated development environment (IDE – Integrated Development Environment) and uses the C++ programming language as a simple learning language for students in the educational process. It also could expand with compatible shields. A shield is a complete add-on circuit that can be placed directly on the Arduino board and can be programmed and used with various applications. Such an example is a shield for network communication between controllers (CAN BUS – Controller Area Network) which enables the Arduino protocol and the Servo Motor Shield which makes the Arduino capable of controlling servo motors. Arduino is a popular open access platform with various variants, including the Arduino Nano, the smallest board with low power consumption, ideal for low-power applications and ideal for those requiring minimal expandability. The Arduino Uno digital development board is one popular development board in the Arduino family of digital development boards. There are several different types of integrated protocols, but there is no video output as a standard option. It is often used as a prototype for projects and products before the board is scaled down and adapted to the application [2], [3], [9], [15].

The Arduino Corporation initiated a collaboration with companies compatible for designing and developing digital boards and developed a new board, that is, a digital electronic development board called the Arduino Galileo. The Arduino Galileo digital development board has been launched as an Internet of Things (IoT) development board and has a more powerful processor than its predecessor and can run a Linux operating system. It has the same physical form factor as the Arduino Uno digital development board, which means it can be used with most existing shields and code with minor modifications [9], [12], [15], [16].

The Arduino digital development circuit board was a turning point for the concept of single-board computers as we know them today. It has received a lot of support from the online community and has shown to be beneficial in a wide range of applications, including autonomous vehicles, robotic arms, smart home appliances, Internet of Things projects, weather stations, air quality monitoring, wearable technology, STEM learning kits, surveillance systems, object detection, and ultrasonic radar. Thanks to open source, various versions have been developed and extended to different application areas. There are several development boards available in the market with different specifications and vendors. This has also led microprocessor manufacturers to add more features to the processor itself [9], [10], [11], [15], [17], [18], [19].

III. SYSTEM MODEL OF ARDUINO MEGA 2560 DIGITAL DEVELOPMENT ELECTRONIC BOARD

Arduino Mega 2560 represents a platform based on the Atmel ATMega 2560 microcontroller. In addition to the microcontroller, it also contains several elements and components necessary for its proper operation. Programming and communication with the computer are done using a USB port. It is compatible with several other Arduino boards and with the Duemilanove and Diecimila platforms. The Arduino Mega 2560 digital development electronic board, unlike other Arduino boards, has more inputs to which sensors can be connected [4], [13], [15], [20], [21], [22], [23].

The operating voltage that can enable this microcontroller through a pin, as with most Arduino boards, is 5 V. The limit value of the input voltage has a range from 6 to 20 V, and the recommended voltage at which this microcontroller works is from 7 to 12 V. There are 54 digital input/output pins, 14 of which support pulse-width modulation. It also has 16 analog inputs and a 16 MHz crystal oscillator. It can be powered by a USB port or an external source [3], [4], [13], [15].

IV. DIGITAL ELECTRONIC COMPONENTS AND PARTS FOR THE PRACTICAL FRAMEWORK

In this section are shown all the digital electronic components and parts that were used for the practical part of URSAD for object detection in short range in a 360-degree radius (see Tab. 1).

TABLE 1: Used digital electronic components and parts for the practical part [15]

Components	Name of components
	Arduino Mega 2560
	USB cable
	Breadboard
	Jumping Wires
	Servo Motor
	Ultrasonic Sensor HC-SR04
	Ultrasonic Sensor HC-SR04

V. ALGORITHMS FOR FUNCTIONS IN THE INTEGRATED AND PROCESSING DEVELOPMENT ENVIRONMENT

The code in the Arduino IDE integrated development environment is done with a combination of the C and C++ programming languages. As already mentioned earlier in this paper, the code of the integrated development environment consists of two main functions void setup() and void loop() [1], [15], [18], [19], [20]. In the Fig. 1 is depicted the algorithm for the functionality of the servo motor, which allows to rotate from 0 to 360 degrees and with that the ultrasonic sensors placed on the servo motor can detect the objects in the range of 40 cm and in a 360-degree radius by appearing the detected objects in the screen of the laptop. In Fig. 2 is shown the algorithm for the function calculateDistance() that is used in the code, which precisely gives the mathematical equation of the way of measuring the distance of the object.

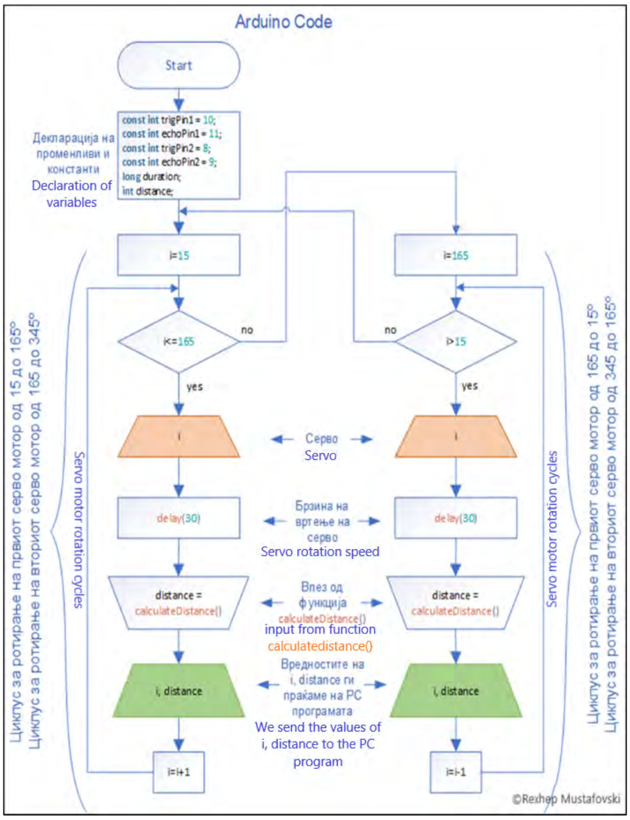

Figure 1: Algorithm for void setup() and void loop() functions for URSAD in a 360 degree radius [15]

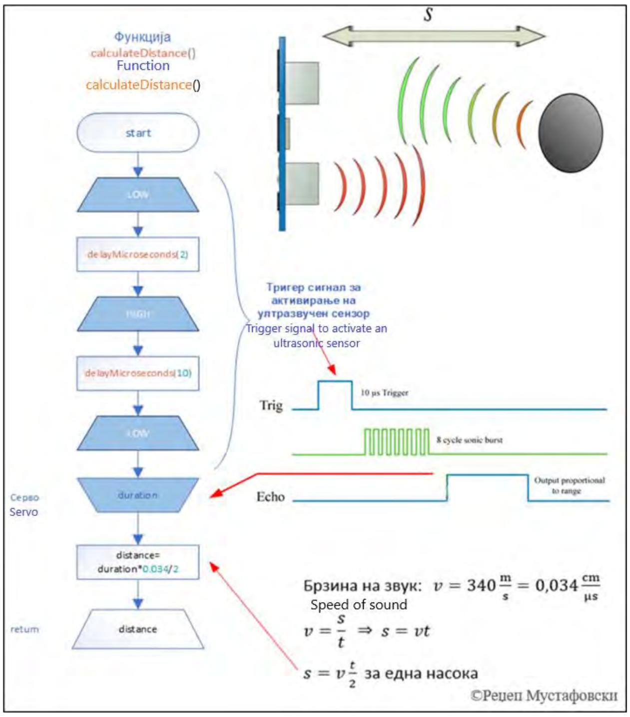

Figure 2: Algorithm for the calculateDistance process for URSAD in a 360 degree radius [15]

Figure 3 illustrates the algorithm written in Processing code within the Processing Development Environment for URSAD in a 360-degree radius. This code facilitates the creation of the URSAD display and enables the visualization of potential detected objects on the PC screen.

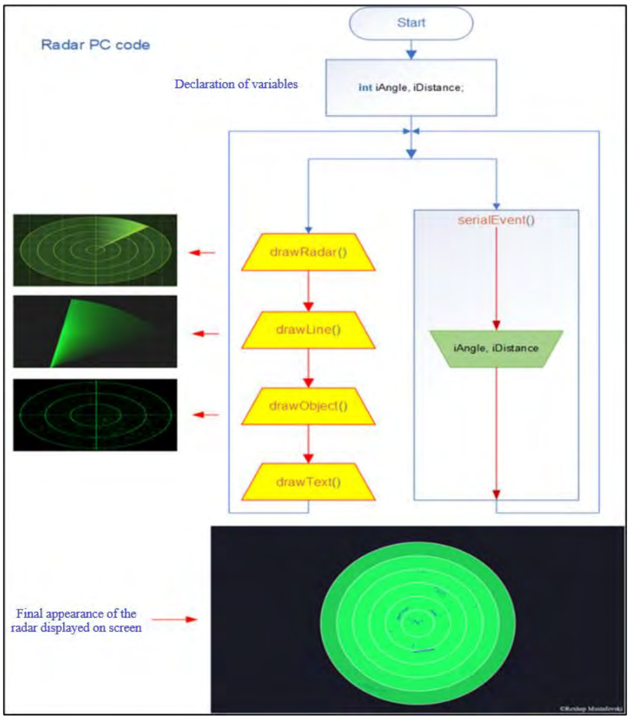

Figure 3: Algorithm for Processing's code for URSAD in a 360 degree radius [15]

VI. PRACTICAL APPEARANCE AND CONNECTION OF THE URSAD IN A 360 DEGREE RADIUS

From the information presented thus far, we've developed a conceptual understanding of the ultrasonic radar in a 360-degree radius potential appearance and functionality. This section will specifically show the appearance of the URSAD in a 360-degree radius and its function through pictures.

Through the graphic display shown in Fig. 4, a visual representation of what the URSAD in a 360-degree radius looks like in reality is obtained. The difference is that the ultrasonic sensor itself is attached to the servo motor.

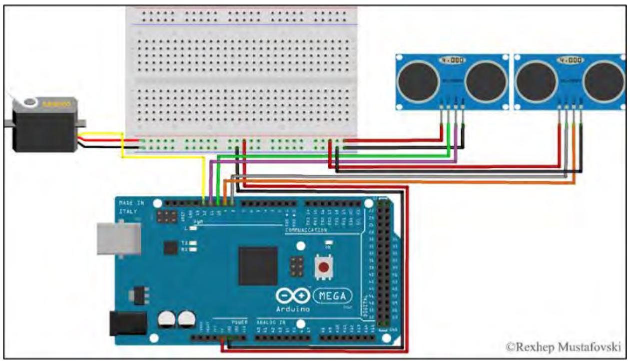

Figure 4: Connecting the components of the URSAD in a 360 degree radius

The Fig. 4 presents the connection of different colored wires, usually the black wire is used to connect the common end or the minus, the red wire is used to connect the positive pole of the power supply, while the rest of the wires can be chosen as desired. What is important when connecting the rest of the parts and the various wires is visibility during the connection. Transparency in connectivity allows for easier inspection of connected elements [15].

The Processing program created in the processing development environment plots the URSAD in a 360-degree radius surface based on the information and display of the detected target. The developed URSAD for the detection of objects at short distances in a 360-degree radius as part of this paper in our laboratory is shown in Fig. 5.

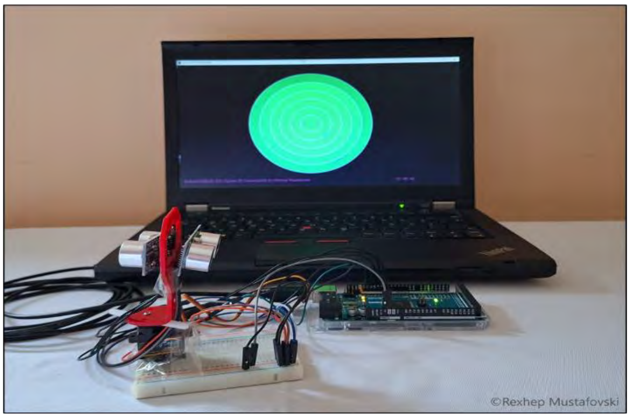

Figure 5: The realistic appearance of the radar system for detecting objects at short distances in a 360-degree radius

VII. LIMITATIONS AND CHALLENGES OF THE SYSTEM

While developing the ultrasonic radar system for object detection at short ranges based on the Arduino platform that has demonstrated promising results for object detection, several limitations and challenges emerged during the implementation and development process. In the future work of this paper will be given some steps to enhance the system's performance and reliability and implement in the future similar or enhanced radar systems for object detections in different situations. The several limitations and challenges faced during the implementation of this system were:

1. Sensor Accuracy and Range: Ultrasonic sensors, despite being inexpensive and simple to use, have certain performance restrictions and difficulties that may arise when incorporating them. The range of detection is constrained between a few centimeters and 1 meter, preventing the system from being used for long-distance object detection and monitoring. Moreover, the sensors' precision is reduced in varying conditions like uneven surfaces or terrains, very cold or hot temperatures, or when faced with dust, fog, or other environmental obstacles. These elements can lead to incorrect or unsuitable distance measurements, especially in outdoor settings [20], [21].
2. Angular Resolution: The system's angular resolution is restricted by the servo motor that rotates the ultrasonic sensor. The accuracy of object recognition relies on the velocity and increment of the motor's turning. Decreasing the size of steps results in greater detail, however, this also leads to longer scan times and causes delays in real-time tasks. In high-stakes situations, like obstacle detection for self-driving cars, this delay can create major obstacles [22], [23].
3. Arduino Processing Limitations: The Arduino Mega 2560 platform is adequate for simple control functions, but it has limited processing capabilities and memory. These limitations are evident when attempting to oversee numerous sensors, process extensive datasets, or conduct intricate signal processing. More complex functions, like running real-time filters or intricate decision-making algorithms, would need stronger microcontrollers or external processing units to ensure high performance and effectiveness [23].
4. Power consumption: The presence of numerous sensors, a servo motor, and wireless modules leads to higher energy usage, particularly during continuous system operation. This restriction is particularly important for portable apps or devices running on batteries. Optimizing power efficiency or integrating power-saving modes is vital for prolonging the operational lifespan of these systems [23].
5. System scalability: The current system can only scale up to the processing capabilities of the Arduino platform and the mechanical restrictions of the servo motor. Expanding the radar's coverage area or including additional sensors

would necessitate a complete overhaul of both the hardware and software [23].

VIII. Results and Analysis

This part of the paper will show and explain the practically performed tests in laboratory conditions that show the functionality, accuracy and precision of the systems, specifically the 180 and 360 degree object detection system.

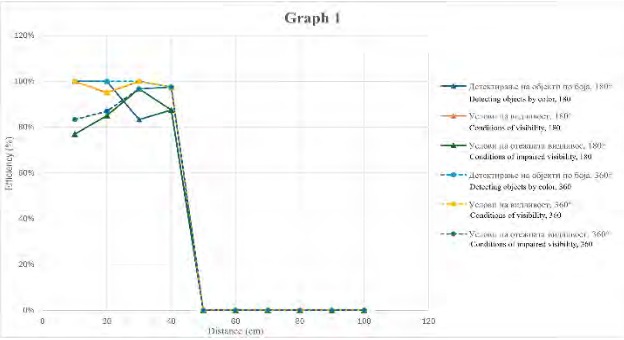

Figure 6: Perfomed test for detection of objects by color, visibility conditions and conditions of difficult visibility

Figure 6 shows the performed tests for the ultrasonic radar system for the detection of objects at short distances for 180 and 360 degrees, namely: detection of objects by color, visibility conditions and conditions of difficult visibility. According to the presented results for the same tests, we can notice that the ultrasonic radar system for detecting objects at short distances for 360 degrees has better results compared to the 180 degree system up to 40 centimeters of the total capabilities of the ultrasonic sensor itself.

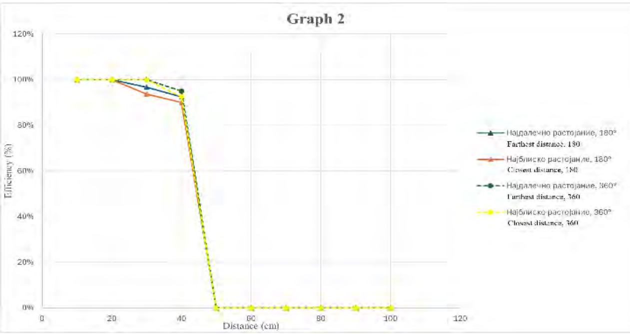

Figure 7: Perfomed test for farthest distance and closest distance

Figure 7 shows the farthest distance and closest distance tests performed for the 180 and 360 degree system. According to the results shown in the table comparing the two systems, we can notice that the 360 degree system at a distance of 20 to 40 centimeters has better results than the 180 degree system by a few percent, which makes the system itself functional and display better performance than the 180 degree object detection system.

IX. Conclusion

The paper presents several achievements with the application of digital development electronic boards or single board computers. Their application in many other different scientific fields and branches or combination with new codes or models allows controlling, operating and giving instructions to many digital development electronic boards and digital components to build different systems with specific functions and capabilities.

In the overall work of this scientific paper, the flexibility, characteristics and possibilities of digital development electronic boards, their open code, and their application for various scientific fields, through which their unlimited connection and combination with other digital development electronic boards, components, software, and computers are shown. These digital development electronic boards, i.e. single-board computers, have a price that is accessible to everyone, offer advanced features, while being simple and can be used by students in the educational process, for various other scientific projects and experiments in other scientific fields and disciplines. Digital electronic boards can be used in the educational process and the study process, which are an important factor for the development of education itself and can also be used in the industry to carry out various processes with which they save certain human and time resources. In contrast to the 180 degree system, the 360 degree system provides many unexpected results in terms of object detection in a variety of conditions, with better detection accuracy and full coverage of 360 degrees compared to 180 degrees, which solves many issues in comparison to various 180 degree systems. This thesis aimed to illustrate the improvements and accuracy of the 360-degree system in comparison to the 180-degree system. Additionally, more data volume and component cost compared to a 180-degree build-up system. With the help of this system, we can help the community develop even more accurate systems in the future that can monitor and recognize objects in a variety of settings with high precision and at a lower cost.

The URSAD in a 360-degree radius system detects nearby objects and connects with the Arduino Mega 2560 board through the Arduino IDE and Processing PDE. The goal of the project was to showcase and represent the most recent system that has been proposed. This system is capable of accurately detecting and monitoring objects in 360-degrees, and it can gather a wealth of data regarding the objects' angles and distances. It also covers the entire 360-degree sector, and, in comparison to the 180-degree system, it has significantly more advancements and developments in its component parts, code, and system integration. The configuration shows cases for object detection on a computer screen by utilizing data gathered from the Arduino Mega 2560 hardware, summarizing the accomplishment achieved with the short-range ultrasonic radar system for object detection in a 360-degree radius.

Also, the URSAD in a 360-degree radius system demonstrates promising potential in short-range object detection, showcasing a practical fusion of hardware and software capabilities to enable precise and efficient identification of nearby objects, marking a significant stride in innovative technological advancements.

The presented results of the practical tests clearly show the performance of the Arduino Mega 2560 digital development electronic board, as well as the capabilities of the ultrasonic sensors, so that in the future, different sensors and digital components can be used to increase the system's performance in object detection, under different conditions.

The authors firmly believe that numerous strategic breakthroughs centered on improving techniques and system design will lead to improvements in ultrasonic radar systems for 360-degree object detection. The goals of these initiatives are increased accuracy, improved results, and general system development.

X. FUTURE WORK

To enhance the Arduino Mega 2560 ultrasonic radar system for short-distance object detection in a 360-degree radius, we should consider these future steps [19], [15]:

1. Enhance Detection Accuracy: Refine radar sensitivity and signal processing for more accurate object detection.
2. Expand Object Recognition: Develop algorithms for recognizing specific objects detected by the radar.
3. Optimize Hardware Setup: Streamline connections and components for better efficiency and reduced size if applicable.
4. Implement Range Adjustment: Enable adjustable range settings for versatile detection capabilities.
5. Enable Remote Monitoring: Investigate ways to monitor detections remotely, possibly via wireless connectivity.
6. Develop User Interface: Design a user-friendly interface for intuitive system control and data visualization.
7. Test and Validate: Conduct thorough testing under various conditions to validate and refine the system's performance.

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Ambient CO_2 and Temperature IoT Monitoring Solution

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Abstract ***—CO_2 monitoring is an important step towards lowering threats from airborne transmittable diseases (e.g. COVID-19, influenza, tuberculosis etc.). Such efforts are in compliance with the existing ISO standards for indoor air-quality. Further, the controlled air quality via concurrent monitoring of CO_2 and temperature contributes to the contemporary strives toward energy conservation, savings and management. In view of the above, the herein presented work elucidates the process of developing a novel IoT solution for monitoring exhaled ambient CO_2 and temperature in a confined space, via employing Wi-Fi and 4G technologies, which finally resulted in a commercial solution – DamaLUFT. The paper elaborates the complete process, from conceptualizing, through prototype and subsequently final product development, focusing on the results regarding the used technologies and final user benefits. From an energy efficiency perspective, via combining this IoT solution with a corresponding Building Management System (BMS), it holds a potential to significantly contribute in optimizing energy consumption. As a result, the proposed and designed IoT solution for monitoring ambient CO_2 and temperature acts as a self-preventive health risk tool for the potential clients, by providing an indicative insight into ambient air quality, thus signalizing if the ambient air is of good quality (in terms of CO_2 content) or the room should be ventilated.***

Keywords—CO_2 and temperature monitoring, ambient monitoring, IoT, health risk prevention

I. Introduction

An increasing evidence exists that carbon dioxide (CO_2) levels in buildings strongly correlate with airborne spread infectious diseases, s.a. COVID-19, influenza etc. [1]. The extensive review of Mendell, Chen, Ranasinghe et al. (2024) [2] draws attention to a significant conclusion that, although various countries offer advisory guidelines or mandatory standards for minimum ventilation rates to maintain indoor air quality (including CO_2 concentration) (e.g. US EPA [3], Canada [4]), the evidence basis for the various CO_2 limits has not been clear. In that view, following the, ASHRAE [2022] [5], ISO [6] findings and recommendations, indoor air CO_2 concentrations should be maintained below 1000ppm. Further, the World Health Organization (WHO) states that COVID-19 spreads more easily in confined and enclosed spaces with poor ventilation [7].

Having all above mentioned aspects in perspective, this paper elaborates on the complete process of designing a novel IoT based product on the market that addresses the identified risks of spreading airborne diseases, and in particular COVID-19 as the issue that sparked this research for the design of a complete IoT solution:, from conceptual design, through prototype development and product development.

The rest of the paper is organized as follows: Section 2 elaborates the related work, Section 3 presents the design of the ambient monitoring IoT solution, Section 4 presents the results and discussions related to the designed IoT systems, while Section 5 concludes the paper.

II. Related Work

Considering air quality and air disease spread many studies have been conducted. Facing COVID-19, initiated a new surge of similar research, thus presenting new results as in [8], [9], and [10]. A well-maintained and operated air-conditioning system can reduce the spread of COVID-19 in indoor spaces by increasing the rate of air exchanges, reducing recirculation of air and increasing the use of outdoor air [8]. Ambient (indoor) carbon dioxide is generated by the exhaled air of people who stay indoors, whereby, each person in a building will exhale approximately eight liters of air per minute: air that has been in close contact with the lung tissue [9].

As stated in [12], CO_2 monitoring is an important step into lowering threats by both COVID-19 and other airborne transmittable diseases. Further, the director of the Centre for Research into Atmospheric Chemistry in UCC, Prof John Wenger, suggested that "a target of 1000 ppm of CO_2 is being used as a proxy for COVID-19 in classrooms, and argues that room level transmission is the key. It's in the air, and it can fill a room. The amount of the virus in the air can accumulate, and we get an increased exposure. If you're indoors, in a poorly ventilated room for a long time, then you're at quite a high risk even if you're distanced, because the air moves around". Other similar insights are given in [13], referring to a 2019 study on a tuberculosis outbreak in Taipei University, Taiwan, where many rooms were poorly ventilated and reached CO_2 levels above 3000 parts per million (ppm). When engineers brought levels down to under 600 ppm the outbreak stopped. Further recommendations on how to combat COVID-19 and similar diseases, which are in compliance with the existing ISO standards with respect to indoor air-quality [6] and [14] are provided in [15].

Via a conducted needs assessment in [11], an open market gap was established/identified that requires introducing a CO_2 and temperature monitoring solution, to address the therein identified set of risks:

A-1. Risk of airborne diseases caused by viruses;

A-2. Risk of low cognitive, intellectual performance in any working/dwelling environment;

A-3. Risk of improper conditions of the working ambient in terms of air quality, implying reduced contentment and satisfaction among employees and increased occurrence of headaches, disorientation, dizziness etc.;

A-4. Risk of increased energy consumption for maintaining standardized air quality that has a potential to be optimized.

In view of the above, the presented research proposes a complete IoT hardware software solution incorporating several state of the art technologies from hardware and software viewpoint as well. The final goal was to design and deliver a market based solution that will assist people in their efforts to reduce the risk against infections of airborne diseases, thus to provide them with a self-preventive health risk tool. The efforts finally resulted in developing an integrated turnkey (hardware and software) IoT solution, named DamaLUFT, for indoor areas (such as offices, schools, stores, shopping malls etc.) where a lot of people are present due to their daily activities.

III. DESIGN OF THE DAMALUFT IOT SOLUTION

The DamaLUFT IoT solution provides measuring and monitoring of exhaled CO_2 levels and ambient temperature. The solution takes CO_2 and ambient temperature measuring results and presents them in a diagram (Figure 3 and 4). It shows results for 1, 3 and 7 days for standard users and allows the admin user to get respective data for a period of 30 calendar days or 12 months backwards from the current month. The admin has the option to collect air quality data presented through a pie diagram, whereby 3 ranges of CO_2 levels are presented (as percentage). The 3 ranges are: very good (bellow 800 ppm), good (between 800-1200 ppm) but activating the HVAC or opening the windows should be planned, and critical (over 1200 ppm) where immediate action is recommended.

A. Conceptual design and methods

A conceptual design of the software solution focused on outlining the key components and their interactions. The solution has been implemented in a cloud based environment using a Master-Slave architecture. The design of the solution is primarily based on distribution, redundancy, and scalability.

A Master server manages and coordinates tasks across the system, handles the main database (write operations), application logic, and acts as the primary entry point for requests. A Slave server replicates the database (read-only operations), distributes the workload and handles specific tasks like caching. Both servers run under Ubuntu operating system and have the following components: Apache Web Server which handles incoming HTTPS requests and serves the web pages; Application server that runs the application code. React for Frontend and Vanilla PHP have been used for the backend, while MySQL was implemented as a database server.

The logical design of the DamaLUFT solution is presented in Fig. 1.

After respective number of consecutive CO_2 and temperature readings, DamaLUFT device activates the Wi-Fi modem to connect to the local Wi-Fi network and send data via streaming Application Programming Interface (API) to the server. Communication with the server is established via HTTPS protocol to the DamaLUFT application backend where data is stored in a database and prepared for the front end and to be presented to respective user(s).

B. Prototype and comercial solutions

The evolution path of the DamaLUFT IoT ambient CO_2 and temperature monitoring prototype solution started December 2020 during the high pick of the COVID 19 pandemic. The first prototype version –testing and piloting phase – was presented in April 2021. Commercial launch of the solution, under the brand name DamaLUFT, began in September 2021, followed by the implementation amongst first clients, in October 2021.

The first version of the prototype exhibited several challenges to be solved, such as, from a hardware point of view, positioning on/off switch and charging plug-in, thus corresponding housing design while from a software point of view initialization of the CO_2 and temperature measuring. The repositioning of the on/off switch and charging plug-in implied necessary changes on the PC Board in order to fit in the new version of housing. Aside of enclosing the new version of PC board the new housing design required suitable modification of the openings to allow better fluctuation of the air and thus more accurate sensor measurement.

After the prototype design process and the final choice of elements for the solution, the main hardware design components of the DamaLUFT IoT solution are presented in Table 1.

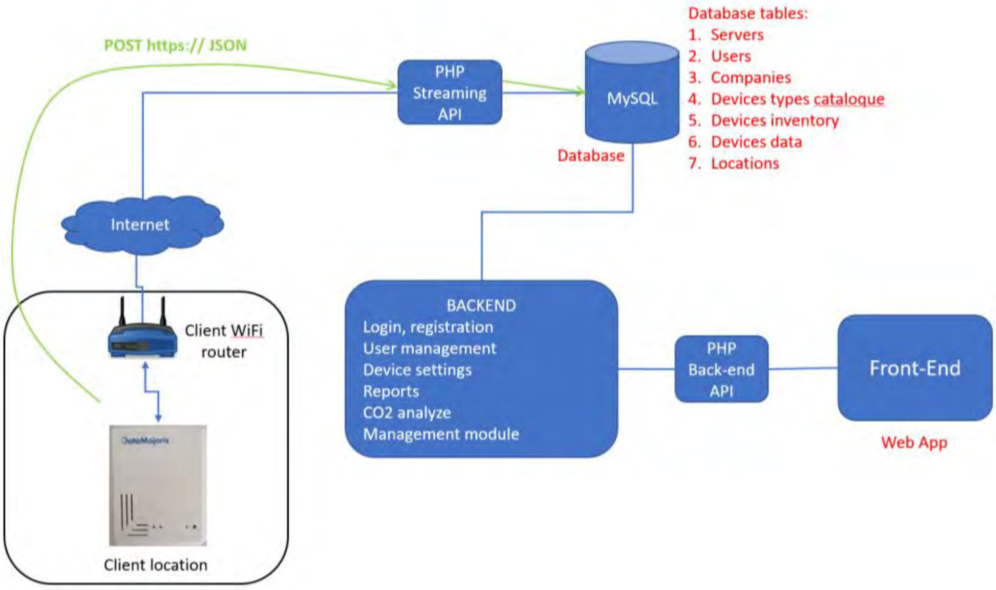


Fig. 1. Conceptual Design of DamaLUFT solution.

TABLE I. HARDWARE COMPONENTS OF THE DEVICE

Component	Vendor	Model	Note
Sensor for CO_2 & Temperature	Senseair	Sunrise	Self-calibration
Printed Circuit Board – PCB	Datamajoris	DamaLUFT-PCB version 2.	Vendor Datamajoris
Microcontroller	Espressif Systems	ESP8266 12F	with built-in WiFi modem
Battery	Panasonic or Samsung	Li-Ion 18650	Rechargeable
Housing	Datamajoris	DamaLUFT-H version 3.	Including wall and desk holder

The Senseair Sunrise CO_2 and temperature sensor has been chosen due to the fact that it is most accurate and power efficient sensor and one of the best on the market in terms of self-calibration and very low power consumption (45uA). It complies with several modern standards including Addendum ab to ANSI/ASHRAE Standard 62.1-2022 [16]. Another key point is that Sunrise also has both a UART and I2C interface providing for a simple hardware and firmware interface.

The hardware monitoring device is designed to be powered by Li-Ion battery, type 18650 that provides 3400 mAh electric charge. It was decided the device to be battery operated because it is giving flexibility for placing it on the wall, desks or any adequate flat surface in the room without taking care about cabling and position of 220V plug-in for charging adapter.

The microcontroller used in the final solution is ESP8266 12F. It has built-in Wi-Fi modem and can easily be programmed in Arduino IDE environment. In order to save energy and ensure longer battery life within a single charge, the microcontroller is in 'deep sleep' mode most of the time. To be specific, every 2 minutes the microcontroller 'wakes up' to read the current CO_2 level and the ambient temperature, followed by a consecutive period where the controller is again entering into 'deep sleep' mode, thus providing significant energy saving. At the 7th consecutive CO_2 and ambient temperature reading, the controller additionally reads the battery level and activates the Wi-Fi modem to connect the local Wi-Fi network and, via streaming API, to send to the server the 7 readings of the CO_2 and ambient temperature measurements including the level of battery voltage. Since, empirically it has been assessed that, in a period of 14 minutes, neither CO_2 nor temperature is changing rapidly, it has been decided that seven readings are sufficiently enough for accurate measurement of the respective values. Hence, it provides a pretty satisfactory presentation of the CO_2 and temperature level for the end users. This interval is configurable. Communication to the server is established via the HTTPS application protocol and the data are transferred to the database in JSON format. For the purpose of recording the measured data into the database, the device itself, concurrently sends its serial number to the database.

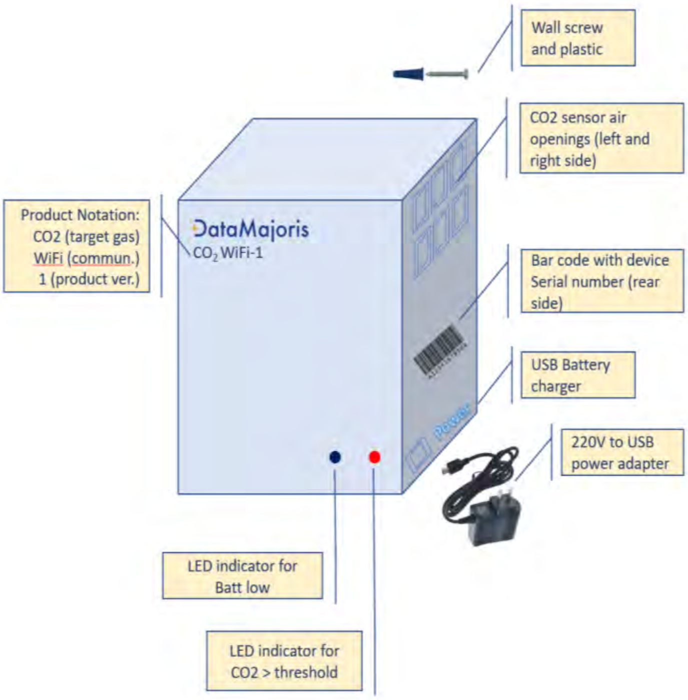
When the whole process is finished, the microcontroller is measuring and recording the time needed for the data transfer in order to have an insight of the time needed for the device to be connected on the WiFi network. This measurement is used as a direct indicator to estimate the time duration of one separate cycle of the battery (longer time for connection with the WiFi router implies sooner exhausting of the battery).

The Senseair Sunrise sensor itself, filters the data that via a FIR filter, i.e. there is no possibility that an abrupt change of two adjacent readings appears. Namely, such readings may occur while the room is being ventilated and the CO_2 level drops rapidly in a short period of time. To avoid this, the sensor is set in a constantly active mode whereby every 16 seconds, it measures the CO_2 level and ambient temperature. Thus, in the

2-minute period, when the controller is in 'deep sleep" mode, sufficiently big data sets (samples) are provided, hence avoiding the strict (rigid) effect of the FIR filter, but concurrently, in the case of noise readings, measurement quality is maintained. It is worthwhile noting that besides the fact that every 16 seconds the sensor measures the level of CO_2 and temperature, every 2 minutes, when the controller wakes up, it reads the last sensor measuring.

C. Final design of the DamaLUFT hardware platform

Taking all design elements from the previous sections into consideration, Fig. 2 presents the final hardware platform of the DamaLUFT ambient IoT solution and its elements. Additionally, the basic but very important parameters of the device are also stated in the figure. As elaborated in the previous subsection *B. Prototype and commercial solutions*, DamaLUFT-PCB version 2 and DamaLUFT-H version 3 correspond to the thereby required PC Board and housing design changes.



DataMajoris CO2 WiFi-1 product for Indoor Air Quality:

IP20 enclosure with one wall plug and screw
CO2 NDIR sensor
Microcontroller
WiFi 802.11/g/n @2.4GHz built-in module, ASP and client mode
Battery: Li-ion, 18650, 3400mAh, with short circuit protection
USB C power supply module and socket, overvoltage protection
RED LED blinking when CO2 > threshold
BLUE LED blinking when battery low
QR code for reading via mobile phone – web link to this device's data in the Web app
Barcode for device serial number - for asset management
220V Adapter to USB C 5V, 1A

Technical specification	
Target Gas	Carbon dioxide (CO2)
Measurement Range	400–5,000 ppm. Extended range 10,000 ppm
Accuracy	±30 ppm ±3% of reading [1,3]
Warm-up time	1 minute
Power Input	Battery , USB charger "C" 5V, 1A (supplied)
Power Consumption	90mA @ 5V
Wireless Outputs	WiFi 802.11/g/n @2.4GHz
Operation range	0–50°C, 0-85% RH
Dimensions (wxhxd), weight	

Fig. 2. Hardware concept of the DamaLUFT solution.

D. Design elements of the software DamaLUFT solution

The DamaLUFT software platform provides the following modules: login and registration module, mo

dule for user management, module for device settings, CO_2 and temperature reports and DamaLUFT management module. It distinguishes two types of client users: admin (more than one) and standard with different privileges.

The admin user is managing the standard users' rights and the devices. Further, the admin user can approve, restrict or delete any standard user and can assign or revoke the admin user (if more than one). Last but not least, the admin user has an overview of all installed devices in the company.

The standard user has access only to the reports module where he/she can see the respective diagram for CO_2 and temperature level as shown on the Figure 3 and 4, as well as, battery status for the respective device(s) for which he/she has been granted privileges by the admin. He/she can see the respective CO_2 and temperature levels for 1, 3 or 7 days.

The DamaLUFT software platform has an additional module for analysis accessible only by the admin user(s). He/she can generate reports for 30 calendar days or for respective months in the past 12 months, for chosen or for all devices. Also, the admin user(s) has rights to change the default values for good and critical levels of CO_2 for concrete device(s) to be presented on the respective diagram.

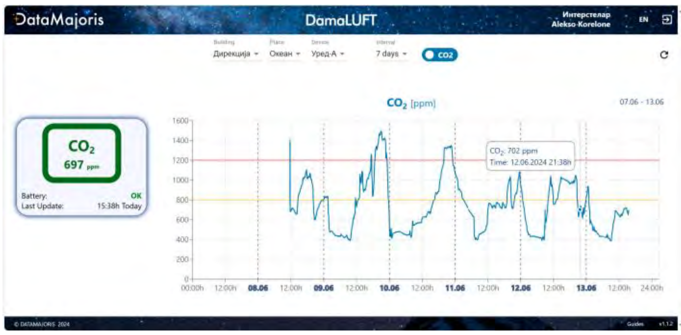


Fig. 3. CO2 report.

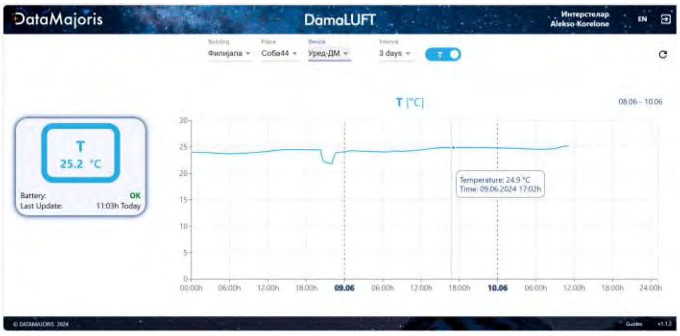


Fig. 4. Temperature report

Sample reports of CO_2 measurements and ambient temperature are depicted on Fig. 3 and Fig. 4 respectively. Each value, CO_2 and ambient temperature can be presented for one, three and seven days.

IV. RESULTS AND DISCUSSION

The ambient monitoring IoT solution - DamaLUFT is a preventive tool to reduce risks from infection caused by airborne diseases (A-1). It contributes to improved cognitive and the intellectual performance and to better working conditions (A-2 and A-3). Via adding temperature measurement, it as well contributes to energy savings via proper management of ventilation or HVAC system (A-4).

Further advantages of the proposed DamaLUFT IoT solution are as follows: the device uses Wi-Fi technologies for communication with the server whilst it is battery operated, whereby the battery needs to be charged every 3-4 months via classical USB type C smart phone charger. The device can be mounted on the wall or it can be positioned on any flat surface due to specific design of the casing and its holder.

The first prototype of the DamaLUFT solution was developed at the beginning of 2021, in a period of only a few months, while the testing started promptly afterwards. The emerged challenges were solved consecutively and piloting started with a set of few devices. The main goal was to be prepared prior to the start of the following virus season (Autumn 2021).

Choosing components for the hardware segment from quality and reliable vendors (with an optimized design) allowed quick production and launch of the products. Up to date, there is only 1% defective devices from the overall active device database (200+ active devices).

The initial client feedback was from a company that nominally conducts trainings in groups of 8 to 9 people in a room of 40 m^2 in time slots of 90 minutes. Accordingly to the parameters of the space only one device was installed. During the training CO_2 levels reached critical level of 1200 ppm only after 45 minutes. Having this experience into account, with the purpose to improve the quality of service provided and to reduce risks of airborne infectious diseases as well as the cognitive abilities of the trainees (A1-A3), the client decided to restructure the trainings into time slots of 45 minutes each.

The second client feedback originated from a ICT company with 30-35 employees distributed in an ocean system with a total area of 300 m^2. In accordance to the number of oceans and meeting rooms, 5 devices were installed. All participants were given access to all the devices readings. This enabled them to independently maintain CO_2 levels below 800 ppm via regular ventilation of the rooms to reduce the risks of airborne infectious diseases as well as tto enhance cognitive abilities of the employees (A1-A4). Additionally, via temperature monitoring and limiting it to 21^0C to 22^0C, the customer reported reduction of the energy consumption for operating the heating system.

The software was developed as a web based solution in the sense to be intuitive and simple to be used by any user, implying that no IT knowledge from the client(s) is needed for utilizing the application and reading/interpreting the reports (graphical representation and review of CO_2 and temperature levels). The solution is working with any of the known browsers, such as Microsoft Edge, Google Chrome, Firefox, and Apple Safari. Further, installing, configuring the device, and management of the users does not require any IT knowledge.

The solution is open to be operated, monitored and maintained by various sectors in the company such as: Building Management, Health Care Protection, Human Resources, Marketing sector etc.

V. CONCLUSION

This paper elaborates on the development of a new commercial IoT solution – DamaLUFT – for monitoring CO_2 and temperature using Wi-Fi and 4G technologies, from conceptualizing, through prototype development, product development and finally, emerging on the market including 2.5+ years of production and customers' experience. Namely, DamaLUFT comprises of a standalone device with battery power supply and a software platform. It is a single-vendor, user-friendly and easy-to-operate solution, which can be maintained without any IT knowledge. The software platform provides a variety of built-in reports and analyzes of the exhaled CO_2 and the ambient temperature for periods of 1, 3 and 7 days and 30 consecutive days, in addition to monthly (calendar month) reports, backward, for the past 12 months, which encompass CO_2 and temperature readings for a predefined period, 24 hours a day. It is the only IoT CO_2 monitoring solution in the world with Wi-Fi internet possibility, battery operated.

The proposed IoT solution for CO_2 and temperature monitoring facilitates indicative insight into ambient air quality, in particular, with the purpose to indicate the user(s) if the ambient air is of good quality (in terms of CO_2 content) or the room should be ventilated.

As future developments, the DamaLUFT solution can be upgraded with: a QR-code for instant CO_2 and ambient temperature reading; an additional sensor for humidity, and; a software module for proactive e-mail notifications. In order to increase power source independence of the device (solution), and thus to increase energy efficiency, NB–IoT technology can be implemented instead of 4G.

From an energy efficiency perspective, via combining DamaLUFT with a corresponding Building Management System (BMS), it holds a potential to significantly contribute in optimizing energy consumption.

Acknowledgment

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Design and Implementation of a Cloud-based System for IoT Sensor and Security Metrics Analysis

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Abstract*—With the development of Industry 4.0 as well as the Internet of Things (IoT), the need for extensive real-time monitoring and analysis of data sent by a plethora of IoT devices becomes quite significant. This serves the purpose of simplifying the usage of these devices, drawing important conclusions from the data and optimising the processes. Furthermore, monitoring a specific set of important parameters of the IoT network as a whole becomes a necessity, since IoT devices are notorious for being the target of different cyber-attacks. In this paper, a complete system for monitoring and analysis of IoT data is implemented on a cloud platform utilizing and optimizing available services for the task at hand. The cloud provider of choice is Amazon Web Services (AWS) because of its extensive support for IoT devices and the flexibility of its services for IoT data. The design of the system encompasses several different AWS services incorporated together in a tight communication and storage system in order to provide the final result – a complete and secure IoT data analysis system. The designed and implemented system in this research allows the user to analyse and monitor his IoT device fleet in a seamless, scalable, cost-effective and detailed way, and in near real-time. The designed system is general enough that it can be implemented for monitoring of all types of IoT devices, networks, and system applications. The final web platform encompasses visualization of different types of data – sensor metrics, security metrics, connectivity status and security alarms of every single device in the network as well as infrastructure metrics about all used AWS services.

***Keywords*— Internet of Things, IoT device monitoring, data analysis, cloud services, cybersecurity, sensor metrics, connectivity, security alarms**

I. INTRODUCTION

As widely known, the term Internet of Things (IoT) is used to describe embedded devices connected on the Internet that have sensors and/or actuators used to monitor or control a certain physical phenomena. These devices can gather data from the environment they are interacting with and can exchange that data with each other without any human intervention. It is thought that IoT devices carry a complete new perspective and a lot of different possibilities, while also serving as the primary conduit for the development of Industry 4.0. This technology is used in a lot of different fields such as smart homes, smart grids, smart cities, power plants, smart agriculture, health sector, commercial and residential buildings, industrial processes [1] etc, and its usage keeps growing. The growth of IoT technologies is happening rapidly and by one Statista report [2] it is thought that the number of connected IoT devices by 2030 will be over 32.1 billion, more than double the number registered in 2020 (15.1 billion devices).

The fast growing world of IoT carries some challenges as well. The large number of connected IoT devices and the vast quantities of IoT data generated amplify the need to simplify data analysis, as well as the monitoring of the devices and the network that interconnects them. Additionally, due to their prevalence, heterogeneity, limited hardware resources, the sensitive data they share across the Internet and the lack of best cybersecurity practices, IoT devices are the target of many modern cyber-attacks [3]. Thus, successfully securing the devices and monitoring the interconnection network metrics presents a great challenge in modern IoT infrastructures. In order to overcome such challenges, a comprehensive system for analysis and monitoring of IoT devices, network and data is needed. The system should enable the users to be comprehensively informed regarding all events in the monitored IoT network, while simultaneously allowing them to draw conclusions and make important decisions based on the data from each IoT device. If such a system is effectively implemented, it would allow greater control over the IoT network and enhance organization of enterprise resources. Such an arrangement would enable the enterprise to optimize the overall IoT processes in a cost-effective way, while simultaneously increasing the security of the IoT network.

In this paper, a multi-purpose all-encompassing cloud-based system for monitoring and analysis of IoT data, devices and the interconnection network is proposed. The system is scalable and can be configured to include varying numbers of devices, each capable of transmitting different types of sensor metrics according to user requirements, while maintaining the main goals: provide a simple, yet detailed picture of the enterprise IoT network, its components and the state of the used cloud services; visualise all of their sensor and security metrics; generate security alarms for every security anomaly detected on each IoT device; present the connectivity status and security alarms of every single IoT device.

The rest of the paper is organized as follows: Section 2 elaborates the related work, Section 3 presents the design of the final system and the several versions it underwent, its elements and characteristics, Section 4 presents the results and discussions related to the proposed system, while Section 5 concludes the paper.

II. RELATED WORK

The integration of cloud technologies and IoT devices has gained significant attention over the years in academia and in the research communities. This led to numerous studies exploring the benefits and challenges of such fusion of new and widespread technologies. For example, Botta et al. [1] describe the prevalence of IoT and cloud integrations over the years because of their complementary aspects in terms of computation, storage and communication. Pierleoni et al. [4] give a comparative analysis of Platform-as-a-Service (PaaS) architectures of the cloud providers Google Cloud, Azure, AWS, discussing their suitability for IoT applications. Yangui [5] gives a critical review of existing IoT PaaS (Platform-as-a-Service) cloud architectures suitable for industries based on a set of six well-defined architectural requirements.

Apart from critical and analytical research papers that discuss positive and negative sides of cloud-based IoT systems, there has been a recent growth of more practical studies. These studies focus on developing PaaS applications for the monitoring and analysis of IoT data in cloud environments and with numerous purposes including smart homes, agriculture, smart cities, medical care etc. There are multiple papers that focus on implementing such systems using the AWS cloud infrastructure. For example, Dineva et al. [6] thoroughly explain and present a scalable architecture for the analysis of livestock data gained through various IoT equipment using numerous AWS services. The main functionalities of the system are the abilities to maintain a great number of IoT devices, store and process large and scalable amounts of data, use machine learning for object recognition and forecasting, notify the farmers of any detected anomalies in the monitored parameters etc. Another study (Esposito et al. [7]) presents the design and implementation of a framework for smart home automation, using AWS services such as Lambda, DynamoDB and AWS IoT Core as the MQTT broker for sending and receiving data and commands to numerous home appliances. This AWS framework is integrated with Amazon Alexa for voice-enabled commanding, thus making it more accessible and seamless for usage. Tärneberg et al. [8] present a cloud-based system for the dynamic control of intersection traffic lights based on the analysis of vehicle volumes/patterns and public transport punctuality, while focusing on increasing safety and minimizing vehicle idle time in traffic.

III. DESIGN OF A SYSTEM FOR PROCESSING OF IOT DATA IN THE CLOUD

A. *Overview of the system*

The main purpose of the system is to process and visualise the IoT data and network security data and it is not obligated to control the devices. Thus, the devices will send only **sensor metrics**, i.e. values for a set of predefined physical measures, and **security metrics** i.e. metrics about the inbound and outbound network traffic of the devices. This system is designed as a complete online platform that is able to gather, analyse and visualise the time series data gathered by the devices and the AWS services. The system has been designed and implemented as a cloud platform due to the following: great processing power needed to analyse large and ever-growing quantities of IoT data; the interoperability between heterogeneous devices designed by different vendors; scaling enterprise resources for storing IoT data as it grows over time; flexibility of adding and removing services, as well as testing different capabilities on the cloud; easier maintenance of resources by alleviating the burden of caring for enterprise's own hardware infrastructure [1].

The final goal of the proposed system is to enable a simple, yet detailed picture of the enterprise's IoT network and its components – from the highest level, by presenting the state of the entire network and the used cloud services, up to the lowest level, by presenting the connectivity status and alarms of every single IoT device and visualising all of their sensor and security metrics. The near real-time monitoring and analysis of important device-side and cloud-side security metrics allows for a way to frequently check if the IoT devices in the network adhere to the best security practices, while also enabling the network administrators to react fast when an anomaly occurs, allowing them to investigate all problems and discover and possibly prevent potential cyber-attacks in the network.

In order to design a comprehensive and full-featured system the following concepts have been followed: provide a possibility for near real-time visualisation of sensor and security metrics, connectivity status and alarms for all devices on the web platform; enable and maintain simultaneous connection of multiple IoT devices sending different types of sensor and security metrics in a scalable way; continuous 24/7 monitoring and gathering of IoT sensor and security data; analyse security data near real-time for the purpose of detecting anomalies and security vulnerabilities in the IoT network; notify the user for every security data anomaly detection and device disconnects in the network by generating alarms visible on the web platform. Following these principles the design of the system, utilizing different cloud services and technologies, underwent two design versions, each with various own advantages and disadvantages.

B. *Initial design of the system*

The first proposed design utilized the AWS services presented in Fig.1. The IoT device communication in both versions of the system, was simulated using only three devices - one Raspberry Pi and two ESP 32 boards. Each device sent sensor metrics in a periodic manner - once every 5 minutes, using the MQTT communication protocol with a payload in JSON format. Additionally, the Raspberry Pi device sent one MQTT client message every 5 minutes containing a JSON payload with device-side security metrics. All three devices were evaluated for representative cloud-side security metrics such as connection attempts, message size etc. All of the AWS service resources were allocated in the Europe (Frankfurt) region in both designs. From Fig.1, it can be observed that the service used as an MQTT broker, real-time acquisition of sensor and security metrics and routing of the data to other services is AWS IoT Core. In IoT Core, three "thing" logical representations were created for every device used to communicate with the cloud. Each IoT device connects to an endpoint in AWS IoT Core, using TLS for a secure, authenticated and encrypted connection and has a security policy attached which defines the level of control access the device has on the cloud. In this case, each device is allowed to connect and publish messages to the cloud.

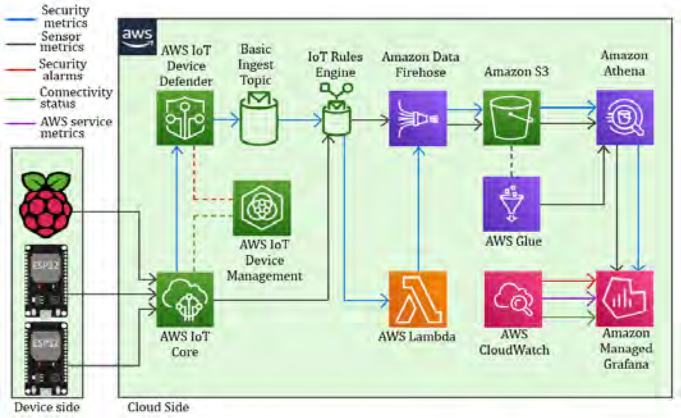

Fig. 1. Architecture of the first version of the proposed system

AWS IoT Device Defender service is used for detection of anomalies in the network and for security metrics export. The Raspberry Pi sends the device-side security metrics to a predefined MQTT topic designated to forward the data directly to IoT Device Defender. For the reporting of the connectivity status and security alarms on all devices, the service AWS IoT Device Management is used to generate fleet metrics for every indexed IoT device. The sensor and security metrics are sent to Amazon Data Firehose in batches to be written in an AWS S3 bucket for long-term storage. The routing of the sensor metrics to Firehose is done using the Rules Engine in IoT Core. For this architecture, two rules were created for forwarding the sensor and security metrics. A Basic Ingest Topic can be used to avoid additional messaging costs in IoT Core, as in the case of the security metrics.


```
{
  "version":"1.0",
  "metrics":[
    {"name":"aws:num-listening-tcp-ports","thing":"raspi5","value":{"count":2},"version":1,"timestamp":1711981370866},
    {"name":"aws:all-packets-out","thing":"raspi5","value":{"count":110},"version":1,"timestamp":1711981370866},
    {"name":"aws:num-established-tcp-connections","thing":"raspi5","value":{"count":1},"version":1,"timestamp":1711981370866},
    {"name":"cpu_usage","thing":"raspi5","value":{"number":0.0},"version":1,"timestamp":1711981370866},
    {"name":"aws:all-bytes-in","thing":"raspi5","value":{"count":49302},"version":1,"timestamp":1711981370866}
  ]
},
{
  "version":"1.0",
  "metrics":[
    {"name":"aws:num-messages-received","thing":"esp32-1","value":{"count":1},"version":1,"timestamp":1711981500000},
    {"name":"aws:total-message-byte-size","thing":"esp32-1","value":{"count":1030},"version":1,"timestamp":1711981500000},
    {"name":"aws:num-disconnects","thing":"esp32-1","value":{"count":0},"version":1,"timestamp":1711981500000},
    {"name":"aws:num-authorization-failures","thing":"esp32-1","value":{"count":0},"version":1,"timestamp":1711981500000},
    {"name":"aws:source-ip-address","thing":"esp32-1","value":{"cidrs":["77.29.46.92"]},"version":1,"timestamp":1711981500000},
    {"name":"aws:num-messages-sent","thing":"esp32-1","value":{"count":2},"version":1,"timestamp":1711981500000}
  ]
}
```


Fig. 2. Example of two export messages from IoT Device Defender

The security metrics are exported from IoT Device Defender in batches as a JSON message named 'metrics' with variable-sized list of multiple security metrics as elements (Fig.2). This format is inefficient for querying, thus, before sending the exported security metrics from IoT Device Defender to Firehose, they are transformed using a Python Lambda function. This function loops through the batched security metrics and separates them as single metrics. The service AWS Glue is used to determine the data scheme to create the structure, tables and partitions from the S3 bucket data. The scheme and partitions are then available for Amazon Athena to scan the contents in S3 and send the data to be visualised in AWS Managed Grafana. Additionally, the service AWS CloudWatch is used to obtain important metrics for all AWS resources to keep track of the performance and service cost, and for the visualisation of fleet metrics customly created with IoT Device Management.

Several problems were identified with this version, leading to the second system implementation. Although useful for lowering the costs of write operations in S3, the batching of the data with Firehose, inevitably increases the latency of data transfer, making it less suitable for near real-time analysis if low-latency alternatives exist. Further problems arise when using Glue and Athena. In order to visualize all of the S3 bucket data in AWS Grafana, the service AWS Athena has to query the data once in a user-defined time-interval to refresh the dashboards and panels and thus save on query and scanning costs. For this, the data records in S3 need to be indexed by time. This indexing is done by AWS Glue Crawler. Every time the crawler program executes, the bill of AWS Glue increases. Since all new data records need to be scanned, a compromise must be made between the granularity of scanning new data records and the minimum delay of data visualization on the web platform. If quick response to data changes is essential, the enterprise/user will prioritize minimal data delay, thus significantly increasing AWS Glue costs. However, if the enterprise/user is looking for a solution to analyse high volumes of data once in a longer period, using Data Firehose, S3, Glue and Athena services presents as cost-effective.

Another significant disadvantage of the first version was the price and limitations of the custom fleet metrics for alarms and connectivity in IoT Device Management. These metrics are created by indexing every device in the IoT fleet and by querying their alarm events and connects/ disconnects once in a user-defined period, e.g. one minute. Again, if quick response to data changes is essential, the price for querying by metric increases. More devices in the network also increase the price. Additionally, this solution is not suitable for networks with a large number of IoT devices, since the IoT Device Management service has a limit of just 100 fleet metrics per account, at the time this paper was written. Furthermore, these metrics can only be viewed in CloudWatch which has a cost for every GetMetric request made by any other service. Thus, with every refresh of the Grafana dashboards the cost for CloudWatch API calls increases significantly due to retrieving all custom made metrics for every device in the network.

C. Final implementation of the system

Fig. 3 depicts the second version of the designed IoT cloud system and features the exact same configuration and code for the three devices used for testing the system functionalities. In this version, AWS IoT Core and AWS IoT Device Defender are both utilized for the same purpose and in the same manner as the first version with one difference - IoT Core has three rules to redirect the data to other services. AWS Device Defender exports the security metrics to a Lambda function again, but instead of sending the separated security metrics to Data Firehose, the Lambda writes them to a database in AWS called Amazon Timestream. The function also classifies the security metrics into cloud-side and device-side in order to write them in two separate Timestream tables.

With every anomaly detection in the security metrics, IoT Device Defender generates an alarm which can be viewed in the console but can also be routed to other services without the Rules Engine. To inform the user about which device has generated a security alarm, Amazon SNS is used. This service receives all of the alarms generated from AWS IoT Device Defender and can send them to a set of predefined AWS and external services, including AWS Lambda. To ensure that the user is notified about which device is disconnected from the system, the messages contained in the topic *"$aws/events/presence/+/+"* are routed with the Rules Engine to another Lambda function. This is a reserved MQTT topic on AWS IoT Core, where all changes in system connectivity are transmitted.

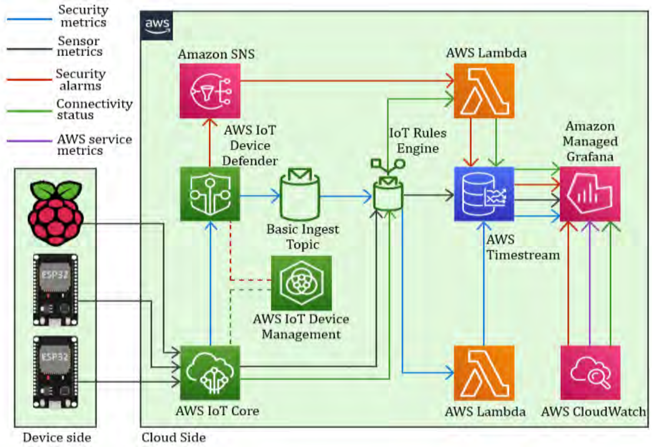

Fig. 3. Architecture of the second version of the proposed system

The SNS notifications are also sent to this Lambda function. The code of the function classifies the incoming messages either to security alarms or connectivity events, filters only the needed information, transforms the messages as data records and writes them to the same Timestream database in a different table. This database is added as a data source in Amazon Grafana and visualized in user-defined dashboards.

Fleet metrics (2) Info

Delete | Create fleet

Choose specific properties to report statistical data, such as count, average and standard deviation. You can save search queries for reuse and report the values in a query result to CloudWatc metric.

Name	Aggregation type	Aggregation field	Fleet hub	Set interval	Date created
deviceConnection	Statistics	thingName	No	1 minute	March 21, 2024, 09:25:19 (U
ActiveAlarms_ruleBased	Statistics	deviceDefender.violationCount	No	1 minute	April 20, 2024, 22:19:56 (U

Fig. 4. Fleet metrics in IoT Device Management

IoT Device Management is used again, but now only for two custom metrics: the total number of connected devices and the total number of active alarms (Fig.4). This is intended to reduce the number of custom metrics and thus the overall cost. At first, the usage of this service might seem redundant, but it is useful for giving the user information about alarms and disconnected devices when no change has occurred in the network for a longer period, as further explained in Section 4. CloudWatch is utilized again as a data source in Grafana to visualise AWS service performances and the two IoT Device Management metrics.

1) Amazon Timestream for storing time series data

In this final design, the services Data Firehose, S3, Glue and Athena are replaced with a single service - Timestream. This database is designed specifically for storage and analysis of time series data and used to handle near real-time data efficiently by automatically creating time partitions with high level of granularity, without incurring additional costs. Even though this database is more costly for data query compared to AWS Athena, this solution presented as more cost-effective for filtering smaller amounts of data in near real-time at the time of writing this paper. As for write operations, the price per record is much lower than it is with S3, thus eliminating the need for batch writing and Data Firehose. On the other hand, due to the high price per query, AWS Timestream is not cost-effective for analysis of large batches of historical data.

As mentioned, the Lambda function for filtering alarms and connectivity messages, writes the data in a Timestream table as multi-measure records, a feature available in Timestream to allow a faster and more efficient writing of data by storing multiple time series measures in a single table row. Part of the contents and the columns of this table can be seen in Fig. 5.

Rows returned (134)

device_id	message_type	measure_name	time	state	value	bool_val
raspi5	alarm	Packets_in	2024-04-21 18:43:13.46	alarm-cleared	{'count': 232}	false
raspi5	alarm	Bytes_out	2024-04-21 18:43:13.46	alarm-cleared	{'count': 10706}	false
raspi5	alarm	cpu_usage	2024-04-21 18:43:13.46	alarm-cleared	{'number': 0.0}	false
esp32-2	connectivity	IP_Address	2024-04-21 18:39:22.35	connected	46.217.26.228	true
esp32-1	connectivity	IP_Address	2024-04-21 18:39:17.31	connected	46.217.26.228	true
esp32-1	connectivity	Disconnect_Rea	2024-04-21 18:39:07.85	disconnected	MQTT_KEEP_AL	false

Fig. 5. Contents of the alarms and connectivity Timestream table

The sensor metrics are written directly to a Timestream table, without any transformations as a single measure per record, i.e. one measure name with one measure value per row, associated with a timestamp and a device_id for dimension. After the Lambda transformation and classification of the security metrics exported from IoT Device Defender, they are written in two separate tables for cloud-side and device-side metrics. Each metric is written as a single measure record in both tables, having a device_id as a dimension again, and associating each metric name with one value, shown in Fig.6.

After all of the types of data are stored in Timestream, the last thing to do is add it as a data source to Amazon Managed Grafana. Since the web platform custom-built in Grafana is the resulting product of this implementation, further explanation of this service and web platform will be given in Section 4. Prior to that, a review of the utilised security metrics is given, highlighting the importance of detecting their anomalies.

2) Detecting network traffic anomalies

The service AWS IoT Device Defender can detect network anomalies with two types of security profiles: user-defined rule-based thresholds or machine learning models that are created for every metric and either for a single device or a user-defined group of devices.

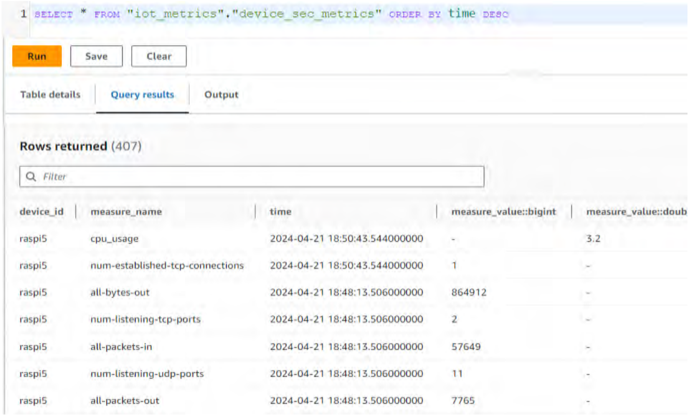

Fig. 6. Single-measure records of security metrics in Timestream

The ML models are trained on the cloud side, leaving the responsibility to the user to provide the models with significant amount of data points on a daily basis to update the ML models. In this paper, only the Rules-Detect security profile was implemented due to the small amount of generated network traffic by the three devices. IoT Device Defender offers monitoring and anomaly detection for a selection of security metrics presented in Table I. As mentioned, the Raspberry Pi was evaluated for both device-side and cloud-side metrics, while the ESP32 devices were evaluated only for the cloud-side metrics.

TABLE I. LIST OF USED METRICS FOR THE SECURITY PROFILE OF THE IOT DEVICES

Rule-based security metrics	
Cloud-side metrics	***Device-side metrics***
Authorization failures Connection attempts Number of disconnects Disconnect duration Messages sent Messages received Message size Source IP	Bytes-in, Bytes-out Packets-in, Packets-out Listening TCP ports Number of listening TCP ports Listening UDP ports Number of listening UDP ports Number of established TCP connections Destination IPs CPU usage (custom metric)

Detecting out of bound values can indicate a potential attack in the IoT network and even determine the type of attack. For example, a significant increase in outbound packets or bytes from the IoT device could indicate a potential botnet attack or data exfiltration [9],[10]. Botnet attacks are also indicative if the IoT device communicates with an unusual destination IP address [13],[11]. A sudden increase in inbound and outbound traffic could also indicate a DoS/DDoS attack on the device [11]. CPU usage that is greater than usual could mean a crypto jacking attack [12] and so on.

3) *System pricing factors*

As noted, the second system design was chosen for its cost-effectiveness. Nevertheless, estimating the exact cost is challenging: AWS price models and service costs vary; the number of IoT devices and storage allocations can change; the number of Lambda executions (for security metric transforms and device connectivity and alarm events), number of Timestream write and query operations and the number of SNS notifications cannot be defined. The pricing factors that influence the overall cost of the proposed system are listed in Table II.

TABLE II. AWS SERVICE COST FACTORS

AWS service	**Pricing factors that influence the cost of this system**
IoT Core	- Number of messages transmitted (from devices) Messages with Basic Ingest Topic don't incur these costs - Total time of connectivity to IoT Core (for all devices) - Number of rules triggered and actions applied within a rule
IoT Device Management	- Number of index updates and search queries executed
IoT Device Defender	- Metric reporting frequency for Rules Detect
CloudWatch	- Number of GetMetric requests made from A. Grafana
AWS Grafana	- Number of Editor and active Viewer licences
Lambda	- Number of function invocations - Average function execution duration
SNS	- Number of notification deliveries to Lambda
Timestream	- Writes: Number of Memory writes to the database - Queries: Duration of Timestream compute units (TCUs) used by your application in TCU-hours - Memory storage duration - Magnetic storage duration

During the implementation of both system versions, Timestream queries were billed based on data volume, making the second design more cost-effective. However, during the period when this study was conducted, the pricing model shifted to charging based on Timestream Compute Unit (TCU) duration, potentially altering the cost differences between the two designs. This change highlights the need for future analysis of these architectures or exploring alternatives to optimize overall costs

IV. RESULTS AND DISCUSSION

This section lays out the Amazon Managed Grafana system features, the performance of the system in terms of latency, as well as a features comparison regarding similar systems.

A. *System monitoring*

The final web platform of the system was designed using a set of transformation functions and panels for visualising data. The monitoring encompasses multiple dashboards, each with a different refresh time interval based on the importance of the data. All dashboards using Timestream as a data source include a source panel used to retrieve data from the necessary tables. That panel is later used as a data source to derive other panels for a more comprehensive view of the IoT data. The derived panels use multiple transformation functions such as reduce row, filter data by values or by name, group to matrix etc.

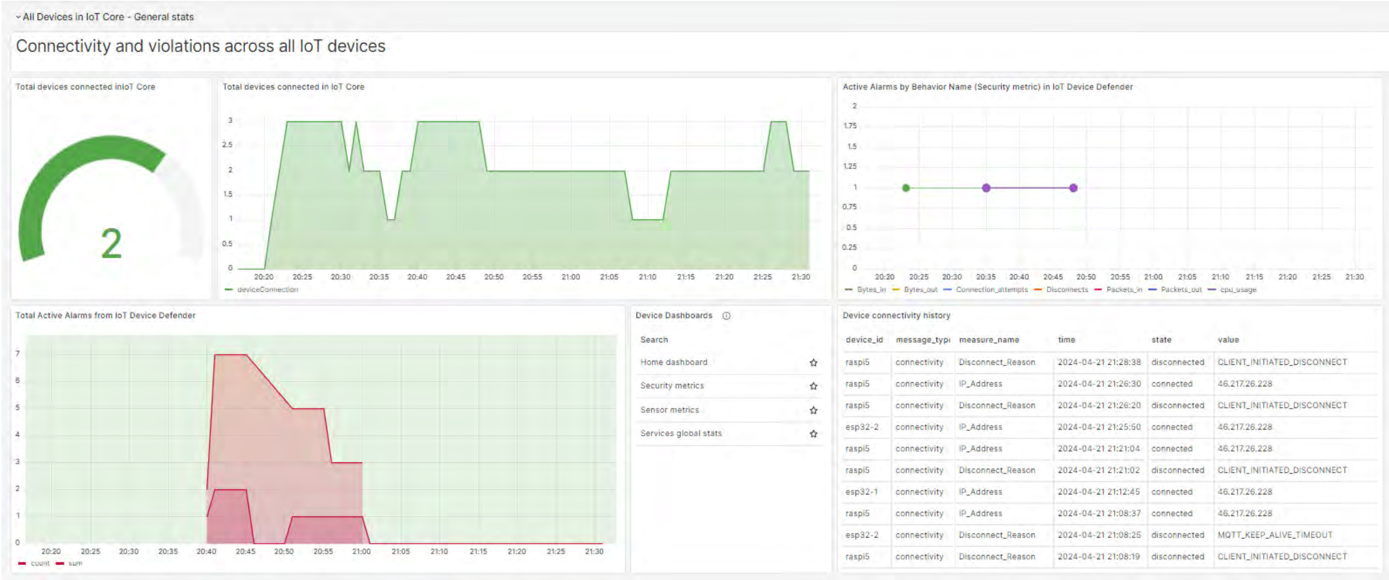

Fig. 7. Total number of connected devices and alarms in the system

This is done to lower the costs of the queries, every time the dashboards refresh. Instead of querying the same data multiple times for every panel, the data is queried only once or twice for the source panels in the dashboard and is later distributed in the rest of the panels.

A total of four dashboards were created in the Grafana workspace – **home**, **sensor metrics, security metrics** and **global service stats**. The **home** dashboard visualises the alarms and connectivity messages in the IoT network available to the user with CloudWatch and from the Timestream database. As presented in Fig.7 it contains the following panels: active alarms by device and total active alarms in the network; the total number of connected devices in the system; navigation panel to the other dashboards; table with the records in the alarms and connectivity table from Timestream; the type of alarms in the network by security metric available in the AWS/IoT namespace in CloudWatch. The IoT Device Management fleet metrics notifies the user about the current network status (no connectivity or alarm events in a period longer than the time range used to filter the records in the Timestream table). The second part of the Home dashboard contains panels about the connectivity and alarm events for each IoT device. The connectivity and alarm events for one ESP32 and Raspberry Pi are presented in Fig.8.

The **sensor metrics** dashboard hosts panels derived from the Timestream table with sensor metric data records. Fig. 9 shows the sensor metrics in a time series and stat panels for visualisation. For the testing of the system's functionalities, simulated air quality and weather-related metrics were sent from the three devices.

The security metrics, both cloud-side and device-side are shown in the **security** metrics dashboard. Fig.10 displays the device-side metrics sent by the Raspberry Pi. The table on the right side of Fig.10 is the Timestream source panel used to transform all of the other panels in the dashboard-the stat panel

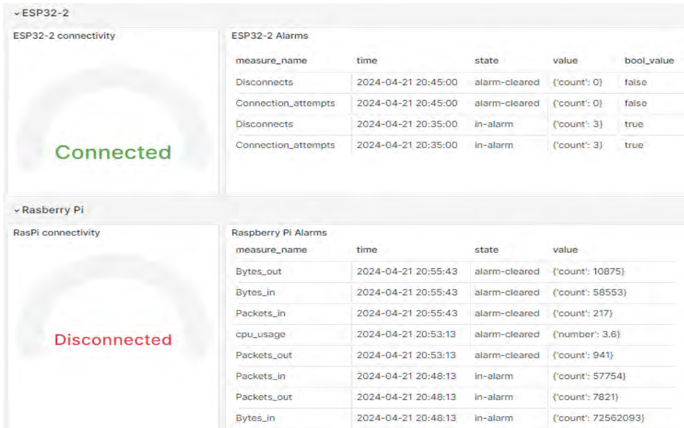

Fig. 8. Connectivity and violation panels per device

Fig. 9. Visualisation of sensor metrics per device

showing the values last sent by the device and the time series charts showing the metrics sent across time. Fig.11 shows the cloud-side security metrics for all three devices connected to

IoT Core derived from the cloud security metrics table in Timestream.

The last dashboard is the **global service stats** dashboard where Cloudwatch is the only data source used to visualise the state of the most important resources used in AWS so the user may gain system-wide visibility into resource utilization, application performance, and operational health. Fig. 12 shows three panels visualizing the resource metrics for IoT Core, Timestream and Lambda.

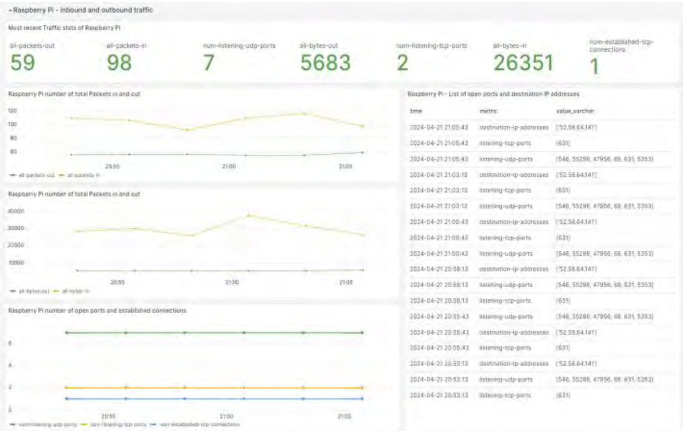

Fig. 10. Device-side security metrics for the Raspberry Pi

Fig. 11. Cloud-side security metrics per device

Fig. 12. Service resource stats

B. Time delay in the system

Since the time delay of every metric type is in the range of a few minutes, it is assumed that Rules Engine forwarding, SNS forwarding, Lambda execution duration, SQL queries to Timestream delays are negligible.

According to the IoT Device Defender quota, the minimum sampling interval for devices to send security metrics reports is 300 seconds (5 minutes). However, observations have shown that messages can be sent at one minute intervals, with a significant number of them being successfully received by IoT Device Defender. Nevertheless, if metrics are sent to IoT Core every 5 minutes, Rules-Detect alarms will be generated at precise 5-minute intervals (e.g. a report sent at 15:31 and another sent at 15:34 both trigger an alarm at 15:35). Therefore, the worst-case scenario for IoT Device Defender to generate alarms is a latency of five minutes. If the rest of the data transfer delay is negligible, the maximum time delay of the security alarms measured from the moment the device sends the anomalous data point to the alarm visualisation in Grafana is around 6 minutes, assuming a refresh rate of the Home dashboard to be once in a minute. Although this latency is acceptable for most cases, it might be a problem for enterprises needing real-time network security.

Security metrics export from IoT Device Defender also occurs at a 5-minute interval. This results in a maximum delay of around 10 minutes for visualization in Grafana, assuming the security dashboard also refreshes every 5 minutes. Sensor metrics can be sent at user-defined intervals, with IoT Core allowing up to 100 messages per second per device. In this implementation, sensor data was sampled once every 5 minutes per device. Once sent to IoT Core, the data is routed directly to a table and queried via the in-built Timestream SQL engine in Grafana. Therefore the maximum time delay only depends on the Grafana refresh interval, set to be 1 minute. Messages about device connectivity that are sent from the reserved MQTT topic also have a time delay which depends solely on the Grafana refresh interval time, thus it is 1 minute in this implementation. Alarms and connectivity messages from Device Management are sampled every minute. This results in a delay of maximum 1 minute for sampling added to the time delay of the dashboard refresh, thus having a 2 minute delay in the implemented web platform.

Due to its data analysis latency of a few minutes, the system qualifies as near-real-time. Nonetheless, it remains suitable for implementation in most use cases.

C. Comparison with similar systems

Table III presents a comparison of the proposed system features compared to the several similar systems mentioned in Section 2. The comparison clearly shows that the proposed system puts its focus on the security aspects of IoT networks compared to the mentioned papers. Another strong point is the generality of data that can be used, while the other papers have a specific application focus. Monitoring connectivity status per device is another advantage.

TABLE III. FEATURE COMPARISON

Feature	Dineva et al. [6]	Esposito et al. [7]	Tarner-berg et al. [8]	This system
Application focus	Smart farming	Smart home	Smart city	General data
Type of data analysed	Video and sensor	Sensor and voice (text)	Sensor	Sensor
Long-term data storage	Yes	Yes	Yes	Yes
Sensor data analysis	Yes	No	Yes	No
Security metrics analysis	No	No	No	Yes
ML analysis	Yes – object recognition & forecast	No	No	Possibility for integration w/ IoT Device Defender
Device control	No	Yes	Yes	No
Data visualization platform	Possibility for integration	No	No	Yes
Alarms and notifications	Yes	No	No	Yes
Device connectivity information	No	No	No	Yes
Smart phone app	No	Yes	No	No

One drawback of the system is the ability to analyse the sensor metrics sent by the IoT devices more thoroughly. This feature would make the overall functionality of the system even more powerful by giving the user valuable insights from his entire IoT fleet. It might further help to diagnose device problems, optimize processes by identifying inefficiencies, integrate with ML for predictive maintenance or enhance overall decision-making.

V. CONCLUSION

In this paper, a web platform for the analysis and visualisation of IoT data on a cloud-based system was presented. The main goal was to integrate several key cloud services for analyzing IoT sensor and security metrics and to visualise them in a clear and consolidated manner, making it easier for the user to identify any issues and extract valuable insights from the provided data. The end product is a user friendly, comprehensive web platform characterized by high flexibility, easily adjusted to meet the user's needs, allowing the addition of various data sources. This design when compared to other similar systems, puts more focus on the security of the IoT network and device connectivity. This implementation opens the possibility to further expand the system for even more thorough IoT data analysis and research of other more cost-effective designs for cloud-based systems.

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Enhancing Music Genre Classification: A Divide and Conquer Approach

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Abstract—**Music genre classification (MGC) is a fundamental task in Music Information Retrieval (MIR), enabling applications such as music recommendation, organization, and automated tagging. This study evaluates the effectiveness of five traditional supervised machine learning models: Random Forest Classifier (RFC), Support Vector Classifier (SVC), K-Nearest Neighbors (KNN), LightGBM (LGBM), and XGBoost (XGB) in tackling the MGC task. We introduce a two-step hierarchical classification approach (HClass) that simplifies genre classification by organizing 10 original genres into 6 supergroups, with the first layer predicting the supergroup and the second layer classifying the specific genre within each group. Experimental results demonstrate that while the HClass outperforms the baseline classifier, it achieves only a marginal improvement in weighted F1-score (+0.031) over the best-performing single-step LGBM model. These findings suggest that although the hierarchical approach offers a structured way to simplify the classification task, further optimization is needed to fully realize its potential. We also propose potential enhancements, such as implementing a one-vs-rest classification scheme in the first layer, which could improve performance by reducing misclassifications at the supergroup level. This research aims to contribute to the ongoing efforts in music categorization, providing insights that may be useful for future, more efficient, and precise genre classification methods.**

Keywords—Music Genre Classification; Machine Learning, Supervised Learning; Two-step Hierarchical approach; Supergroups; Feature Selection; Music Information Retrieval; GTZAN Dataset;

I. INTRODUCTION

Music genre classification (MGC) is a fundamental task in Music Information Retrieval (MIR), enabling applications such as music recommendation, organization, and automated tagging. While humans possess an innate ability to analyze and classify music genres [1], translating this capability into algorithmic steps for a computer system has proven to be a challenging endeavor [2]. The complexity and accuracy required for MGC surpass the capabilities of traditional tools like Finite State Machines. In this paper, we explore the effectiveness of traditional supervised machine learning algorithms to tackle the MGC problem. The rise of the music streaming industry, led by giants such as Spotify, Tidal, and Apple Music [3], has highlighted the need for further investment and research in MIR methods and techniques.

Given the challenges posed by MGC, supervised learning models emerge as a promising solution due to their ability to provide better accuracy and high efficiency with smaller parameter sizes [21]. While unsupervised learning approaches might be deployed faster because they don't require the extensive feature extraction and data processing that supervised methods need [22], they lack transparency and are more difficult to interpret due to the absence of labeled data. A supervised approach, on the other hand, offers clearer insights into classification decisions and allows for more precise fine-tuning compared to unsupervised methods [21][22].

The groundbreaking work of Dannenberg, Thom, and Watson [4] and Tzanetakis and Cook [5] has not only paved the way for MGC but has also demonstrated the feasibility of using Machine Learning (ML) to construct effective genre classification models. In this study, we focus on five different traditional ML approaches that follow the supervised learning paradigm. Specifically, we evaluate the performance of Random Forest Classifier (RFC), Support Vector Classifier (SVC), K-Nearest Neighbors (KNN), and two popular gradient boosting frameworks, Light Gradient Boosting Machine commonly referred to as LightGBM (LGBM) and eXtreme Gradient Boosting model commonly referred to as XGBoost (XGB), in the context of genre classification. Our objective is to identify the strengths and weaknesses of these models for MGC. Furthermore, we introduce a novel approach to enhance the performance of MGC by employing a divide-and-conquer strategy. We propose a two-step Hierarchical classification (HClass) that leverages logical groupings of genres, referred to as supergroups, to simplify the classification task. By reducing the original 10 genres to 6 supergroups, we aim to improve the overall classification accuracy. The HClass's implementation involves a first-layer model that predicts the supergroup, followed by a second-layer model specifically trained to distinguish the original genres within each supergroup.

Through experimentation, we compare the performance of the individual models and evaluate the effectiveness of our proposed two-step approach. By demonstrating the merits of supervised learning techniques for MGC, we aim to contribute to the ongoing research in this field and provide insights into the suitability of different ML models for this task. The rest of the paper is organized as follows: Section 2 describes our dataset, Section 3 explores the preprocessing steps and the details of our proposed HClass, Section 4 presents the results and a comparative analysis of the models' performance, Section 5 outlines possibilities or future work and finally, Section 6 concludes the paper.

II. Dataset

In the early stages of our study, we aimed to test our models on a relatively small, well-defined piece of data before scaling our experiments. We selected the GTZAN dataset, a widely recognized benchmark in music genre classification, for initial feature extraction and model validation. Originally compiled by Tzanetakis in 2002, the GTZAN dataset consists of 1000 audio tracks, each 30 seconds long, evenly distributed across 10 distinct music genres [6].

TABLE I. GTZAN original genres

A	Rock	**B**	Metal	**C**	Disco	**D**	Pop	**E**	Blues
F	Jazz	**G**	Reggae	**H**	Hip-hop	**I**	Country	**J**	Classical

Each genre (as presented in Table I) in the GTZAN dataset is represented by 100 tracks, sourced from diverse mediums such as radio, CDs, and the internet. This variety ensures the dataset reflects a wide range of audio qualities and characteristics, which is crucial for testing the robustness of our models in real-world scenarios.

In exploring the foundational idea of our paper on MGC, we initially focused on fine-tuning models using the GTZAN dataset. This early stage involved recognizing the potential for broader genre categorizations, aiming to create a more robust classification model. While the dataset offers ten distinct genres, certain genres share overlapping musical characteristics that can be logically grouped for a broader classification approach. It is important to note that all musical genres are bound to have some similarities. This is due to the tendency of music being composed around the same set of octaves [7]. Therefore, grouping the genres presented a significant challenge, primarily due to the varied sound profiles encountered within individual genres, which becomes even more complex when considering the broader spectrum of music categorization. Consequently, our approach was informed by the methodologies and findings of Georgee, et al. (2015) [8] and Groth (2014) [9], particularly their insights into genre similarities identified via supervised learning techniques. Additionally, our analysis included a comprehensive review of existing literature that examines both the cultural contexts and sound characteristics unique to each genre. This exploration led to the categorization of genres into groups, which we have described as 'supergroups' within the context of this paper:

- *Blues and Jazz* both have roots in African American musical traditions and share certain rhythmic and harmonic elements, making them suitable for a combined category [10].
- *Pop and Disco* often share upbeat tempos and melodic hooks, leading us to group them under a single label.
- *Rock and Metal* exhibit strong electric guitar components, such as high distortion, while also having similar rhythmic patterns, allowing them to be merged into a single category.
- *Reggae and Hip-hop* both have rhythmic vocal and instrumental patterns, and they often share a strong emphasis on vocal performance, making them candidates for grouping.

For the purpose of this paper, the original 10 genres will be referred to as the *α-group* and the supergroup genre regrouping to 6 genres will be referred to as the *β-group*.

To enhance the robustness of our model, we expanded the dataset by increasing it by 300% for eight of the genres of the α-group, however, within our defined β-group, Classical and Country could not be paired with other genres. Consequently, these genres stood alone, necessitating a different approach to maintain a degree of balance across all parts of the β-group. We adjusted the expansions for Classical and Country by increasing their datasets by 450% each. This rate, higher than the increase for other groups, aimed to somewhat balance the dataset volumes, compensating for the absence of pairing and ensuring these genres received sufficient data for effective training. This approach was crucial for allowing a more balanced representation and robust training across the dataset.

III. Methodology

A. Feature Engineering

This stage employs advanced tools for analyzing and interpreting audio signals, integrating statistical methods to extract meaningful patterns essential for accurate classification. In music feature extraction, the key qualities of an audio track are captured by a specific set of features found in the sound wave. These features, derived from the audio signal, provide a comprehensive representation of the track's musical and acoustic properties. In our approach, we based the initial feature selection on prior research from McKinney & Breebaart (2003) [11], McKay & Fujinaga (2006) [2], and Li & Ogihara (2003) [23], which provided a strong foundation for understanding the characteristics of sound waves in relation to musical genres. However, rather than relying solely on these selections, we focused on fine-tuning the coefficients associated with these features. Through multiple iterations, we tested different parameter settings for each feature, refining them based on their impact on model performance.

To determine the most effective features, we ran various configurations through our models and compared F1 scores, selecting the feature sets that consistently delivered the best results. This process allowed us to refine our approach through empirical testing, ensuring that the features retained in the final model were those that demonstrated the highest classification accuracy. Specifically, the following features had the greatest impact:

- *Chroma Features*: With the incorporation of Chroma Short-Time Fourier Transform (STFT), Chroma Constant-Q Transform (CQT), and Chroma Energy Normalized Statistics (CENS), we capture the energy distribution across twelve pitch classes, enhancing our ability to identify harmony and chords.
- *Tonal Centroid Features (Tonnetz)*: Reflects the tonal content of music, capturing spatial characteristics of sound in a tonal space, useful for understanding the harmonic and melodic aspects.
- *Mel-frequency Cepstral Coefficients (MFCCs)*: Captures the timbre of audio by representing the short-term power spectrum of a sound, with 20 coefficients providing a detailed signature.
- *Spectral Features*: Including Spectral Centroid, Spectral Bandwidth, Spectral Contrast, and Spectral Rolloff, these features help differentiate tracks by brightness, timbral texture, and dynamic range.
- *RMS Energy*: Represents the average energy of the audio signal, providing a measure of perceived loudness.
- *Zero Crossing Rate (ZCR)*: Indicates the rate at which the audio signal changes from positive to negative or vice versa, offering insights into the perceptiveness of the sound.

For each of these features, we computed multiple statistical measures—mean, standard deviation, skewness, kurtosis, median, minimum, and maximum. These statistics are not arbitrary; they are critical for capturing the dynamic range and variability of sound characteristics across the entirety of a track. For instance:

- *Mean and Median* provide central tendencies which are foundational for understanding the typical behavior of a feature.
- *Standard Deviation* illustrates the variability or consistency of a feature throughout a track, indicating the presence of dynamic changes in sound.
- *Skewness and Kurtosis* offer insights into the shape of the feature's distribution, revealing asymmetries and the prevalence of outliers, which can be indicative of specific musical techniques or genres.
- *Minimum and Maximum* values frame the range of the feature, highlighting the extremes of sound expression within a track.

These statistical measures allow for a nuanced analysis of audio signals, facilitating a deeper understanding of the intricate patterns within tracks that are crucial for distinguishing between closely related musical genres.

After processing, the dataset consisted of 4,259 rows, each representing a unique audio track with a corresponding feature vector and genre label. In total, 518 distinct features were extracted for each track. Consequently, the complete feature set across the dataset amounts to 2,206,122 individual data points.

B. Model Selection

In our approach, we utilize two groups of models to tackle the music genre classification task. The first group comprises KNN, SVC, and RFC. These models represent the most popular supervised machine learning algorithms, known for their versatility and efficacy across various datasets [13]. The second group includes LGBM and XGB, two decision tree frameworks based on gradient boosting. These models were chosen due to their strong performance and robustness in classification tasks [14][15]. Aside from their popularity, given the nature of our dataset, which includes both continuous and discrete features, we decided to employ a combination of logic-based (RFC, LGBM, and XGB) and statistical-based (SVC and KNN) algorithms [16]. This approach ensures thorough coverage in feature analysis and allows us to validate the effectiveness of our feature selection process. Furthermore, utilizing a diverse set of algorithms serves a dual purpose: it not only validates our feature selection but also generates a range of predictions. These predictions are crucial for examining our central hypothesis regarding the viability of MGC using supervised machine learning techniques. Furthermore, we have decided to establish a meaningful baseline for MGC against which we can test the other models and our main hypothesis. For this task we opted for a One-vs-Rest Logistic Regression (LR) classifier as the baseline. LR is a well-known and interpretable algorithm that provides a more informative baseline by allowing us to compare how well more advanced models (like RF, XGB and LGBM) improve upon a simple, linear classification method.

C. Hyperparameter Tuning and Optimization

After the initial model construction, we focused on hyperparameter tuning and manual experimentation to optimize performance. Through a 5-fold cross-validation, we identified the set of hyperparameters that yielded the best results in terms of accuracy. To ensure the reproducibility of our experiments, we provide a description of the hyperparameters used for each model in Table II.

TABLE II. MODEL HYPERPARAMATERS

Model	Hyperparamater	Value
RFC	n_estimators	2000
LGBM	objective num_leaves learning_rate n_estimators min_data_in_leaf	Multiclass 80 0.05 800 50
XGB	objective n_estimators max_depth learning _rate booster gamma subsample	multi: softmax 100 7 0.1 gbtree 0.1 0.8
SVC	kernel degree gamma max_iter	poly 2 0.1 400000
KNN	n_neighbors	10

D. Two-Step Hierarchical Approach

To enhance the performance of MGC of music genre classification, we propose a two-step hierarchical approach that leverages the concept of supergroups. The HClass utilizes a divide-and-conquer strategy to simplify the classification task by first predicting the supergroup and then further classifying the sample into its specific genre within that supergroup.

The HClass shown in Figure 1, consists of two layers both implemented using the best performing model, LGBM. The first layer is an LGBM classifier trained to predict the supergroup of a music sample. If the predicted supergroup is already a specific genre, that prediction becomes the final output. Otherwise, the sample is passed to the second layer for further classification. The second layer comprises four LGBM classifiers, whose hyperparameters, shown in Table III, are specific to each classifier and tuned to a subset of the relevant genre data corresponding to a specific supergroup. These classifiers perform binary classification to distinguish between the genres within their respective supergroups. For example, if a sample is classified as belonging to the "Rock/Metal" supergroup in the first layer, it is then passed to the corresponding second-layer classifier, which further classifies it as either "Rock" or "Metal".

By breaking down the classification task into two steps, our HClass approach aims to improve the overall accuracy and robustness of MGC. The first layer focuses on identifying the broader category (supergroup) of the music sample, while the second layer specializes in distinguishing between the specific genres within each supergroup. This divide-and-conquer approach enables the models to concentrate on learning more targeted and discriminative features for each classification step, potentially leading to improved performance compared to a single-step approach. The implementation of our HClass is straightforward and efficient, leveraging the strengths of the LGBM model. In the following sections, we will evaluate the performance of our proposed HClass, and compare it with the traditional single-step classification methods using various evaluation metrics.

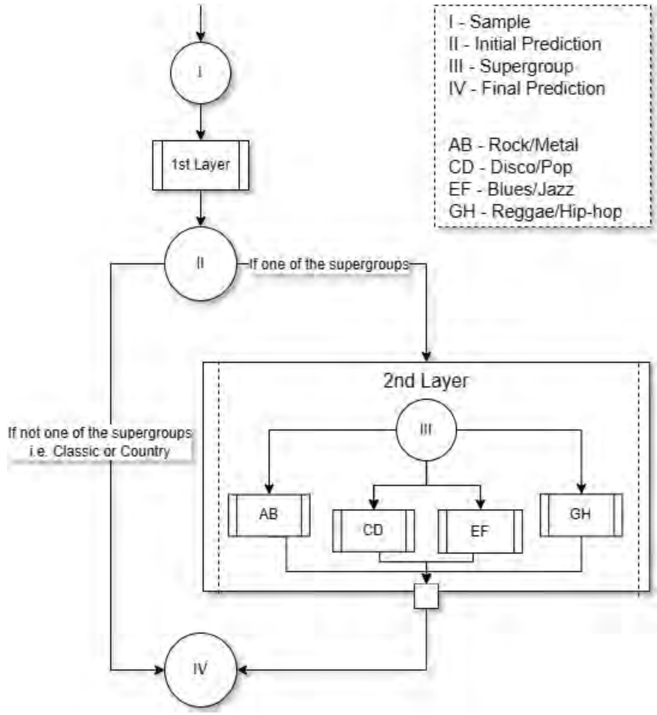

Fig. 1. Diagram of HClass architecture

TABLE III. HYPERPARAMATERS OF SPECIALIZED LGBM MODELS

Specialized Model	Hyperparamater	Value
Blues/Jazz	objective num_leaves learning_rate n_estimators min_data_in_leaf	binary 20 0.01 1000 50
Disco/Pop	objective num_leaves learning_rate n_estimators min_data_in_leaf	binary 20 0.01 1000 50
Reggae/Hip-hop	objective num_leaves learning_rate n_estimators min_data_in_leaf	binary 20 0.1 200 50
Rock/Metal	objective num_leaves learning_rate n_estimators min_data_in_leaf	binary 20 0.1 1000 100

IV. RESULTS

A. Single-step model evaluation

To assess the effectiveness of our proposed HClass approach for music genre classification, we first established a baseline performance using a simple OvR Logistic Regression model. Given the imbalanced nature of our dataset, particularly after the creation of supergroups, we opted to evaluate the performance of our models using the F1-score, taking the weighted average (WA) across classes. The F1-score is particularly suitable for situations with skewed class distributions, offering a balanced measure of precision and recall [24]. Our baseline analysis revealed a WA F1-score of 0.545 for the α-group and 0.62 for the β-group. These scores now become the reference point for evaluating the performance of the models, highlighting their ability to learn and identify patterns in the data beyond what is achievable through simple frequency-based predictions.

From the conducted experiments with our models, we observed that the logic-based models significantly outperformed the baseline in both the α-group and β-group. Specifically, the logic-based models achieved a mean F1 score of 0.764 for the β-group and 0.68 for the α-group. The improvement in F1 amounted to a delta of +0.112 for the β-group, indicating learning capabilities. It's important to note that these results are based on deploying the models without the use of the HClass.

Analyzing the deviation from the baseline (DB) in accuracy across models (as presented in Table V), we observed low DB, suggesting the success of our feature selection process. The logic-based models (LGBM, XGB, and RFC) notably outperformed the statistical-based models (SVC and KNN) by a significant margin. Their superior performance is linked to the advanced dimensionality reduction techniques used by gradient boosting models, such as LGBM and XGB, which allow these models to effectively learn from intricate data patterns, thereby improving classification accuracy. Upon examining the confusion matrices for the α-group and β-group, we observed that the β-group consistently outperforms the α-group in terms of the WA F1 score. This is to be expected since the complexity of the classification task is reduced.

TABLE IV. MODEL PERFORMANCE ON ALPHA-GROUP AND BETA-GROUP

Model	F1-Score		DB	
	α-group	β-group	α-group	β-group
Baseline	0.545	0.620	0	0
KNN	0.392	0.480	-0.153	-0.14
SVC	0.493	0.510	-0.052	-0.11
RFC	0.659	0.720	+0.114	+0.1
LGBM	0.699	0.802	+0.154	+0.182
XGB	0.683	0.770	+0.138	+0.15

One notable finding that we saw from our experiments is the performance of models on country and classical samples within the β-group. In particular, country music is characterized by its thematic approaches to lyricism, which are often more pronounced than its sound or pattern characteristics [17][18]. Its relatively high performance indicates that the feature selection was effective in capturing the nuanced aspects of country music, despite data imbalance issues with the expanded dataset. Unsurprisingly, classical genre samples exhibited the highest performance among all genres. While this genre also faced data imbalance issues, its performance remained relatively stable. This high performance and stability can be attributed to the inherent characteristics of the genre and the design of the initial features [5]. Classical music, characterized by its harmonic sounds and predictable patterns in sound waves, often consists of samples composed of a few notes or simple harmonies. This simplicity, combined with the systematic harmonic patterns and composition rules that are more predictable than those found in genres like metal, disco, or pop, makes classical music particularly suitable to the types of feature extraction and analysis used in our study.

The biggest DB observed is in the SVC model and the gradient boosting frameworks. We gather that the main reason why SVC shows the biggest DB might be due to data piling which occurs with higher dimensionality and the nature of support vectors, explained in the work of Marron, et al. (2007) [19]. Furthermore, we observe the highest performance gains in the gradient boosting frameworks (LGBM and XGB) due to their robust iterative learning process, explained in the work of Friedman (2002) [20]. Friedman's work emphasized stochastic sampling and shrinkage, key techniques that improve gradient boosting by correcting residuals and controlling the contribution of each model, thereby leading to more stable models by effectively reducing bias and variance, resulting in progressively better performance over multiple iterations. Additionally we would like to highlight LGBM's Gradient-based One-Side Sampling (GOSS) and Exclusive Feature Bundling (EFB) further optimize performance by focusing on informative samples and efficiently handling sparse data [15]. GOSS retains data with high gradient values while EFB reduces dimensionality by bundling mutually exclusive features.

On the other hand, XGB excels in handling high-dimensional data due to its efficient split-finding algorithms and sparsity-aware techniques, which optimize the use of sparse features and improve model robustness [14]. Together with built-in regularization, these techniques help both models mitigate overfitting and handle complex datasets effectively.

In summary, both LightGBM and XGBoost are well-suited to our high-dimensional dataset due to their respective data and feature handling techniques.

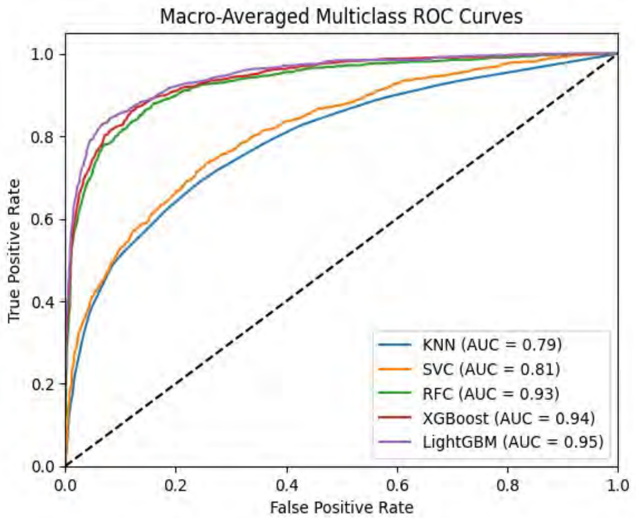

Fig. 2. ROC curves of all models in the β-group

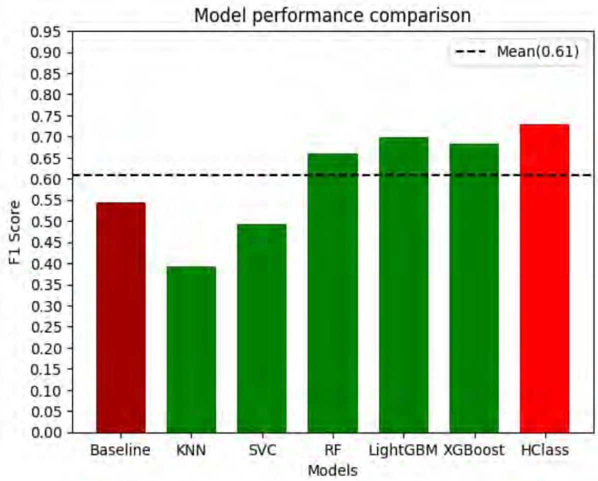

Fig. 3. Bar plot of model performance against the hierarchical approach and baseline for the α-group

The ROC curves (included in Figure 2) obtained using a One-vs-Rest (OvR) classifier, show that the logic-based models, particularly LGBM and XGB, demonstrated superior performance compared to the statistical models. This finding aligns with our earlier observations regarding the DB in model performance, suggesting that the robust nature of gradient boosting frameworks and their techniques for data minimization, and dimensionality reduction contribute to their resilience in handling high-dimensional and sparse data.

B. Two-step model evaluation

To evaluate the performance of our hierarchical classification and test our central hypothesis, we compared the WA F1-scores of the α-group with those of the two-step approach. Its design allows us to transition back from the supergroup genres to the original 10 genres, effectively returning to the α-group classification task. The hierarchical classification achieved a WA F1-score of 0.730, representing an improvement over the α-groups' baseline F1 score of 0.545, with a delta of +0.185. However, when comparing the HClass performance against the best-performing model for the α-group, the LGBM (which achieved a WA F1 score of 0.699), we observed only a marginal improvement. While we initially expected the hierarchical approach to yield more significant performance gains, the results provided only a modest delta of +0.031, which suggests that the expected benefits of hierarchical classification, such as targeted feature learning and specialization within supergroups, did not materialize as strongly as anticipated.

This improvement is not substantial enough to suggest that the HClass should entirely replace LGBM as a classifier for this task; however, it does highlight the potential for further refinement and optimization of the two-step approach. The HClass architecture, which leverages the strengths of LGBM and the divide-and-conquer strategy, offers a foundation for exploring more advanced techniques and enhancements that could lead to greater improvements in classification accuracy. Factors such as reduced training data for the second-layer classifiers and error accumulation across the hierarchical layers likely contributed to the observed limited performance gains.

The observed performance not only validates our central hypothesis but also highlights the effectiveness of our proposed two-step approach for music genre classification. By leveraging the strengths of LGBM, employing a hierarchical structure, and exploiting the benefits of supergroup classification, we were able to significantly improve upon the α-groups' performance and achieve a more accurate classification system. These results demonstrate the potential of our HClass approach to enhance music genre classification accuracy and provide a foundation for further refinements and optimizations. The combination of advanced machine learning techniques, strategic data grouping, and a divide-and-conquer strategy has proven to be a promising framework for tackling the complexities of music genre classification. In the following section, we will discuss the implications of our findings and explore potential future directions for our work in the field of music genre classification.

C. Limitations

A limitation of our study is the use of the GTZAN dataset, which is over 20 years old and has been heavily used in music classification research. While it remains a valuable benchmark, the dataset does not reflect modern music genres and subgenres, which have evolved significantly in recent years. Future research should explore the performance of machine learning models on more contemporary and comprehensive datasets, incorporating newer genres and subgenres. This would provide more relevant insights and test the adaptability of the models to current music trends.

V. Future Work

While our hierarchical classification approach (HClass) has shown promise, there are several avenues for future research and potential improvements to enhance its performance. The most obvious avenue is increasing the dataset by exploring our findings against The Million Song Dataset [25]. This dataset would provide an opportunity to evaluate the efficiency and efficacy of the HClass on commercial-scale datasets, potentially revealing patterns in the feature selection or the model training process that wouldn't be apparent without using such a large dataset. Another avenue that might increase the robustness of the existing HClass is changing the existing architecture in order to implement a more robust supergroup classification in the 1st layer (refer to Figure 1). This proposed change would replace the single multi-class LGBM model with a one-vs-rest classification scheme. Namely, there would be a binary LGBM classifier per *β-group* genre. Each classifier would learn to distinguish its genre from all others. The final supergroup prediction would be made based on the confidence score of this one-vs-rest classifier, i.e., the 1st layer, which would then be passed down to the 2nd layer if the genre calls for that. Despite the increase in computational resources and training time, the potential benefits of incorporating a one-vs-rest classifier into the HClass might be significant. By making the 1st layer more robust, it could potentially reduce misclassifications at the supergroup level, which would cascade down to improved original genre (*α-group)* predictions in the 2nd layer. This could be particularly beneficial for genres that are harder to distinguish and separate, usually due to having significant overlap in their musical characteristics or having similar feature outputs. Of course, the actual impact of this modification would need to be empirically evaluated, but it presents a promising direction for further enhancing the HClass architecture and pushing the boundaries of our proposal.

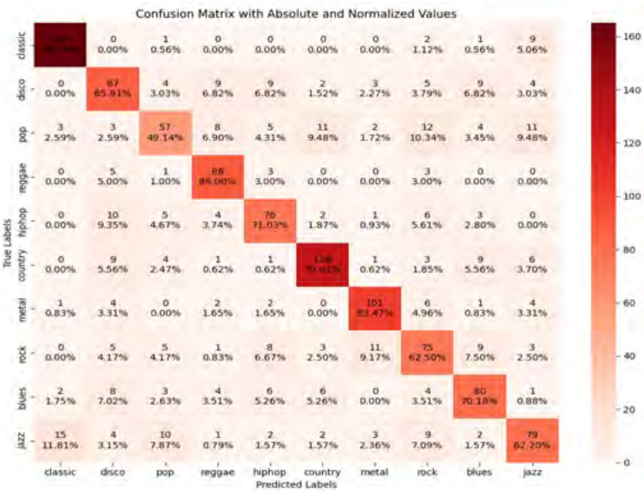

Fig. 4. Confusion matrix of Hclass (Refer to Appendix A for a clearer image).

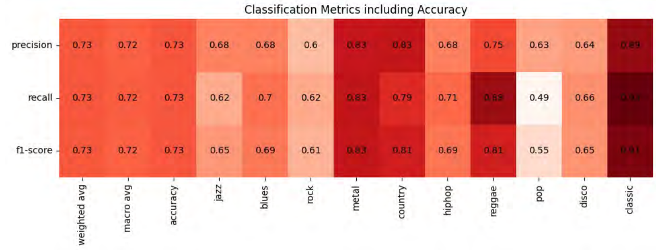

Fig. 5. Classification metrics of Hclass (Refer to Appendix B for a clearer image).

VI. Conclusion

This study explored the effectiveness of supervised learning models for Music Genre Classification (MGC) and introduced a two-step hierarchical classification (HClass) framework. The analysis of the dataset highlighted a diverse range of audio features crucial for distinguishing between genres, with features such as Mel-frequency Cepstral Coefficients, Spectral Centroid, and Chroma showing significant variability across genres, making them particularly effective for classification tasks. The addition of an audio engineering expert could enhance feature extraction by offering domain-specific insights into audio signal processing, providing a more advanced framework for genre classification.

Through experimentation, we demonstrated that our HClass approach significantly outperformed the baseline for both the α-group (10 genres) and β-group (6 supergroups), underscoring its potential. However, while we expected more substantial gains, the hierarchical classification framework only provided a marginal improvement in WA F1-score (+0.031) compared to the best-performing single-step LGBM model for the α-group. This suggests that factors such as reduced training data in the second layer and error accumulation across the hierarchical layers likely limited the expected performance gains.

Although the hierarchical approach did not outperform LGBM by a large margin, its divide-and-conquer structure remains valuable for simplifying the classification task. By first predicting broader supergroups and then classifying individual genres within those groups, the hierarchical framework enables more targeted feature learning. This approach offers a promising foundation for future research, despite the modest initial improvements, and demonstrates the potential for more sophisticated methods to be applied to modern, larger datasets like The Million Song Dataset.

In conclusion, our research presents a pragmatic approach to MGC by combining traditional supervised learning models with a hierarchical strategy. While immediate gains were marginal, the framework provides a solid foundation for further refinement and optimization. Future work should explore more robust architectures, such as a one-vs-rest scheme for supergroup classification, as well as larger, more diverse datasets to better reflect the evolving landscape of music genres and further push the boundaries of music genre classification accuracy.

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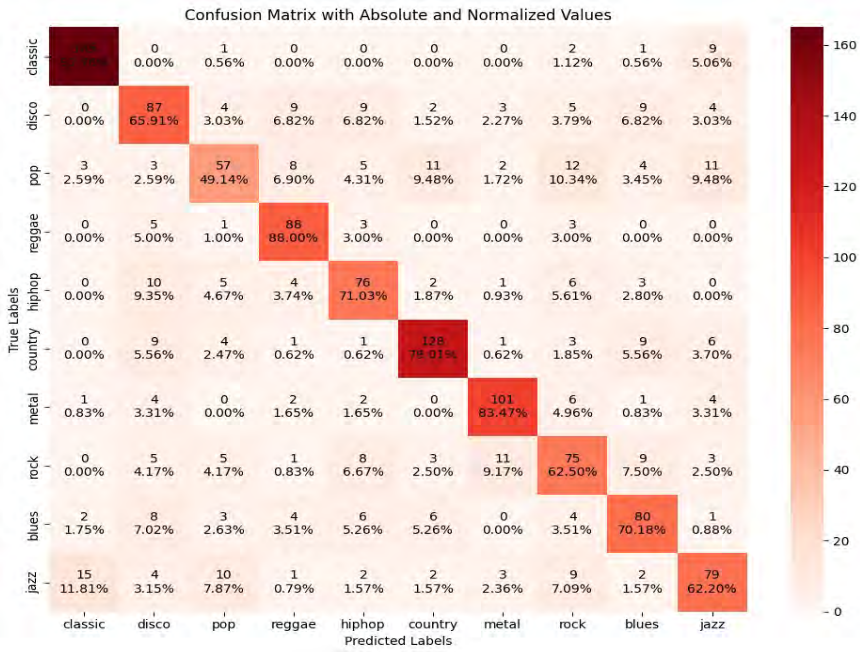
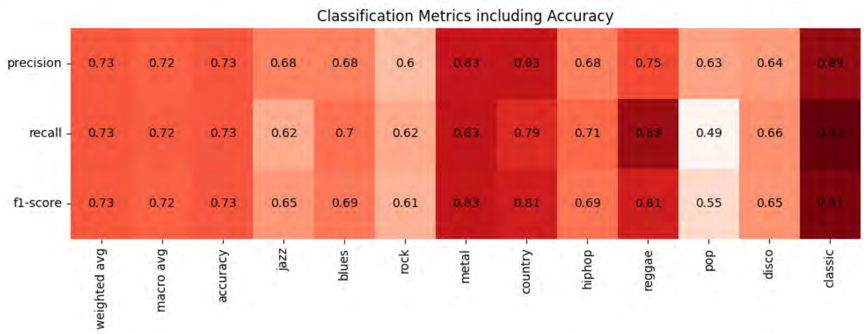
APPENDIX A



Confusion matrix of Hclass

APPENDIX B



Classification metrics of Hclass

Control and Control Applications Cont

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Complex Networked Time-delay Systems: Synchronization by Variable-Structure Control Coordinator

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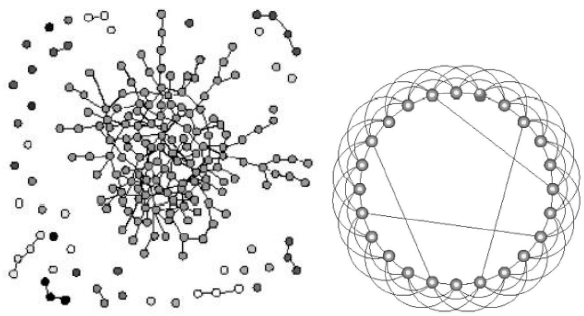
Abstract— **The synchronization problem for a class of coupling delay dynamical networks via employing variable structure control has been explored and a solution proposed. The synchronization controller guarantees the state of the dynamical network is globally asymptotically synchronized to arbitrary state. The switching surface has been designed via the left eigenvector function of the system, which assures the synchronization sliding mode possesses stability. The hitting condition and the adaptive law for estimating the unknown network parameters have been used for designing the controller so that the network state hitting the switching manifold in finite time. Two illustrative examples along with the respective simulation results are given, which employ the designed variable structure controllers. Two illustrative examples along with the respective simulation results are given, which employ the designed synchronization using variable structure control. The simulation results demonstrate the effectiveness and the performance of the proposed synchronization controllers.**

I. I. INTRODUCTION

NETWORK structures have been subject of research for considerable time in mathematical science. Furthermore, it has been observed for some time that complex dynamic networks exist in all fields of science and humanities as well as in nowadays networked individuals, societies and technical and non-technical systems. Thus the latter have been studied extensively over the past decades. It is well-known, traditional networks are mathematically represented by a graph, e.g. a pair of sets $G = \{P, \quad E\}$, where P is a set of N nodes (or vertices) $P_1, P_2, \cdots, P_N$ and E is a set of links (or arcs or edges) $L_1, L_2, \cdots, L_N$ each of which connects two elements of P. The well known chains, grids, lattices and fully connected graphs have been formulated as completely regular networks.

In recent developments of the mathematical theory of complex networks, the theory of random graphs (Figure 1-a) was first introduced by Paul Erdos and Alfred Rényi [1], who discovered the probabilistic methods were often useful to tackle problems in graph theory. In recognition to their work, now these are known as ER random graph models. The *ER random graph* models have served as idealized coupling architectures for gene networks and the spread of infectious diseases for a long time while recently for the spread of computer viruses too.



(a) (b)

Fig. 1 A random graph network (a), and a small-world network (b) [7]

In recent studies, Watts and Strogatz [2] introduced the so-called small-world networks (Figure 1-b), or so-called WS networks, in order to describe the transition from a regular network to a random network [3], [7]. Subsequently, in their studies [4-6], Barabasi and Albert have argued that the scale-free nature (Figure 2) of real-world networks is rooted in two general mechanisms: growth and preferential attachment respectively. It thus gives rise to dynamical nodes in networks and not solely static ones.

In the real world at large, many real systems such as biological, technological and social systems can be described by various models of complex networks [8], [9]. One of the interesting and rather significant phenomena in complex dynamical networks [10] is the synchronization of all dynamical nodes as well as the appearance of chaotic modes.

Hence dynamical networks may be rather complex and the respective phenomena taking place within them are rather rich and often appear and disappear unexpectedly. The present study is devoted to such networks.

In this paper, a class of general complex dynamical network models with coupling delays is explored with regard to controlled synchronization by variable structure control (VSC). Synchronization properties of these models with both matched and unmatched uncertainty conditions via VSC and using Lyapunov functional stability theory.

Fig. 2 A Scale-free network [7]

Section II presents a selected survey, a continuous-time dynamical network model with coupling time-delays and some preliminaries. In Section III, the switching surface is constructed by using the left eigenvector function method. Sections IV and V investigate the stabilities of the network synchronized states in both cases with known bound and unknown boundary on nonlinear terms. Simulation results of a benchmark example are given in Section VI. Then concluding section and references follow thereafter.

II. Mathematical Preliminaries On Complex Dynamic Network Model And The VSC-Synchronization

The synchronization in networks of coupled chaotic systems has received a great deal of attention during the last decade or so, e.g. see [10]-[18] for instance. In their work [10], Wang and Chen have established a uniform dynamical network model for such studies; also they explored its synchronization and control. Although, the model of Wang and Chen reflects the complexity from the network structure, still it is a fairly simple uniform dynamical network. A new model and chaos synchronization of general complex dynamical networks was also explored by Hu and Chen in [11], and by Lu and co-authors in [12]. Further, Wang and Chen [13] explored the synchronization problem in small-world dynamical networks, and similarly Barhona and Pecora studied the synchronization in heir small world systems in [14]. In [15], Wang and Chen investigated the synchronization in scale-free networks with regard to robustness and fragility. Subsequently, X. Li and Chen [16] have explored both synchronization and de-synchronization of complex dynamical networks from an engineering point of view.

More recently, in works [17]-[21], the complex dynamical networks with time-delays have received particular attention more attentions because its presence is frequently a source of instability. For, time-delays commonly, or even unavoidably, exist in various network-like systems due to some inherent mechanism and/or the finite propagation speed of information carrying signals. Z. Li and Chen proposed in [17] a linear state feedback controller design to realize the synchronization for the networks with coupling delays. Similarly, C. Li and Chen proposed a solution in the case with coupling delays in work [18]. Further, P. Li and co-authors explored in [19] one way of global synchronization in delayed networks, and Z. Li and co-authors in [20] solved the same with regard to desired orbit. It should be noted controlled synchronization in complex dynamical networks with either nonlinear delays or with coupling delays in [18]-[21] was studied via the methodology of Lyapunov stability analysis. In parallel, also the design of robust decentralized control for large-scale systems with time-varying or uncertain delays has been revisited via several approaches and feasible designs derived in [22]-[25]. These studies too were carried out via Lyapunov stability analysis and synthesis, and the approach of variable structure control (VSC) is to be noted for their efficiency in dealing with all sorts of time-delay phenomena in dynamical systems, nonlinearities and even uncertainties.

In this paper, we consider a complex dynamical network consisting of N identical nodes (n dimensional dynamical systems) with time varying delay coupling:

$$\dot{x}_i = Ax_i + f(x_i,t) + \sum_{j=1}^{N} A_{ij} x_j (t - \tau_{ij}(t)) + B_i u_i, \quad i = 1, 2, \cdots, N \tag{1}$$

Here symbols denote: $x_i = (x_{i1}, x_{i2}, \cdots, x_{in})^T \in R^n$ is the state vector of the dynamic system at the i-th node, $f(x_i,t): R^n \times R \to R^n$ is a smooth nonlinear vector function, $\tau_{ij}(t)$ is a bounded time varying delay and differentiable satisfying $0 \le \tau_{ij}(t) \le \tau_{ij} < \infty$, where τ_{ij} is positive scalar, $A \in R^{n \times n}$, $B_i \in R^{n \times m}$ are constant matrix with appropriate dimensions, $u_i \in R^m$ are the control input, and term $\sum_{j=1}^{N} A_{ij} x_j (t - \tau_{ij}(t))$ represent uncertain time-delay interconnections of the network graph.

When the network achieves synchronization, namely, the state $x_1 = x_2 = \cdots = x_N$, as $t \to \infty$, the coupling control terms should vanish: $\sum_{j=1}^{N} A_{ij} x_j (t - \tau_{ij}(t)) + B_i u_i = 0$. This ensures that any solution $x_i(t)$ of a single isolate node is also a solution of the synchronized coupled network.

Let $s(t)$ be a solution of the isolate node of the network, which is assumed to exist and is unique, satisfying:

$$\dot{s}(t) = As(t) + f(t, s(t)) \quad (2)$$

Here $s(t) = s(t; t_0, s_0)$ can be an equilibrium point, a nontrivial periodic orbit, or even a chaotic orbit. The objective of control here is to find some smooth controllers $u_i \in R^m$ such that, solution of systems (1) asymptotically synchronize with the solution of (2) in the sense that

$$\lim_{t\to\infty} \| x_i(t) - s(t) \| = 0 \, , i = 1,2,\cdots,N \quad (3)$$

Let $e_i = x_i(t) - s$, then subtracting (2) from (1) gives the error dynamical system

$$\dot{e}_i = Ae_i + \widetilde{f}(x_i, s) + \sum_{j=1}^{N} A_{ij} x_j(t - \tau_{ij}(t)) + B_i u_i \quad (4)$$

where

$$\widetilde{f}(x_i, s) = f(x_i, t) - f(s, t) \, .$$

For deriving the proofs given in sequel, certain convenient assumptions are given next.

Assumption 1: The matrix pair $(A, \quad B_i)$ is controllable.

Assumption 2: Each input matrix B_i is of full rank.

Assumption 3: The nonlinear function f satisfying

$$\| f(x_i, t) - f(x_j, t) \| \le \mu_i \| x_i(t) - x_j(t) \| \quad (5)$$

where $\mu_i > 0$ are constants, $i, j = 1,2,\cdots,N$.

Assumption 4: Suppose the interconnection matrix satisfy matching condition as follow:

$$A_{ij} = B_i H_{ij} \quad (6)$$

Assumption 5: The time delay terms in system (4) satisfy

$$\| x_j(t - \tau_{ij}(t)) \| \le x_{j\max}(t) \quad (7)$$

where

$$x_{j\max}(t) = \max \| x_j(t) \| \, .$$

is the maximum possible value of $x_i(t)$ over a certain time period.

Therefore the equation (4) can be rewritten as follows:

$$\dot{e}_i = Ae_i + \widetilde{f}(x_i, s) + \sum_{j=1}^{N} B_i H_{ij} x_j(t - \tau_{ij}(t)) + B_i u_i \quad (8)$$

III. Application Of Variable Structure Control And Switching Surface Design

The composite sliding surface of system (8) is defined by letting the composite sliding vector $\sigma(e)$ in the state space be zero. This is to say that

$$\sigma(e) = \left[\sigma_1^T(e_1), \quad \sigma_2^T(e_2), \quad \cdots \quad \sigma_N^T(e_N) \right] \quad (9)$$

where

$$\sigma_i(e_i) = C_i e_i = 0 \, , i = 1,\cdots,N \quad (10)$$

are called the local sliding surface and $e = \left[e_1^T, \quad \cdots, \quad e_N^T \right] \in R^N$, while C_i are $m \times n$ constant matrices to be determined in due course.

In order to construct the controller, we introduce the following two relevant lemmas.

Lemma 1[24] Assume β is a scalar and $b_1, b_2, \cdots, b_N$ be arbitrary vectors, then

$$2a^T(\sum_{i=1}^{N} b) \le \beta a^T a + \frac{1}{\beta} \sum_{i=1}^{N} b_i^T b_i \quad (11)$$

where $\beta > 0$ is a positive constant.

Lemma 2 [24] Suppose matrix $D = \begin{pmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{pmatrix}$ is invertible and $\| D_{22} \| \ne 0$, then

$$D^{-1} = \begin{pmatrix} D_{11,2}^{-1} & -D_{11,2} A_{12} A_{22}^{-1} \\ -D_{22}^{-1} D_{21} D_{11,2}^{-1} & D_{22}^{-1} + D_{22}^{-1} D_{21} D_{11,2}^{-1} D_{12} D_{22}^{-1} \end{pmatrix} \quad (12)$$

where $D_{11,2} = D_{11} - D_{12} D_{22}^{-1} D_{21}$ is the inverse.

Further, we select the isolate subsystem as follows

$$\dot{e}_i = Ae_i + B_i u_i \quad (13)$$

Because $(A, \quad B_i)$ is controllable, there exists matrix $K_i \in R^{m\times n}$ that can make the matrix $\widetilde{A}_i = A + B_i K_i$ be stable. And B_i is full rank matrix, we can assume $B_i = \begin{pmatrix} 0 \\ \widetilde{B}_i \end{pmatrix}$, $\widetilde{B}_i \in R^{m\times m}$. When the controller $u_i = K_i e_i + v_i$ is substituted in to (13), the equation can be transformed to

$$\dot{e}_{i1} = \widetilde{A}_{i11} e_{i1} + \widetilde{A}_{i12} e_{i2} \quad (14)$$

$$\dot{e}_{i2} = \widetilde{A}_{i21} e_{i1} + \widetilde{A}_{i22} e_{i2} + \widetilde{B}_i v_i \quad (15)$$

Assume the stability eigenvalues of $\widetilde{A}_i$ are $\lambda_{i1}, \cdots, \lambda_{im}, \mu_{i1}, \cdots, \mu_{in-m}$. Then let

$$
\Lambda_{i1} = \begin{pmatrix} \mu_{i1} & & \\ & \ddots & \\ & & \mu_{in-m} \end{pmatrix}, \ \Lambda_{i2} = \begin{pmatrix} \lambda_{i1} & & \\ & \ddots & \\ & & \lambda_{im} \end{pmatrix} \tag{16}
$$

The corresponding eigenvectors constitute the eigenvector matrix as $\begin{pmatrix} G_{i1} & G_{i2} \\ V_{i1} & V_{i2} \end{pmatrix}$. The eigenvector matrix is inverse through the pole placement, so that the following equation holds

$$
\begin{pmatrix} G_{i1} & G_{i2} \\ V_{i1} & V_{i2} \end{pmatrix} \begin{pmatrix} \widetilde{A}_{i11} & \widetilde{A}_{i12} \\ \widetilde{A}_{i21} & \widetilde{A}_{i22} \end{pmatrix} = \begin{pmatrix} \Lambda_{i1} & 0 \\ 0 & \Lambda_{i2} \end{pmatrix} \begin{pmatrix} G_{i1} & G_{i2} \\ V_{i1} & V_{i2} \end{pmatrix} \tag{17}
$$

$$
\begin{pmatrix} \widetilde{A}_{i11} & \widetilde{A}_{i12} \\ \widetilde{A}_{i21} & \widetilde{A}_{i22} \end{pmatrix} \begin{pmatrix} G_{i1} & G_{i2} \\ V_{i1} & V_{i2} \end{pmatrix}^{-1} = \begin{pmatrix} G_{i1} & G_{i2} \\ V_{i1} & V_{i2} \end{pmatrix}^{-1} \begin{pmatrix} \Lambda_{i1} & 0 \\ 0 & \Lambda_{i2} \end{pmatrix} \tag{18}
$$

$$
\begin{pmatrix} G_{i1} & G_{i2} \\ V_{i1} & V_{i2} \end{pmatrix}^{-1} = \begin{pmatrix} \xi_{i1} & \xi_{i2} \\ \eta_{i1} & \eta_{i2} \end{pmatrix} \tag{19}
$$

$$
\begin{pmatrix} \widetilde{A}_{i11} & \widetilde{A}_{i12} \\ \widetilde{A}_{i21} & \widetilde{A}_{i22} \end{pmatrix} \begin{pmatrix} \xi_{i1} & \xi_{i2} \\ \eta_{i1} & \eta_{i2} \end{pmatrix} = \begin{pmatrix} \xi_{i1} & \xi_{i2} \\ \eta_{i1} & \eta_{i2} \end{pmatrix} \begin{pmatrix} \Lambda_{i1} & 0 \\ 0 & \Lambda_{i2} \end{pmatrix} \tag{20}
$$

Therefore

$$
\widetilde{A}_{i11}\xi_{i1} + \widetilde{A}_{i12}\eta_{i1} = \xi_{i1}\Lambda_{i1} \tag{21}
$$

From the above, we know that $\begin{pmatrix} \xi_{i1} & \xi_{i2} \\ \eta_{i1} & \eta_{i2} \end{pmatrix}$ is the right eigenvector matrix of $\begin{pmatrix} \widetilde{A}_{i11} & \widetilde{A}_{i12} \\ \widetilde{A}_{i21} & \widetilde{A}_{i22} \end{pmatrix}$. If we select

$$
C_i = \begin{bmatrix} V_{i1} & V_{i2} \end{bmatrix} \tag{22}
$$

when the system trajectory hit the sliding mode, i.e. $\sigma_i = C_i e_i = V_{i1}e_{i1} + V_{i2}e_{i2}$, then

$$
e_{i2} = -V_{i2}^{-1}V_{i1}e_{i1} \tag{23}
$$

Substituting (23) into (14), we can get the sliding mode equation

$$
\dot{e}_{i1} = (\widetilde{A}_{i11} - \widetilde{A}_{i12}V_{i2}^{-1}V_{i1})e_{i1} \tag{24}
$$

Because $V_{i2} \in R^{m\times m}$ and $(G_{i1} - G_{i2}V_{i2}^{-1}V_{i1})$ are inverse, and due to Lemma 2, we obtain

$$
\eta_{i1} = -V_{i2}^{-1}V_{i1}\xi_{i1} \tag{25}
$$

Upon substitution of (25) into (21), we obtain

$$
(\widetilde{A}_{i11} - \widetilde{A}_{i12}V_{i2}^{-1}V_{i1})\xi_{i1} = \xi_{i1}\Lambda_{i1} \tag{26}
$$

From the above we can know the eigenvalues of the sliding mode equation of system (13) represent the desired $n-m$ stable eigenvalues. It is obvious that the sliding mode equation (14) is stable. From the above analysis, C_i is the left eigenvector of $\widetilde{A}_i$ with desired m stable eigenvalues, then

$$
C_i\widetilde{A}_i = \Lambda_{i2}C_i \tag{27}
$$

For the error system (4) of complex network, because the coupling term is satisfying matching condition, then the sliding mode equation of system (4) is still satisfying equation (24), which has desired eigenvalues. If the nonlinear and the coupling terms do not satisfy the matching condition, the system (4) can be written as follows:

$$
\dot{e}_{i1} = \widetilde{A}_{i11}e_{i1} + \widetilde{A}_{i12}e_{i2} + \widetilde{f}_{i1}(x_i, s) \tag{28}
$$

$$
\begin{aligned} \dot{e}_{i2} &= \widetilde{A}_{i21}e_{i1} + \widetilde{A}_{i22}e_{i2} + \widetilde{f}_{i2}(x_i, s) \\ &+ \sum_{j=1}^{N} \widetilde{B}_i\widetilde{H}_{ij}x_j(t - \tau_{ij}(t)) + \widetilde{B}_i v_i \end{aligned} \tag{29}
$$

When $\sigma_i = 0$, then $e_{i2} = -V_{i2}^{-1}V_{i1}e_{i1}$, so the above sliding mode equation of system (28) is

$$
\dot{e}_{i1} = \overline{A}_i e_{i1} + \widetilde{f}_{i1}(x_i, s) \tag{30}
$$

where $\overline{A}_i = \widetilde{A}_{i11} - \widetilde{A}_{i12}V_{i2}^{-1}V_{i1}$, it is obvious the matrix $\overline{A}_i$ is stable.

The synchronization condition for the complex network with unmatched uncertainty is fulfilled according to the below summarized Theorem 1.

Theorem 1 If the nonlinear term $\widetilde{f}(x_i, s)$ is unmatched, then the decentralized sliding mode of the interconnected system (30) is asymptotically stable, if and only if the following condition

$$
k_1\mu_i < -\beta_i(\lambda_i + \beta_i) \tag{31}
$$

holds true, where $k_1 > 0$ is constants, and $\lambda_i = \max\{\lambda_{i1}, \ \cdots \ \lambda_{im}\} < 0$.

Proof: Let V be a candidate Lyapunov function for the dynamic system (30),

$$
\dot{V} = \sum_{i=1}^{N} e_{i1}^T e_{i1} \tag{32}
$$

Taking the derivative of V along the trajectory of system (30), we have

$$\dot{V} = \sum_{i=1}^{N} 2e_{i1}^T \left[\overline{A} e_{i1} + \widetilde{f}_{i1}(x_i, s) \right] \tag{33}$$

From Assumption 3, there exist positive constant k_1 that makes $\left\| \widetilde{f}_{i1}(x_i, s) \right\| \le k_1 \mu_i \left\| e_{i1} \right\|$. Thus, from Lemma 1

$$\begin{aligned} \dot{V} &\le \lambda_i \left\| e_{i1} \right\|^2 + \beta_i \left\| e_{i1} \right\|^2 + \frac{1}{\beta_i} k_1 \mu_i \left\| e_{i1} \right\|^2 \\ &= \left(\lambda_i + \beta_i + \frac{1}{\beta_i} k_1 \mu_i \right) \left\| e_{i1} \right\|^2 \end{aligned} \tag{34}$$

And then because $\lambda_i < 0$, if $\beta_i + \frac{1}{\beta_i} k_1 \mu_i < -\lambda_i$ it follows $\dot{V} < 0$ at once.

IV. Designing Synchronization Condition: Case With Known Bounds On Nonlinear Terms

Although we have a set of stable sliding surfaces, unless the initial states and all system dynamics are always ensured to stay on the surface for all time, a set of decentralized sliding controllers is required, such that the global robust stability of the surface is assured. Traditionally, the hitting condition for small-scale system is

$$\sigma(t)^T \dot{\sigma}(t) < 0 \tag{35}$$

where $\sigma(t) = 0$ is the sliding surface of some small-scale systems. Since the existence of interconnections and the lack of global information, equation (35) is not easily satisfied for the interconnected system. Hence, we require a global hitting condition of the sliding surface

$$\sum_{i=1}^{N} \frac{\sigma_i^T(e_i) \dot{\sigma}_i(e_i)}{\left\| \sigma_i(e_i) \right\|} < 0 \tag{36}$$

The condition is readily derived from the Lyapunov theory, if $V = \sum_{i=1}^{N} \left\| \sigma_i \right\|$.

Theorem 2: The motion of the system (4) asymptotically converges to the composite sliding surface $\sigma(e) = 0$, if and only if it is satisfied the following condition

$$u_i = K_i e_i - (C_i B_i)^{-1} R_i \frac{\sigma_i}{\left\| \sigma_i \right\|} \left\| e_i \right\|, \tag{37 a}$$

where $\varepsilon > 0$ is a constant and

$$R_i = \mu_i \left\| C_i \right\| + \sum_{j=1}^{N} \left\| C_i B_i \right\| \left\| H_{ij} \right\| \left\| x_{j\max}(t) \right\| + \varepsilon \tag{37 b}$$

<u>Proof</u>: From (4) and (10), the sliding dynamics can be written as

$$\begin{aligned} \dot{\sigma}_i &= C_i \dot{e}_i \\ &= C_i A e_i + C_i \widetilde{f}(x_i, s) + C_i \sum_{j=1}^{N} B_i H_{ij} x_j (t - \tau) + C_i B_i u_i \\ &= \Lambda_{i2} \sigma_i - C_i B_i K_i e_i + C_i B_i u_i \\ &\quad + C_i \widetilde{f}(x_i, s) + C_i \sum_{j=1}^{N} B_i H_{ij} x_j (t - \tau) \end{aligned} \tag{38}$$

Upon substitution of (37) into (38) it follows:

$$\dot{\sigma} = \Lambda_{i2} \sigma_i - R_i \frac{\sigma_i}{\left\| \sigma_i \right\|} \left\| e_i \right\| + C_i \widetilde{f}(x_i, s) + C_i \sum_{j=1}^{N} B_i H_{ij} x_j (t - \tau). \tag{39}$$

Let construct Lyapunov function as

$$V = \sum_{i=1}^{N} d_i \left\| \sigma_i \right\| \tag{40}$$

and thus obtain the time-derivative as

$$\dot{V} = \sum_{i=1}^{N} d_i \frac{\sigma_i^T \dot{\sigma}_i}{\left\| \sigma_i \right\|}. \tag{41}$$

Substituting (37) and (39) into (41) yields

$$\dot{V} = \sum_{i=1}^{N} d_i \frac{\sigma_i^T}{\left\| \sigma_i \right\|} \left[V_\Sigma \right], \tag{42-a}$$

$$\left[\Lambda_{i2} \sigma_i + C_i \widetilde{f}(x_i, s) + \sum_{j=1}^{N} C_i B_i H_{ij} x_j (t - \tau_{ij}) - R_i \frac{\sigma_i}{\left\| \sigma_i \right\|} \left\| e_i \right\| \right] = \left[V_\Sigma \right] \tag{42-b}$$

Because $\lambda_i = \max\{\lambda_{i1}, \cdots, \lambda_{im}\} < 0$ and Assumption 2, it follows:

$$\begin{aligned} \dot{V} &\le \sum_{i=1}^{N} \left[\begin{aligned} & d_i \lambda_i \left\| \sigma_i \right\| + d_i \left\| C_i \right\| \mu_i \left\| e_i \right\| \\ & + d_i \sum_{j=1}^{N} \left\| C_i B_i \right\| \left\| H_{ij} \right\| \left\| x_j (t - \tau_{ij}) \right\| - d_i R_i \left\| e_i \right\| \end{aligned} \right] \\ &= \sum_{i=1}^{N} \left[d_i \lambda_i \left\| \sigma_i \right\| \right] \\ &- \sum_{i=1}^{N} d_i \left[- \left\| C_i \right\| \mu_i \left\| e_i \right\| - \sum_{j=1}^{N} \left\| C_i B_i \right\| \left\| H_{ij} \right\| \left\| x_j (t - \tau_{ij}) \right\| + R_i \left\| e \right\| \right] \\ &= \sum_{i=1}^{N} d_i \lambda_i \left\| \sigma_i \right\| + \sum_{i=1}^{N} \sum_{j=1}^{N} d_i \left\| C_i B_i \right\| \left\| H_{ij} \right\| \left\| x_j (t - \tau_{ij}) \right\| \\ &- \sum_{i=1}^{N} \sum_{j=1}^{N} d_i \left\| C_i B_i \right\| \left\| H_{ij} \right\| \left\| x_{j\max}(t) \right\| - \varepsilon < 0. \end{aligned} \tag{43}$$

Therefore with the controller according to Theorem 2, it follows that motion dynamics of the error system (4) asymptotically converges to the composite sliding surface.

V. Designing Synchronization Condition: Case With Unknown Bounds On Nonlinear Terms

In practice, there exist $\left\| \tilde{f}(x_i, s) \right\| \le \mu_i \|e_i\|$, here μ_i is unknown parameters. In this section, we will design robust adaptive controller with unknown parameters.

In order to derive the proof, conveniently, first we present another two assumptions.

Assumption 6: $rank(\tilde{f}, \quad B_i) = rank(B_i)$

Assumption 7: Let $B_i = \begin{pmatrix} 0 \\ B_{2i} \end{pmatrix}$, where $B_{2i} \in R^{m \times m}$ is an nonsingular matrix.

When the transformation $u_i = K_i e_i + v_i$ is applied, the sliding mode equations become

$$\dot{e}_{i1} = (\tilde{A}_{i11} - \tilde{A}_{i12} V_{i2}^{-1} V_{i1}) e_{i1} \tag{44}$$

It is easy to prove the asymptotic stability of the sliding mode trajectory by the constructing switching function. Therefore the main task here is now to design robust controller that guarantees the system trajectory shall reach the sliding surface from arbitrary initial state.

Theorem 3 Let Assumption 4 and Assumption 5 hold true. Then the following robust adaptive controller

$$u_i = K_i e_i - \\ -(C_i B_i)^{-1} \begin{bmatrix} C_i \hat{\mu}_i \|e_i\| \\ + \sum_{j=1}^{N} \|C_i B_i\| \|H_{ij}\| \|x_{j\max}\| + \varepsilon_i \operatorname{sgn} \sigma_i \end{bmatrix} \tag{45-a}$$

$$\dot{\hat{\mu}}_i = \|C_i\| \|e_i\|, \ \tilde{\mu}_i = \hat{\mu}_i - \mu_i, \tag{45-b}$$

where $\hat{\mu}_i$ is the estimate of the unknown parameter and μ_i, $\varepsilon_i > 0$ are constants, will globally uniformly, asymptotically stabilize the system (4).

Proof: Consider the Lyapunov function as follows

$$V = \sum_{i=1}^{N} \|\sigma_i\| + \frac{1}{2} \sum_{i=1}^{N} \tilde{\mu}_i^2 \tag{46}$$

The time derivative of (46) along state trajectories is given as follows:

$$\dot{V} = \sum_{i=1}^{N} \frac{\sigma_i^T(e_i) \dot{\sigma}_i(e_i)}{\|\sigma_i\|} + \sum_{i=1}^{N} \tilde{\mu}_i \dot{\hat{\mu}}_i$$

$$= \sum_{i=1}^{N} \frac{\sigma_i^T}{\|\sigma_i\|} \begin{vmatrix} \Lambda_{i2} \sigma_i - C_i B_i K_i e_i \\ + C_i B_i u_i + C_i \tilde{f}(x_i, s) \\ + C_i \sum_{j=1}^{N} B_i H_{ij} x_j (t - \tau_{ij}) \end{vmatrix} + \sum_{i=1}^{N} \tilde{\mu}_i \dot{\hat{\mu}}_i$$

$$\le \sum_{i=1}^{N} \begin{bmatrix} \lambda_i \|\sigma_i\| - C_i B_i K_i e_i + C_i \mu_i \|e_i\| \\ + \sum_{j=1}^{N} \|C_i B_i\| \|H_{ij}\| \|x_j(t - \tau_{ij})\| + C_i B_i u_i \end{bmatrix} \tag{47}$$

$$+ \sum_{i=1}^{N} \tilde{\mu}_i \dot{\hat{\mu}}_i \le \sum_{i=1}^{N} \lambda_i \|\sigma_i\| - \varepsilon_i .$$

Because of $\lambda_i < 0$, $\varepsilon_i > 0$, apparently (47) is negative definite. Hence the system (4) can be stabilized by means of the controller (45-a, b) designed according to Theorem 3.

VI. Illustrative Example and Simulation Results

In the explored benchmark example, the plant processes are known to have bounded nonlinear terms. It is amazing to notice that almost identical simulation results are obtained in here as the previous ones in [26-27].

The considered network is assumed to have chaotic Chua circuits (Figure 3) into network's nodes. A Chua circuit is described by piecewise-linear-nonlinear dynamic system

$$\dot{x} = p(-x + y - f(x)), \ \dot{y} = x - y + z, \ \dot{z} = -qy \tag{48}$$

where

$$f(x) = m_0 x + \frac{1}{2}(m_1 - m_0)(|x+1| - |x-1|). \tag{49}$$

Parameter constants are assumed as: $m_0 < 0$ and $m_1 < 0$, $p = 10$, $q = 14.87$, $m_0 = -1.27, m_1 = -0.68$.

Let $x_1 = x, x_2 = y, x_3 = z$. Then the chaotic Chua circuit can also be represented as follows:

$$\dot{x}_1 = p(-x_1 + x_2 - f(x_1)), \dot{x}_2 = x_1 - x_2 + x_3, \ \dot{x}_3 = qx_2 .$$

The corresponding network with coupling time-delay is represented by means of the following equations [18], [23], [26]:

$$\begin{pmatrix} \dot{x}_{i1} \\ \dot{x}_{i2} \\ \dot{x}_{i3} \end{pmatrix} = \begin{pmatrix} -p & p & 0 \\ 1 & -1 & 1 \\ 0 & -q & 0 \end{pmatrix} \begin{pmatrix} x_{i1} \\ x_{i2} \\ x_{i3} \end{pmatrix} + \begin{pmatrix} -pf(x_{i1}) \\ 0 \\ 0 \end{pmatrix}$$

$$+\begin{pmatrix} \sum_{k=i}^{i+2} x_{k,1}(t-\tau_{ij}) \\ 0 \\ \sum_{k=i}^{i+2} x_{k,3}(t-\tau_{ij}) \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} u_i$$

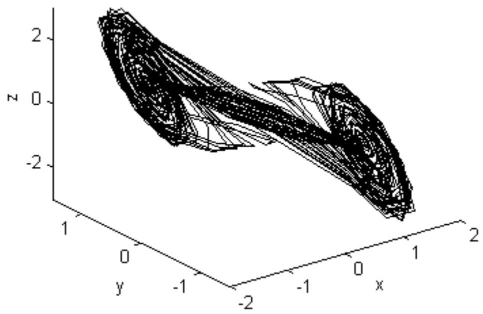


Fig. 3 Dynamic network node systems: Chaotic Chua circuits and phase-state space portrait of its dynamics

It was assumed that all time delays $\tau_{ij} < 0.02$ in order to carry out the simulation; results are depicted in Figures 4-5.

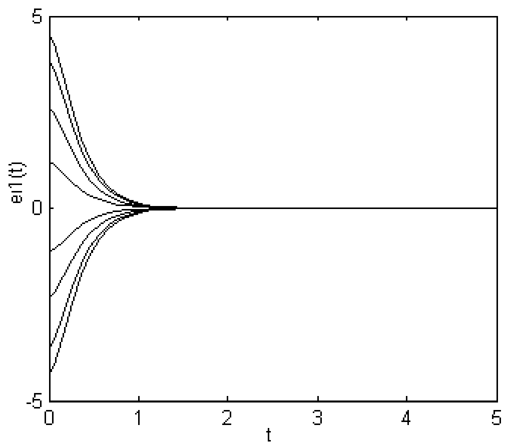


Fig. 4 Network synchronization errors e_{i1} and e_{i2} with the chaotic Chua circuits at nodes of the network.

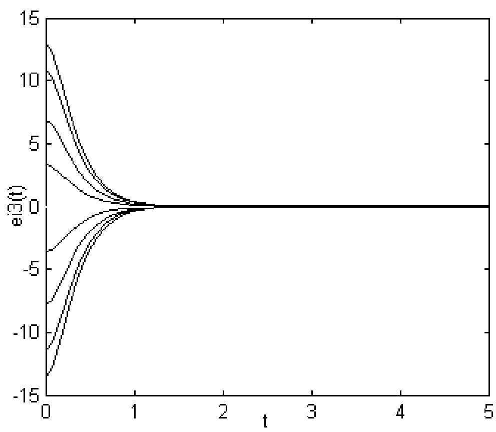


Fig. 3 Network synchronization errors e_{i3} with the chaotic Chua circuits at nodes of the network.

VII. Conclusion

The synchronization problem in coupled complex dynamic delay network has been explored. Systems with both known and unknown bounds on nonlinear terms have been successfully considered. Stability solutions to the synchronization are proposed that employ variable structure control theory along with constructive design of the sliding surfaces and switching. The switching surface has been designed via the left eigenvector function of the system, which guarantees the stability of synchronization sliding mode possesses stability. The hitting condition and the adaptive law for estimating the unknown network parameter have been used in designing the controller, which enforces the network state to hitting the switching manifold in finite time. The benchmark example demonstrated network synchronization efficiency and transient performance. Future research is envisaged to explore the same problem when interconnecting edges among nodes are nonlinear and possibly time-varying with uncertainty as in [26-27].

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Modelling, Simulation and Development of a Test Rig for Comparative Analysis of Temperature Controllers

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Dedicated to Prof. Mile J. Stankovski on his Anniversary

***Abstract*—Heating systems used in living and industrial buildings should ensure energy efficiency as well as comfort needs. Achieving that requires accurate and reliable control of temperature, making the efficient testing of temperature controllers crucial for their optimal performance. This paper covers a mathematical modelling of a thermal process, hardware design and development of a test rig and performance evaluation of two controllers: on-off with hysteresis and time proportional(TP) PID controller. The comparative analysis is done both in Simulink simulation and with experimental testing on the test rig. The controllers were compared using several different metrics such as: standard deviation, integral of absolute error, settling time and energy consumption of the error and control signal. The results highlight the trade-offs between the control accuracy, response time and energy efficiency. Final results show that one of the controllers reaches the desired set-point faster but at a cost of lesser accuracy, while the other controller improves the accuracy at a cost of higher response time.**

***Index Terms*—heating, efficiency, modelling, simulation, test rig, on-off, TP-PID**

I. Introduction

Heating systems used in living and industrial buildings should provide energy efficiency as well as comfort needs. Namely, heating, ventilation, and air conditioning (HVAC) systems are the primary energy consuming sector in a building, using almost 50% of the total energy consumption [1]. Therefore their appropriate selection, good design and operation (which depends on the control mechanisms and optimization parameters) could provide energy saving by 25% while maintaining satisfactory indoor comfort [2] [3].

The general block diagram of the temperature control system is shown in Fig.1. The temperature controller, fed with the error between the set-point and current temperature (measured by the sensor), sends control signal that adjusts the power of the heater and by that accommodates the temperature of the room.

There are many control strategies that can be implemented for temperature regulation of heating processes including on-off, PID, fuzzy logic [4], model predictive, internal model [5], machine learning models [6] etc. In this paper, we implement on-off control with hysteresis and time proportional PID control.

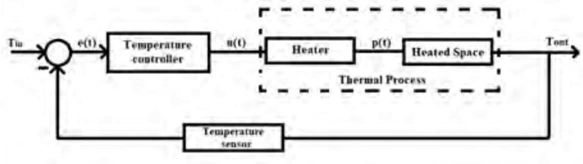


Fig. 1: Block diagram for temperature control system

The bang-bang (on-off) control is the simplest to implement control. The heater is switched either fully on or off based on whether the current temperature is above or below the set-point temperature. The on-off control with hysteresis adds a deadband (upper and lower limit) around the set-point, where the control signal remains unchanged. The hysteresis is the adjustable parameter for this type of control. Besides the simplicity, cost-effectivness and rapid response, the frequent switching and oscillations around the set-point as well as the constant full-power cycle could result in instability, wear and tear of the mechanical components of the system and energy inefficiency. So this type of control could be used only in processes that could handle oscillations and don't require precise regulation i.e. slow processes [7].

Time-proportional control (TPC) is a form of pulse-width modulation control that regulates the temperature by modulating the power delivered to the heating element. Based on the temperature error, it adjusts the on-time (duty cycle) of the heater within a fixed cycle time, and by that vary the average power output. The time proportional PID control combines the precision of the PID control with the modulation efficiency of the TP control. The PID controller calculates the power ratio in the fixed cycle time which is then converted into duty cycle. The adjustable parameter for this type of control is the cycle time and the PID parameters. Because of the fixed cycle time this type of control is suitable for slow processes [7].

There are many comparative analysis done on different control techniques for temperature regulation. Nevertheless, to the best of our knowledge, there are none done on On-Off and TP-PID control, that encompass, both, modeling and simulation and test rig experimental comparison. This was the basic motivation for writing this paper.

For comparison of the performance of the controllers, four metrics will be used:

i) settling time (ST): required time for the output to stabilize at the desired set-point and remain within a given error band of 3%. Lower ST indicates quicker adaptation to temperature changes. [8]

ii) standard deviation (SD): measure of amount of variation of the temperatures around the set-point. Lower SD means that the output makes less fluctuations around the set-point. [9]

iii) sum of absolute error (SAE): measure for the total accumulated absolute error over period of time. Lower SAE indicates higher control accuracy. [10]

iv) energy consumption (EC): total amount of energy used by the controller. Lower energy consumption means lower operational costs. [11]

This paper is structured as follows: i) the mathematical modelling of a thermal process, ii) developing a test rig and iii) testing and comparison of two temperature controllers (on-off with hysteresis and time proportional PID control). The performance comparison is made both in simulation and with the test rig by calculating the previously mentioned metrics.

II. Mathematical Model of the Thermal Process

Thermal circuits are used to estimate the heat flow through a thermal system. In thermal systems, the heat transfer, temperature and thermal resistance are analogous to the current, voltage and electrical resistance, respectively, of an equivalent electrical circuit. The stored energy in the air or other material is represented with capacitors. [12]

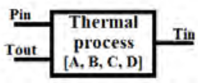


Fig. 2: Thermal process

The space state model for our thermal process (shown on Fig. 2) will be developed using using an electrical circuit analogy. The inputs in the system will be the outside temperature T_{out} and the heater's power P_{in} and the output will be the current temperature inside the box T_{room}. The thermal circuit model (shown on Fig. 3) is of second order with two thermal capacitors.

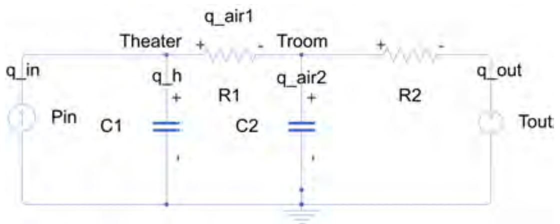


Fig. 3: Thermal circuit model

R_1 represents the thermal convective resistance of air:

$$R_1 = \frac{1}{A_{\text{h}} \cdot h_{\text{air}}} \tag{1}$$

where h_{air} is the coefficient of natural convection of air and A_{h} is the contact area of the heater with air.

R_2 is the thermal conductive resistance of the wall and insulation:

$$R_2 = \frac{l_{wall}}{A_{\text{wall}} \cdot K_{\text{t}}} + \frac{l_{ins}}{A_{\text{ins}} \cdot K_{\text{ti}}} \tag{2}$$

where A_{wall} and A_{ins} represent the area of the wall and insulation, K_{t} and K_{ti} correspond to the conduction coefficient of the wall's and insulation material and l_{wall} and l_{ins} are the wall's and insulation's depth, respectively.

C_1 and C_2 are the thermal capacitance of the heater and the air along with insulation:

$$C_1 = m_{\text{h}} \cdot c_{\text{h}} = \rho_{\text{h}} \cdot V_{\text{h}} \cdot c_{\text{h}} \tag{3}$$

$$C_2 = m_{\text{air}} \cdot c_{\text{air}} + m_{\text{ins}} \cdot c_{\text{ins}} = \rho_{\text{air}} \cdot V_{\text{room}} \cdot c_{\text{air}} + \rho_{\text{ins}} \cdot V_{\text{ins}} \cdot c_{\text{ins}} \tag{4}$$

where ρ_{h}, ρ_{air}, ρ_{ins}, c_{h}, c_{air} and c_{ins} are densities and specific heat capacities of of heater's ceramics, air and insulation, V_{h}, V_{room} and V_{ins} are the volume of the heater and the room, respectively. T_{out} is the outside temperature, T_{room} is box's temperature.

Using the first Kirchhoff's, Ohms Law for thermal circuits and the heat flow equation, we obtain the following equations:

$$q_{in} = q_h + q_{air1} \tag{5}$$

$$q_{air1} = q_{out} + q_{air2} \tag{6}$$

$$q_{\text{in}} = P_{\text{in}} \tag{7}$$

$$q_{\text{out}} = \frac{T_{\text{room}} - T_{\text{out}}}{R_2} \tag{8}$$

$$q_{\text{h}} = C_1 \frac{dT_{\text{heater}}}{dt} \tag{9}$$

$$q_{\text{air1}} = \frac{T_{\text{heater}} - T_{\text{room}}}{R_1} \tag{10}$$

$$q_{\text{air2}} = C_2 \frac{dT_{\text{room}}}{dt} \tag{11}$$

, where q_{in}, q_{air1}, q_{out}, q_{h} and q_{air2} are heat flows from the heater to the room, the heat loss through the walls and the stored heat in the heater and room's air, respectively.

By substituting (7), (8), (9) and (10) in (5) and (6), we get:

$$P_{\text{in}} = C_1 \frac{dT_{\text{heater}}}{dt} + \frac{T_{\text{heater}} - T_{\text{room}}}{R_1} \tag{12}$$

$$\frac{T_{\text{heater}} - T_{\text{room}}}{R_1} = \frac{T_{\text{room}} - T_{\text{out}}}{R_2} + C_2 \frac{dT_{\text{room}}}{dt} \tag{13}$$

To build the state space model, the room temperature x_1 = T_{heater} and x_2 = T_{room} are taken as state variables and for output of the system y = x_2. Inputs are the heater's power and outside temperature u = [T_{out}, P_{in}]. Therefore the following state space model is obtained:

$$\begin{aligned} \dot{x_1} &= -\frac{1}{C_1 R_1} x_1 + \frac{1}{C_1 R_1} x_2 + \frac{1}{C1} P_{\text{in}} \\ \dot{x_2} &= \frac{1}{C_2 R_1} x_1 + \left(-\frac{1}{C_2 R_1} - \frac{1}{C_2 R_2}\right) x_2 + \frac{1}{C_2 R_2} T_{\text{out}} \\ y &= x_2 \end{aligned} \tag{14}$$

$$
A = \begin{bmatrix} -\frac{1}{C_1R_1} & \frac{1}{C_1R_1} \\ \frac{1}{C_2R_1} & -\frac{1}{C_2R_1} - \frac{1}{C_2R_2} \end{bmatrix},
$$

$$
B = \begin{bmatrix} \frac{1}{C_2R_2} & 0 \\ 0 & \frac{1}{C_1} \end{bmatrix}, \tag{15}
$$

$$
C = \begin{bmatrix} 0 & 1 \end{bmatrix}
$$

III. Simulation and Results

The parameters for the materials used for the test rig are given on Table I. [13] [14] [15] [16] [17] It's taken that no heat transfer occurs at the top and bottom wall. The mass and dimensions of a piece of the MDF and insulation were measured and density was calculated by dividing the mass with the volume.

TABLE I: Parameters for material properties

Parameter	**Value**
Thickness of MDF (d_{wall})	0.016 m
Area of Walls (A_{wall})	0.2 m^2
Thermal Conductivity of MDF (K_t)	0.13 W/(m·K)
Density of MDF (ρ_{mdf})	700 kg/m^3
Thickness of Insulation (d_{ins})	0.006 m
Thermal Conductivity of Insulation (K_{ti})	0.036 W/(m·K)
Density of Insulation (ρ_{ins})	60.28 kg/m^3
Specific Heat Capacity of Insulation (c_{h})	1100 J/(kg·K)
Density of Air (ρ_{air})	1.2 kg/m^3
Volume of Room (V_{room})	0.012 m^3
Specific Heat Capacity of Air (c_{air})	1012 J/(kg·K)
Density of ceramics (ρ_{h})	3580 kg/m^3
Surface area of heater (A_{h})	0.0003 /m^2
Volume around heater's contact area with air (V_{h})	0.00579 m^3
Specific Heat Capacity of Ceramics(c_{h})	920 J/(kg·K)
Natural convection coefficient of air (h)	22 W/(m^2·K)

By fine tuning the thermal circuit parameters by comparing to the real step response of the test rig, the following parameters and state space model were obtained:

$$
R_1 = 23, \quad R_2 = 1.6, \quad C_1 = 2, \quad C_2 = 400
$$

$$
A = \begin{bmatrix} -0.0217 & 0.0217 \\ 0.0001 & -0.002 \end{bmatrix}
$$

$$
B = \begin{bmatrix} 0 & 0.5 \\ 0.0016 & 0 \end{bmatrix} \tag{16}
$$

$$
C = \begin{bmatrix} 0 & 1 \end{bmatrix}
$$

The Simulink model with the two controllers is given on Fig. 4. The hysteresis is set to 0.5°C and the cycle time to 260s and 180s, to correspond to the period of the on off cycle time and to the hysteresis, respectively. The PID parameters are given on Table II. The simulation time is set to 1.5h. The results from the performance are summarized on Table III and the graphs on Fig. 5. The SD and SAE are calculated from t_1 = 1153s to t_2 = 5400s using these formulas:

$$
SD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N} |x_i - s|^2} \tag{17}
$$

$$
\text{SAE} = \sum_{i=t_1}^{t_2} |e(t)| \tag{18}
$$

, where x_i are the measured temperatures, s = 60°C is the set-point, N = t_2 - t_1 are the data-points in period (t_1,t_2) and the error e(t) = x_i - s. The energy consumption is calculated as multiple of the heater's power P = 25W and its total on-time T_{on}:

$$
E = P \cdot T_{\text{on}} \tag{19}
$$

TABLE II: PID Parameters for TP-PID252 and TP-PID180

Controller	K_p	K_i	K_d
tppid252	$\frac{1}{30}$	$Kp \times \frac{1}{540}$	$Kp \times 25$
tppid180	$\frac{1}{20}$	$Kp \times \frac{1}{410}$	$Kp \times 10$

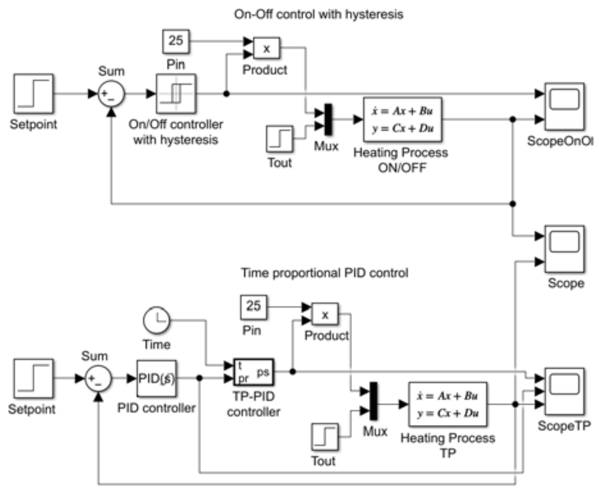


Fig. 4: Simulink model for the thermal control system

TABLE III: Metrics of On-Off and TP-PID Control

Metric	**On-Off**	**TP-PID260**	**TP-PID180**
ST(s)	940	1153	1023
SD	0.58	0.56	0.30
SAE	2291.92	1982.45	1092.63
T_{on}(s)	4252.60	4283.10	4253.40
EC(Wh)	29.53	29.74	29.54

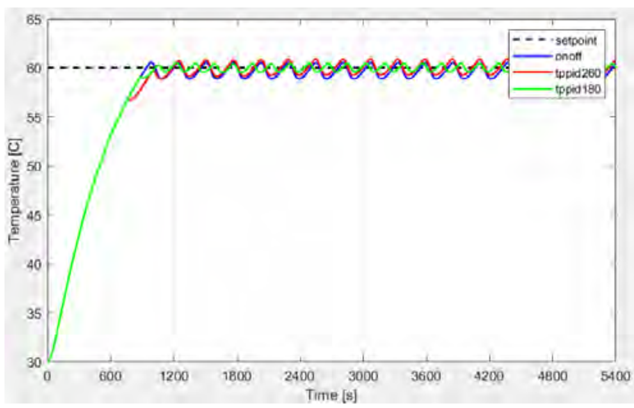


Fig. 5: Simulation Graphs

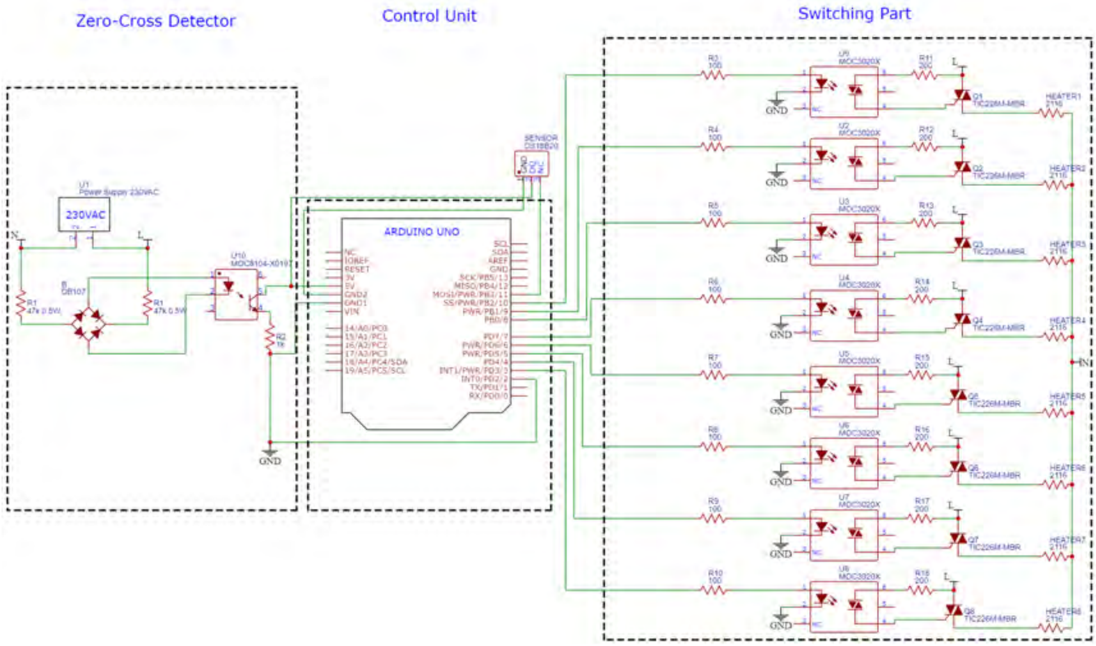


Fig. 6: Schematic for the power board

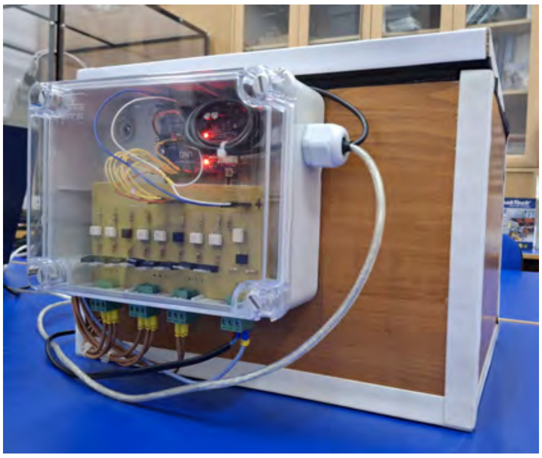
From the results of the simulation, we can conclude that both controllers show similar performance. The on-off control has smaller rise time with overshoot of 60.6°C and undershoot 58.8°C but at a cost of a less accuracy. The TP-PID 180s controller is most accurate with SD of 0.30 and SAE of 1092.63. The overshoot is 60.5°C and the undershoot 59.56°C . The TP-PID 260s controller shows slightly worse performance than the other two controllers. The energy consumption is approximately 30Wh and nearly equal for the three cases.

IV. Design of Test Rig

A test rig representing a room for testing different types of temperature controllers was developed. The width, depth and height of the box are 30 cm x 20cm x 20cm. The walls of the box are made from 16mm medium density fiberboard and covered with 6mm thermal insulation foam ODE R-Flex PRM. For heating actuators are used 8 cylindrical heating elements for soldering iron of 25 Watts. They are controlled by a designed electronic board (power board) managed by an Arduino Uno. The power board is powered by 230 VAC and consists of two parts: zero-cross detector and switching part. The zero-cross detector is made of two 47k resistors, lowering the voltage amplitude to 5V, full bridge rectifier, converting the AC voltage to $T_{\rm on}$ and optocoupler, used to isolate the Arduino from the high voltage part. The switching part consists of eight 100 and 200 ohms resistors, optocouplers and triacs, which act as switches. Each heater is controlled by an optocoupler and a triac. The schematic with the used components is given on Fig.6.

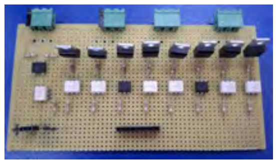
The Arduino serves as central control unit for the system. It receives an input temperature from the sensor. Based on the chosen programmed control logic, it sends control signals to the optocouplers and triacs, turning the heaters on or off. The control logic ensures precise temperature regulation by turning the heaters on or off as needed in order to maintain the desired temperature.

The test rig along with the power board is shown on Fig. 7.



Box

Inside



Circuit Board

Fig. 7: Test Rig

V. Experiments and Results

The experiment is done for 1.5 hours. The hysteresis is set to 0.5, the cycle time to 252s and 180s (for the same reasons as in the simulation) and the PID parameters are given on Table IV. The performance results are summed up in Table V and the graphs on Fig. 8. The SD and SAE are calculated from 3440s to 5400s.

TABLE IV: PID Parameters for TP-PID252 and TP-PID180

Controller	K_p	K_i	K_d
tppid252	$\frac{1}{30}$	$Kp \times \frac{1}{540}$	Kp
tppid180	$\frac{1}{20}$	$Kp \times \frac{1}{300}$	$Kp \times 10$

TABLE V: Metrics of On-Off and TP-PID Control

Metric	**On-Off**	**TP-PID260**	**TP-PID180**
ST(s)	922	3440	2825
SD	0.66	0.80	0.45
SAE	848.60	927.83	538.67
T_{on}(s)	5517.32	5455.19	5459.60
EC(Wh)	38.31	37.88	37.91

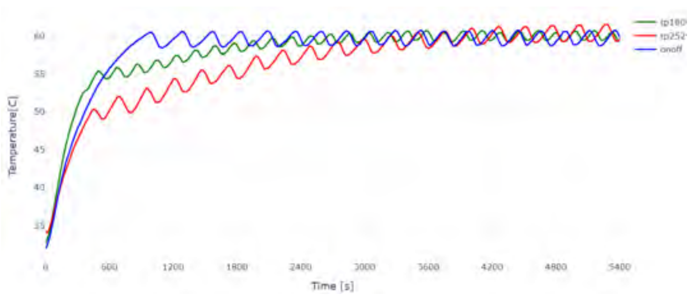


Fig. 8: Graphs from the experiment for both controllers

The experimental results align with the simulation results. The on-off control is fastest at achieving control but shows lower accuracy, overshoot of 60.69°C and undershoot of 58.56°C . While the TP-PID 180s controller demonstrates highest accuracy with overshoot of 60.5°C and undershoot of 59.5°C , SD of 0.45 and SAE of 538.67. The TP-PID 252s appears as worst performing controller. The energy consumption is approximately 38 Wh, almost equal in the three cases.

VI. Conclusion and Future Work

This paper presented modelling of a thermal process and developing a test rig for evaluation of two temperature controllers, on-off with hysteresis and TP-PID. Through simulation and experimental testing, the performance of these controllers was analyzed using metrics like settling time, standard deviation, integral of absolute error, and energy consumption. The findings from both experiments indicate that while the on-off controller is able to achieve the desired set-point quicker, it compromises the system's accuracy. The TP-PID 180s demonstrated slower settling time but achieves superior accuracy. This study underscores the trade-offs between the control accuracy, response time and energy efficiency in temperature control systems.

For future work, we intend to i) do identification of the thermal process to develop a more accurate model, ii) do a finer tuning of the PID parameters to optimize more the performance of the TP-PID and iii) to implement phase angle control.

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Quality control with real-time data analysis using intelligent algorithms

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Dedicated to Prof. Mile J. Stankovski on his anniversary

***Abstract*—In this study we propose a methodology for monitoring and analyzing production data parameters in real-time, using intelligent algorithms. By exploring experimental data from real production facilities, an analysis of the quality level of the products and the condition of the components of the machines was performed. Research is done according to a previously defined research methodology that provides a framework for the entire process. Using the defined flowchart, we examine data, acquired from a packaging machine production process. In this way, the given research confirms how these new intelligence technologies can be integrated for precise and fast data analysis in industrial production. For the whole process of data analysis, the MELSOFT MaiLab program package was used, whereas in order to obtain the largest possible number of heterogeneous data sets, a packaging machine simulator was developed in Python. The analysis provides an assessment of the quality of the products during their production, canceling the need for quality control by an operator, enabling more efficient and economically profitable use of the machine. The estimated quality rating in the given research proved to be entirely satisfactory and trustworthy, indicating that this method is both practical and reliable for application in industrial production settings. The directions given and the research results are a good basis and incentive for new research.**

Keywords—quality control; intelligent algorithms; data analysis; industrial plants; machine learning

I. INTRODUCTION

Quality control is one of the significant components of the manufacturing process, incorporating new cutting-edge technologies to improve both the quality and quantity of products. It is a process in which the characteristics of products or services are examined, measured, and evaluated to ensure that they meet the needs and expectations of users. This activity aims to guarantee quality and prevent the occurrence of defects or irregularities. It is an important component in industrial production and has a significant and direct impact on the efficiency and profitability of a company. Continuous production with a high quality coefficient and without unexpected interruptions is the goal of every manufacturing company. From the very beginning of industrial production, there has been consideration of how to achieve these goals, which is why quality control methods evolve and follow current technologies [1].

Until the early 19th century, manufacturing in the industrialized world tended to follow the craftsmanship model. The quality of products could essentially be controlled by a person who was also the operator, and this procedure is referred to as "operator quality control" [2]. The period from about 1920 to 1940 saw the next phase in the evolution of quality control, known as "inspection quality control". Products were inspected after certain production processes. Standards were established, and inspectors compared the quality of the items produced against those standards [2]. During this period, the foundations of the statistical aspects of quality control were being developed. These became known as "control charts", and the phase is referred to as "statistical quality control". Production requirements grew after 1950, and the importance of quality control was recognized. During this period, Japan developed the "Total Quality Management" approach [3]. The principles of Total Quality Management have proven invaluable to organizations in all sectors of business and commerce, as well as to the individuals they comprise [4]. This improved the main approaches in quality control and began with the implementation of "in-line quality control", where products are checked during the production process. In-line quality control is able to provide direct feedback with regard to quality deviations in production systems [5]. Process parameters should be analyzed in real-time, and at the end of production, each product should be sorted as either good or bad. Implementation of this approach should involve real-time data analysis of all quality characteristics of the product, it is evident that data analysis constitutes the primary task.

In modern production, where many elements interact (human, material, and immaterial resources), a large amount of data accumulates during production operations [6]. To extract useful information and make decisions from production data, data analysis techniques are used, often with the assistance of artificial intelligence. These techniques introduce intelligence into the systems and adapt to changing environments using historical experience (data) through their prior training [7]. The trend of development in artificial intelligence is undoubtedly emerging in industrial production. Despite the growing trend, however, there is significant skepticism and distrust regarding their widespread use in industrial production. Intelligent algorithms, together with digitization, represent a driving force in the process of the new industrial revolution [8], [9], [10]. Additionally, there is an emphasized capability for processing multidimensional data, reducing complexity, improving continuous knowledge, and identifying relevant relationships with processes to increase the applicability of techniques in the processing industry [11]. This enables predicting the future behavior of the production system, which can aid in transitioning to sustainable practices in the processing industry (e.g., waste reduction [12], increasing energy efficiency [13], and predictive maintenance [14]). According to [15], data analysis methods can be classified into three categories: Descriptive analytics, Predictive analytics and Prescriptive analytics. This classification is based on how and when these methods are used. Descriptive analytics focuses on summarizing historical data and providing a description of their structure, primarily using traditional statistical methods such as mean, median, and standard deviation [16], [17], [18]. Predictive analytics uses these data to make predictions about what will happen in the future, based on the assumption that what happened in the past will happen similarly in the future [19]. Prescriptive analytical methods focus on creating an optimal plan (prescription) for utilizing the already predicted future states and needs [20].

Many applications in the field utilize different conventional quality control techniques, as image recognition or direct parameter measurements, applied at the end of the production line. However, these methods require additional time and incur costs for performing quality control. On the other hand, using real-time intelligence data analysis, conventional quality control procedures can be optimized, thereby reducing the reliance on testing stations and accelerating the production process. One of the primary difficulties with this data analyzing method is determining the appropriate process parameters to analyze for in-line quality control. Another crucial step is identifying and selecting the appropriate intelligence algorithms for precise and effective data evaluation[19]. The five popular types of predictive data analytical methods are: (1) regression [18], (2) Bayesian statistics [21], (3) decision tree [22], (4) neural networks [23], and (5) support vector machine [24]. Regression methods require a linear relationship between target and normal attributes. Bayesian statistics use Bayes' theorem to establish a relationship between target and normal attributes. Decision trees divide current data into different groups or branches to improve the degree of their purity (homogeneity) in each division. Neural network methods construct a network with input nodes, hidden layers, and output nodes to build a complex multidimensional relationship between the data. Support Vector Machine enables data classification and can be used in many ways. For the purposes of data analysis from industrial processes, the most commonly used algorithms according to [25] are: Multiple regression, K-nearest neighbors algorithm, Random forest, Gradient boosting decision tree, Deep learning, Mahalanobis Taguchi (MT) Method, Autoencoder, Guard band, Similar waveform recognition and others.

For expressing quality control with some quantitative measure, the production efficiency is used in most cases. This measurement ensures that the production processes are optimized to reduce waste and enhance productivity. For quantitative monitoring of production efficiency, the Overall Equipment Effectiveness index (OEE) is used [26]. The term OEE was originally introduced by the Japanese engineer Seiichi Nakajima (1919–2015), the founder of the Total Productive Maintenance system [27]. OEE is essentially an indicator of how much a production line is utilized compared to its full potential during its planned operation time. It identifies the percentage of production time that is truly productive. Indeed, the calculation of OEE encapsulates three critical factors: Availability, Performance, and Quality. Each component plays a key role in determining the overall efficiency of the production process. Quality assesses the conformity of the output products to the desired specifications or standards. It reflects the proportion of good-quality products produced relative to the total output. Factors such as defects, rework, and scrap contribute to Quality losses. Improving quality involves reducing defects and ensuring that products consistently meet or exceed customer expectations and quality standards and norms [27].

The focus of this paper revolves around integrating quality control with sophisticated data analysis algorithms. Within this framework, advanced algorithms, including those utilized in machine learning and artificial intelligence, are employed to scrutinize extensive datasets in order to forecast product quality. The paper establishes both theoretical and practical underpinnings for quality control within industrial production. It begins by introducing the accomplishments, strategies, and techniques within this domain. Subsequently, practical testing of various algorithm combinations will be conducted through the application of the MELSOFT MaiLab software package, developed by Mitsubishi Electric. To structure the research and outline the necessary steps or phases throughout the study, a research methodology for data measurement and analysis was defined.

Experimental research and data analysis were carried out on a food packaging machine utilizing thermoforming technology. Data for analysis were directly read from the machine, however, to encompass a wide array of errors and machine configurations, a part of the data additionally are generated using Python scripts. Multiple models and combinations of analytical methods were developed to improve prediction accuracy. A thorough analysis and discussion of results from various models were conducted, highlighting their strengths and weaknesses. The best-performing models were then used for real-time data analysis, resulting in satisfactory outcomes and a enhancement in the machine's OEE index. The study concludes with a discussion, including comparisons of results obtained with different methods. The analysis provides an assessment of the quality of the products during their production, canceling the need for quality control by an operator, enabling more efficient and economically profitable use of the machine. The directions given and the research results are a good basis and incentive for new research.

II. Experimental Approaches and Methods

Progress in areas such as the Internet of Things (IoT), Cyber-Physical Systems, Cloud Computing, Big Data, and artificial intelligence is significantly influencing manufacturing, leading the way for the fourth industrial revolution, Industry 4.0 [28], [29]. With the rise of these Industry 4.0 technologies, the amount of raw data collected during production processes is continuously growing (referred to as Big Data) [30], [31]. Consequently, many researchers agree that data plays a crucial role in optimizing production processes and enhancing competitiveness [32], [33]. Data collected throughout the product lifecycle can be harnessed and transformed into what is known as manufacturing intelligence, positively impacting all facets of production [34]. However, the increasing volume of Big Data also complicates the processing and analysis of vast amounts of information within production systems. As a result, the surge in Big Data prompts the development of data analytics [35], [36], although it often encounters challenges due to the limited processing power of existing software applications and personal computers [32]. Nevertheless, when properly utilized, Big Data enables real-time predictive analysis by uncovering correlations in raw data [37]. Therefore, through the use of predictive models, decisions can be made effectively, transitioning from reactive to predictive or modern production practices [32].

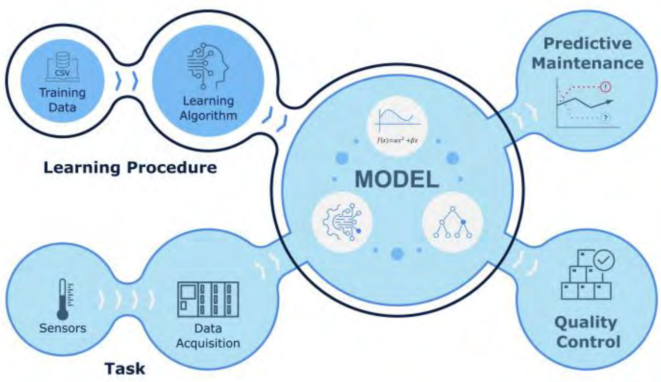

Fig 1. Overview of how intelligence algorithms can be used to resolve certain task in industry production process

Fig. 1 illustrates the comprehensive steps involved in industry process modeling through big data analysis, with the objective of prediction or quality control. Initially, the model is developed (trained) using historical datasets from the actual system (i.e. the model gathers insights from past experiences). Once the model is established, it enables real-time data analysis. Depending on the task and training approach, it can forecast the condition of machine components (predictive maintenance) or anticipate product quality levels (quality control). It can also be used for another purpose in industry.

III. Definition of Research Methodology for Data Measurement and Analysis

To implement the approach from Fig 1, our research will utilize a research methodology, consisting of 6 phases, namely: Goals definition, Data identification, Data collection, Data pre-processing, Creating a Model, Real-time Analysis (the methodology is adopted from [38] [39]).

Phase 1: Goals definition – During this phase, it is essential to establish the quality control objectives, specifying and identifying the influential parameters on quality control index.

Phase 2: Influential data description – Based on the first phase, in this phase, the data that affect the onset of the quality should be defined. This is performed in three steps: specification of data types, recognition of influential parameters, and checking their availability. Influential parameters represent all process parameters that have a significant impact on the occurrence of product quality issues.

Phase 3: Production data collection – In this phase, the defined data from the system should be collected. Data sets should be as large and heterogeneous as possible, encompassing a wide range of scenarios to ensure comprehensive coverage. If it is not possible to measure all influential parameters, defined in the second phase, then we need to verify, whether the goal in Phase 1 is well defined.

Phase 4: Data pre-processing – During this phase, the collected data should be processed and formatted to ensure its suitability for future analysis. Each parameter should be scaled and outliers should be excluded. This way, different datasets with influential parameters will be created.

Phase 5: Creating a model – Initially, we choose the algorithm for model identification. Firstly, we train the model, using the collected data. Then we validate the model and check its accuracy, using testing data (the testing datasets are extracted from the collected data). If the accuracy is not satisfactory, this phase must be repeated and a new model needs to be trained, either defining different model structure, or using different identification algorithm, or both. Essentially, this is the primary challenge in data analysis. Upon achieving acceptable model accuracy, we can advance to the next phase.

Phase 6: Real-time model testing – In this final phase, a verification should be conducted, ensuring that the obtained results align with expectations, meeting the predefined objectives from the first phase. Additionally, the obtained results can be also compared with traditional quality control ("operator quality control"). For example, the quality index assessment generated by Milab (in our scenario) can be compared with the assessment made by the quality control operator of the products.

IV. Milab – Software for Data Analysis

Following the described methodology in the previous chapter, here we present the overall process of data collection and analysis conducted on a real packaging machine process. For observation, we use a real system, namely a machine from a well-known global manufacturer that is fully automated with Mitsubishi Electric's automatic control equipment.

For the experimental research and analysis of the obtained results, we use the MELSOFT MaiLab software, manufactured by Mitsubishi Electric. The primary purpose of the software is real-time data analysis from industrial production, using artificial intelligence and machine learning [40]. The flowchart in Fig. 2 illustrates the sequence of steps for utilizing the MaiLab software. It's evident that these steps closely resemble the phases outlined in the described research methodology from previous chapter.

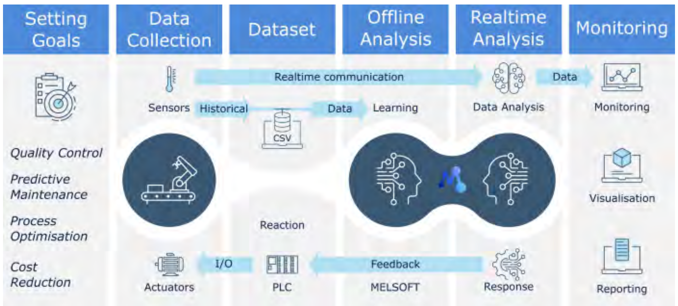

Fig 2. General steps for using MELSOFT Milab Software

V. PACKAGING MACHINE PROCESS DESCRIPTION

As already mentioned, the experimental research and data analysis will be conducted on a food packaging machine. The machine forms trays from foil in which the food is packaged, and then the trays are sealed with another layer of foil. The packaging process is fully automated and is often part of the main production process in the food industry. Figure 3 illustrates the principle of operation of the machine. The bottom foil (1) is unwound from a roll and heated to a certain temperature, using a forming tool (2) the tray (3) is formed. This process is called thermoforming and the machine itself is called also thermoforming packaging machine. When the forming tool closes, hot air is injected into the mold to help the foil achieve the desired shape more easily. Once the tray is formed, the forming tool opens, and upon opening, cold air is injected into the mold to help the tray detach more easily. When the mold opens, the foil, which is attached to both sides, moves forward by the length of one tray. Then, the mold closes again, forming a new tray immediately nearby to the previously formed one. This process is repeated, forming multiple trays one after the other. In the space before the closure of the tray, it is filled with the product to be packaged (4). The filling is usually done by workers, although it can be done with robots or automatic fillers. Once the tray is filled, the top foil (5) is placed over it to seal it. The next step is sealing the tray, which is done with a press (6) heated to a specific temperature. It presses the foil, heats it, and holds it for a specific period. After the foil is sealed, the press opens, and the foil, or the formed packages, move forward again. Finally, the packages are cut crosswise (7) and lengthwise (8). With this, the packaging process is completed, and the products can be packed into larger (cardboard) packages and transported.

The forming (2) and sealing processes (6) occur simultaneously, with the movement of the foil being the same for both processes. Depending on the application and the type of products, the sealing chamber can be vacuumed to obtain vacuum-sealed packages or injected with a specific gas (most commonly nitrogen) to protect them from further oxidation.

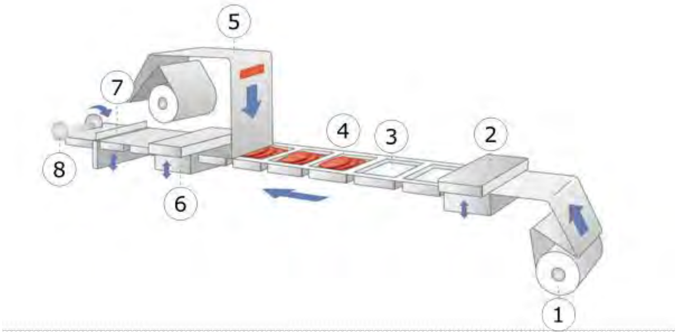

Fig 3. Schematic diagram of thermoforming machine

VI. EXPERIMENTAL RESEARCH AND ANALYSIS

In this part we experimentally implement the presented methodology in chapter III.

Phase 1: Here, our objective is to establish the criteria for packaging quality. Packaging may exhibit either satisfactory attributes, such as proper form, incorrect dimensions, poor sealing, or insufficient vacuum.

Phase 2: In this phase of the research, we define the relevant data or parameters that influence the quality of the product and can be measured. In coordination with machine manufacturer, we have chosen the measurable influential parameters, given in Table 1.

TABLE I. LIST OF INFLUENTIAL PARAMETERS

Nr.	Name	Unit
1	Forming tool position	mm
2	Forming tool temperature	^{0}C
3	Pressure hot air - forming chamber	mbar
4	Pressure cold air – forming chamber	mbar
5	Forming time	s
6	Delay – before blowing air in forming chamber	s
7	Blowing time – hot air	s
8	Blowing time – cold air	s
9	Foil position	mm
10	Motor speed	Hz
11	Motor current	A
12	Pause between steps	s
13	Sealing tool position	mm
14	Sealing tool temperature	^{0}C
15	Pressure – sealing tool	mbar
16	Sealing time	s
17	Vacuum time	s

Since all the defined parameters are measurable and can be stored over time, we can proceed to the next phase of the research, which involves data collection and the creation of data sets.

Phase 3: After defining the parameters, we record them in a suitable format, compatible for further analysis. The methods and techniques of measurement in industrial processes are extensively described in [41]. Most of the sensors are already installed on the machine and connected to the PLC, through which the entire machine is actually controlled. The machine is automated with a modular PLC from the iQ-R Safety series by Mitsubishi Electric. The software package used for PLC programming includes an additional software GX LogViewer, which offers the possibility of real-time signal monitoring and recording. Additionally, a hardware module for high-speed data logging is installed, enabling the tracking and logging of more signals every 2 ms.

Phase 4: The data obtained from direct measurements from the setups are not properly scaled or formatted and need to be further processed or interpolated if some are missing. Due to the quality measurement equipment and programs in the PLC, in our case, we have exceptionally high-quality data sets. Considering that in the previous phase we defined 17 parameters to be analyzed, for just one product we will have over 68,000 data points (4000 data points per parameter). But how many of them actually carry useful information about the product? To clarify, let's examine the case of the foil position (the distance it moves in each operating cycle). This distance is essentially the length of the packed product, so it is one of the most important criteria for packaging quality. For packaging quality, the speed at which the foil moves forward is not important, so the only useful information from this set of over 4000 data points is the maximum value of the foil position. From this maximum value, the error made in each cycle (as a difference with the desired value) can be directly observed. With this approach, the model is independent from the type of packaging, and it is universally applicable for all packaging lengths. Hence, it is undoubtedly more efficient to analyze only the useful information for each parameter rather than the entire array of data over time. For the purposes of this research, we have measured over 6000 packed products (implying 68.000 data points for each packed product). Additionally, for real-time analysis in Phase 6, over 2000 packed products were also measured.

	Name ↑	Data set	Status	Score
☐	AI-01-k-nearest neighbors...	DataSet-Quality	Complete	98
☐	AI-02-Random Forest	DataSet-Quality	Complete	100
☐	AI-03-Gradient boosting d...	DataSet-Quality	Complete	100
☐	AI-04-Deep learning	DataSet-Quality	Complete	72
☐	AI-05-(AI02 and AI03)	DataSet-Quality	Complete	100

Fig 4. List of created models

Phase 5: The data analysis model is developed with the help of the MaiLab software package. All the data prepared in the previous phase are entered into a merged table in tabular form. Only the quality data is defined as a "category," while all other data are of numerical type. Initially, we created models that use only one algorithm, and later, selecting those with the best performance, we created a model with a combination of the initially created ones.

Based on visual-tactile inspection, the operator classifies the products in different groups. The model also needs to make the same classification based on the measured values of the product parameters. As expected, the best results are achieved with the Random Forest and Gradient Boosting Decision Tree algorithms, therefore, we choose the model composed of these two algorithms. The list of created models is shown in Fig 4.

The model's accuracy measured on the same data set used for training is 100%, meaning all predictions match the result from the training set.

Fig 5. Review of results for the selected model

In Fig 5, we can see how the parameters directly affect the quality of the product. The position of the foil, exactly the length of the packaging, along with the temperatures of the forming and sealing tools, have the most significant impact.

Before being used on the real system, the model needs to be tested with a different data set from the one it was trained on, so an additional 330 products and over 1200 simulated data were produced. Figure 6 shows the results of testing the model.

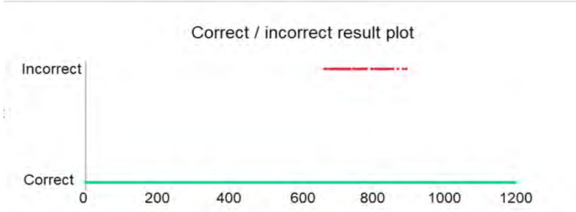

Fig 6. Review of results of testing the model

In Fig 6, it is noted that there is uncertainty in the data between the 700th and 900th index, with an error in that segment hovering around 0.8 mm, which is the maximum allowable deviation for this product. Regardless of the uncertainty in prediction, this still indicates that the model has learned the logic or decision criterion well. When tested with this data set, the model provided acceptable results, so it can be considered reliable enough to be applied for real-time analysis, which we will conduct in the next phase.

Phase 6: After a thorough analysis of the production process, data collection, and model creation, we conducted real-time data analysis during production. In this phase, we directly read data for the products (without quality estimation information) from the PLC and feedback the predicted quality information for the product.

Main challenge was not to achieve accuracy of the model, as it was expected for this type of dataset, but to create a highly reliable model. For this purpose, the combination of two precise models combined through the method of "assembling" their results gives us a model with even greater reliability and precision. However, as we noticed in the last phase, uncertainty occurs in predictions. It occurred when the packaging error was close to the maximum allowable deviation threshold. In such cases, the model always prioritizes classification into a poor product, providing additional reassurance for its use.

VII. Conclusion

The increasing presence of artificial intelligence in industrial production raises the question of how it can be easily implemented and become part not only of its organization but also of production itself. For an industrial system to be intelligent, it must first have a lot of information that needs to be analyzed, and based on that analysis, some conclusion or decision needs to be made. The intelligent systems should identify the correlations between parameters, which are difficult to detect using traditional mathematical methods. These implementations are still often at the pilot project level, because of this, many countries have programs to support their development [42]. Although we are seeing a growing offer of such solutions on the market, skepticism about their use is still at a very high level.

Through the method of implementing systems of this type, we have shown that they are relatively easy to design and implement in real-world scenarios. This contributes to a greater understanding of the topic and increases engineers' confidence in intelligent systems in industrial production. This paper offers a clearer understanding of these methods, their applicability, potential for performance improvement, and directions for their use. All parts and chapters of the work include careful referencing of the literature used, making this material a solid foundation and support for further research. An extensive analysis of the topic, the algorithms used, and a detailed description of the experimental procedure are provided in [43].

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Designing Haptic Interfaces for the Internet of Things: An Open-Source Experimentation Platform

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***Abstract*— This paper presents a study on the design and implementation of Internet of Things compatible, haptic feedback-supported human interface devices. It examines the contribution of technological advancements to human-machine interaction and how haptic feedback enriches the user experience, highlighting its potential in various application areas. Additionally, the process of designing and sharing an open-source, microcontroller-based electronic control system/ experiment kit is detailed; this system can be used as an experimental platform for the development and improvement of haptic applications, as well as for the command and control of functional devices integrated with IoT. Various haptic feedback methods are tested on the presented design, and a user experience evaluation survey is conducted with a specific group to compare the functionality and experience quality of different methods in different scenarios.**

Keywords—Haptic HMI design; user experience, BLDC control

I. INTRODUCTION

In today's world, human-machine interaction (HMI) is pervasive, encompassing everything from home electronics to work on computers. It typically involves users commanding devices and receiving feedback. Haptic feedback enhances HMI by providing touch-based feedback, creating a more intuitive experience. The Internet of Things (IoT) plays a role in HMI advancements by enabling data collection from real-world systems. Haptic feedback simulates touch through vibrations, forces, and movements, providing users with tangible responses. This technology refines digital interactions, making virtual experiences more immersive and intuitive. Haptic feedback goes beyond mere touch; it's a multisensory integration process that impacts human perception, decision-making, and memory[1]. When combined with visual and auditory data, tactile information creates a cohesive and immersive experience, crucial for complex tasks like skill learning or virtual environment navigation. Embodied cognition provides a framework for understanding haptic feedback's significance. It suggests that cognitive processes are rooted in our physical interactions with the environment. Haptic feedback, by mimicking real-world sensations, engages the body in the cognitive process, leading to a deeper understanding of digital content [2]. This extends beyond touch, encompassing the whole body's sensory-motor capabilities, enriching the interaction and making digital experiences more memorable.

Haptic feedback also enhances emotional connection. Tactile sensations can evoke feelings of warmth, security, or familiarity, impacting user interaction. For instance, a smartphone's vibration notification creates a sense of connection and anticipation. This emotional engagement is crucial for applications like entertainment, education, and therapy, where emotional resonance amplifies the experience [3]. Haptic feedback introduces a new dimension to HMI, enabling users to engage with the digital world more naturally. By harnessing the power of touch, it makes virtual experiences more immersive, emotional responses more intense, and the cognitive process more embodied. This evolving technology holds the potential to transform the way we interact with the digital world and is expected to play an even greater role in the future.

This study focuses on the "interaction" aspect of human-machine and human-process interactive IoT interface devices. It aims to design an experimental kit for use in studies that aim to improve user experience through different interaction methods, primarily using haptic feedback technology. The study also conducts a user experience survey on haptic feedback applications using the designed kit and investigates whether the integration of this technology into home automation interface devices improves user experience. The main objectives of this research are as follows:

- To design an experimental kit for use in studies that aim to improve user experience through different interaction methods, primarily using haptic feedback technology.
- To conduct a user experience survey on haptic feedback applications using the designed kit.
- To investigate whether the integration of haptic feedback technology into home automation interface devices improves user experience

This research will employ a mixed-methods approach, combining quantitative and qualitative data collection methods. The experimental kit will be designed to enable researchers to conduct studies on haptic feedback applications in a variety of settings. The kit will include hardware components, such as haptic feedback devices and sensors, as well as software components, such as a data acquisition program and a user interface. A user experience survey will be conducted to gather feedback from users on their experiences with haptic feedback applications. The survey will be designed to measure various aspects of user experience, such as usability, satisfaction, and perceived value. Haptic feedback technology will be integrated into home automation interface devices to assess its impact on user experience. A controlled experiment will be conducted to compare the user experience of participants using haptic feedback-enabled devices with those using traditional devices. Quantitative data from the user experience survey and controlled experiment will be analyzed using statistical methods. Qualitative data from the survey will be analyzed using thematic analysis.

II. DEVELOPMENT OF EXPERIMENTAL PLATFORM DEVICE

A. Conceptual Design

The platform designed, incorporating multiple user input and feedback capabilities, is a derivative of the open-source Haptic Knob project by Scott Bezek [4]. This project is also based on the open-source SimpleFOC platform.

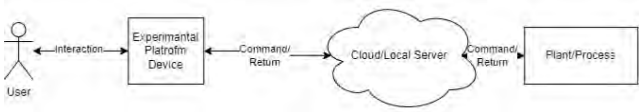

Fig. 1. Diagram of Conceptual Design

Haptic feedback also significantly enhances emotional connection with digital content by evoking emotional response. The platform's design prioritized several key factors.

- Cost-Effectiveness: Utilizing readily available and affordable components ensures broader accessibility for researchers and developers.
- Manufacturability: Straightforward assembly methods and readily available parts allow for easy replication and customization within labs and workshops.
- Ergonomics: The platform's form factor and user interaction methods were carefully considered for comfort and intuitive use during extended research sessions.
- Functionality: The core functionalities were selected to offer a balance between versatility and practicality for exploring various haptic feedback applications

The platform boasts a rich set of user input options, allowing researchers to explore diverse user interaction paradigms

- Infinite-Rotation Knob: This knob facilitates continuous, precise control over virtual parameters, mimicking experiences like adjusting volume or scrolling through menus.
- Joystick-like Bending: Users can bend the knob along the X and Y axes, like a joystick, enabling intuitive control for navigating virtual environments or manipulating objects within simulations.
- Touchscreen Interaction: A touchscreen allows for familiar gestures like tapping, holding, and swiping, expanding the range of user interaction possibilities.
- Non-Contact Hand Gestures: The platform can be designed to incorporate sensors for detecting non-contact hand gestures, further enriching the user experience and exploring the potential for touchless interfaces.

To provide comprehensive feedback to users, the platform offers a multi-modal output system:

- Haptic Feedback via Rotary Knob: By applying torque or force to the knob in specific patterns, the platform can deliver tactile feedback that corresponds to in-system events or user actions.
- RGB LED Ring Animation: An RGB LED ring surrounding the knob can be animated with various colors and patterns, offering visual cues for system status, notifications, or feedback related to user interactions.
- LCD Touchscreen Display: The platform can display text, graphics, and even animations on the touchscreen, providing clear and versatile feedback mechanisms for users.
- Audio Feedback: A buzzer can be used to generate different sounds for specific events or notifications, creating an additional layer of auditory feedback to complement other modalities.

This combination of diverse input and output capabilities empowers researchers and developers to design different user experience (UX) setups.

Fig. 2. Designed IOT device

B. Mechanical Design

A rotary knob and enclosure for hardware were designed using a CAD program. The main constraint during the mechanical design was manufacturability with standard FDM 3D printers. The parts were printed using PLA filament and published in the project's open-source repository (Fig.2).

C. Hardware Design

To achieve an optimal design [5,6,7,8,9], extensive testing and evaluation of different electronic modules were conducted. This process involved considering factors such as compatibility, performance, cost-effectiveness, and ease of use. The final selection of materials and products ensured that the device met the desired specifications while adhering to budget constraints. The experimental device's electronic module design incorporates three primary components:

1) Accessible and Affordable Motor Selection:

The motor type was selected as “Hollow shaft BLDC Motor”. A group of motors shown in Table 1 were tested to determine the optimal one for experimental platform device.

TABLE I: MOTOR COMPARISION

	Model	*Outer Radius (mm)*	*Inner Radius (mm)*	*Pole pair*	*Weight(g)*
A	FlyCat 2804	34.5	5	11	21
B	noname	33	5.5	11	22
C	iPower GBM2804	35	6.5	12	50
D	OT-EM3215D2450Y1R-BEZE	32	6	8	30
E	DYS 2.0kg Gbm5208-75	63	12	24	189

Those experiments listed below are conducted:

a) No-Load Voltage/Current Curves of Motors:

The voltage and current curves of motors were measured under no-load conditions (Fig.3). Voltage/Current Variations Under Load:

Motors were tested with a 50-gram load to measure the variations in coil voltage and current (Fig.4). Ideally, a 90-degree phase difference between voltage and current curves is expected. Deviation from this phase difference indicates inconsistency in the motor's electromechanical structure.

b) Temperature Increase Curves of Motors:

Motors were operated under identical conditions and durations to observe temperature increases. The temperature rise curve provides significant data about the motor's efficiency [10,11]. Exceeding 70 degrees under nominal conditions poses a risk to the device's overall structure and surrounding equipment. (Fig.5)

a) Step Responses of Motors:

The step responses of motors [12,13] were measured and compared (Fig.4). Motors were operated starting at 10 RPM, increasing by 1 RPM every 15 seconds, and step response curves were examined under a 250g load (Fig.6).

By examining these graphs, Motor D exhibits the best performance, providing high efficiency and stability. Among the other motors, Motor A shows the worst performance, with issues related to low efficiency and stability.

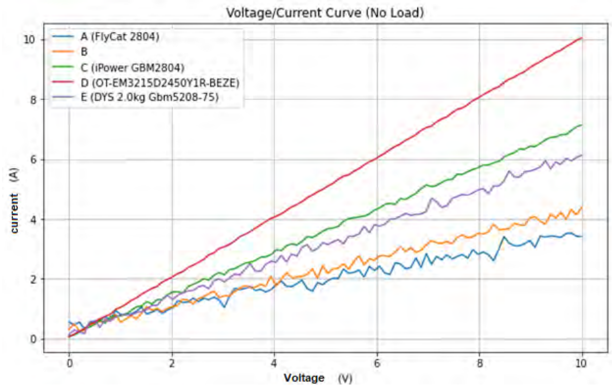

Fig. 3. No-load V/I Curves of Tested Motors

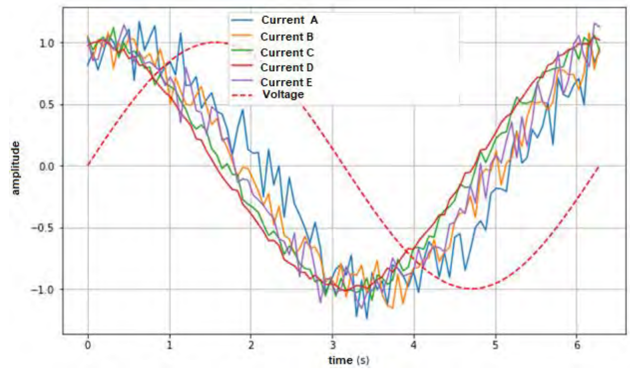

Fig. 4. Voltage/Current Variations Under Load

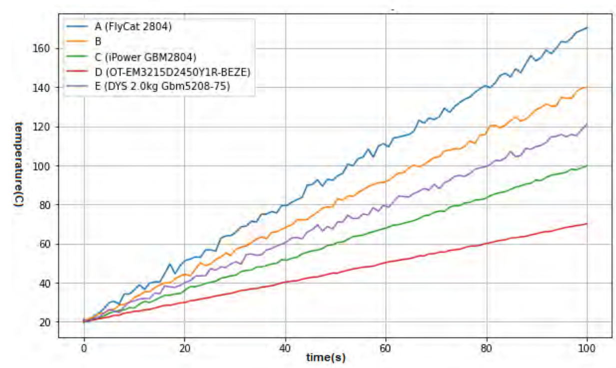

Fig. 5. Temperature Increase Curves of Tested Motors

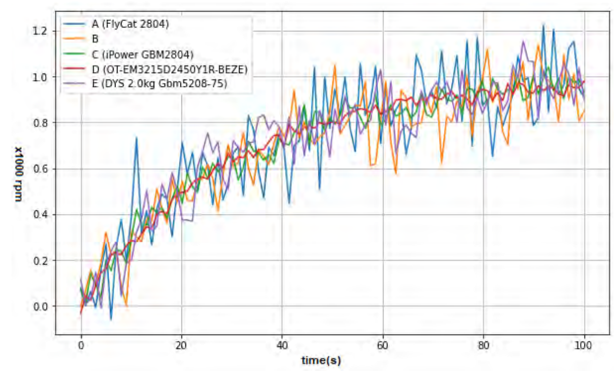

Fig. 6. Step Responses of Tested Motors

1) Haptic Motor Controller:

Controller handles closed loop motor control control. Intensive tests were carried out with numerous motors, motor control circuitry and magnetic encoder IC's. A custom PCB (Fig.7) was designed to utilize closed loop motor control hardware.

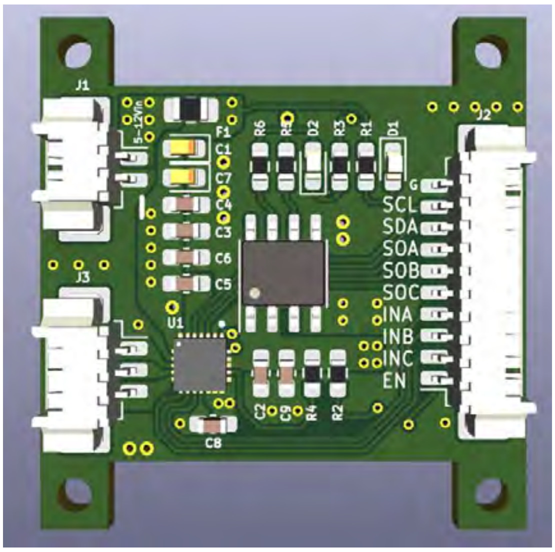

Fig. 7. Motor controller PCB 3D view

After manufacturing, open/closed loop motor control was achieved in position, velocity and current control modes. It is also possible to achieve closed loop torque control mode by using Field Oriented Control and combining current and position feedback

For a BLDC motor, implementing Field-Oriented Control (FOC) with Space Vector PWM (SVPWM) modulation in torque control mode provides efficient torque management. The FOC algorithm starts by measuring the motor's phase currents and transforming them to the stationary reference frame using Clarke transformation. These currents are then converted to the rotating reference frame aligned with the rotor's magnetic field through Park transformation. In torque control mode, the q-axis current (I_q) directly corresponds to the motor's torque and regulated using a Proportional-Integral (PI) controller. The desired voltage commands in the d-q frame are then transformed back to the stationary frame, and the SVPWM algorithm generates the PWM signals based on these voltage commands.

To simulate realistic haptic feedback with detents in a knob, the control algorithm begins by initializing the hardware components, including sensors and the motor, and defining the detent positions along with control parameters such as the spring constant, damping coefficient, tolerance range, and consistency threshold. The system continuously reads (Fig.8) the knob's current angular position and velocity using sensors. It calculates the nearest detent position relative to the current angle and determines the error between this desired attractor angle and the current angle. Using proportional control, the algorithm calculates the required torque to simulate a virtual spring effect, opposing the knob's movement. The algorithm checks if the current angle is within the tolerance range of the attractor angle. If it is, and the angle remains consistent within this range for a duration exceeding the consistency threshold, the motor provides tactile feedback by briefly increasing the torque to simulate a detent click. The motor click is ensured to happen only once per settling event. The system continuously monitors the knob's position and velocity, updates the torque calculation, and adjusts the motor control signals accordingly, using techniques such as Field-Oriented Control (FOC) and Space Vector PWM (SVPWM) for precise motor control. This approach provides a realistic and intuitive haptic feedback experience, simulating the feel of detents and enhancing user interaction.

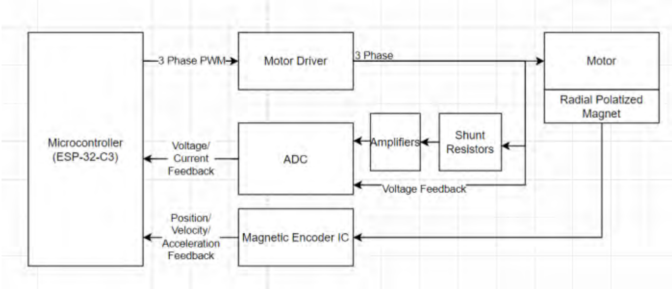

Fig. 8. Functional Diagram of Haptic Controller

2) Front End Controller:

Handles Buzzer, RGB LED ring and LCD screen controls, Gesture sensor and touch panel monitoring. Remote communication is handled by front end controller as well. An ESP-32-S3- based 1.28-inch touch screen module with on-board gyroscope module was selected and used as front-end controller.

D. Software Design

An Object-oriented approach was followed during software design and implementation. Software package of of the experimental device consists of 3 software modules (Fig.9):

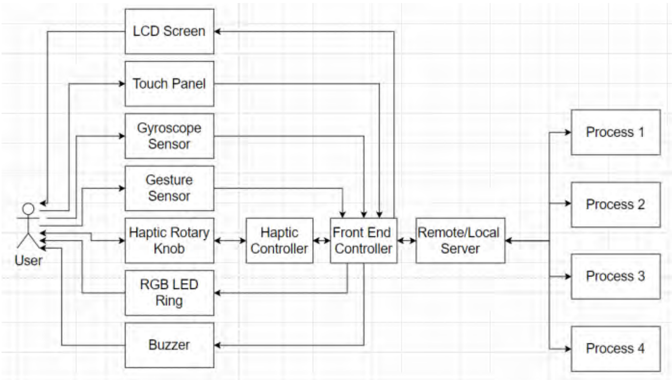

Fig. 9. Overview of Architecture

1) Haptic Controller Software Module:

Main task of this software is to control and monitor the haptic knob, get rotary position/torque input from the user and provide haptic feedback based on certain patterns.

Implementation is made in Objective C language and compiled in Arduino IDE to ensure open-source compatibility (Fig.10).

2) Frontend Controller Software Module:

Responsible for handling non-haptic interactions with user and communication with remote server/process. Touch screen-based UI/UX applications would be abstracted in this software.

3) RemoteLocal Server Module:

The local server module handles real-time data collection, immediate feedback, and initial processing, ensuring responsive and secure operation close to the smart knob. The remote server module manages extensive data storage, advanced processing, and user interface functionalities, enabling sophisticated analysis, control, and integration capabilities. Together, they create a robust IoT ecosystem that enhances the functionality and user experience of the smart knob. All the design files are shared [14].

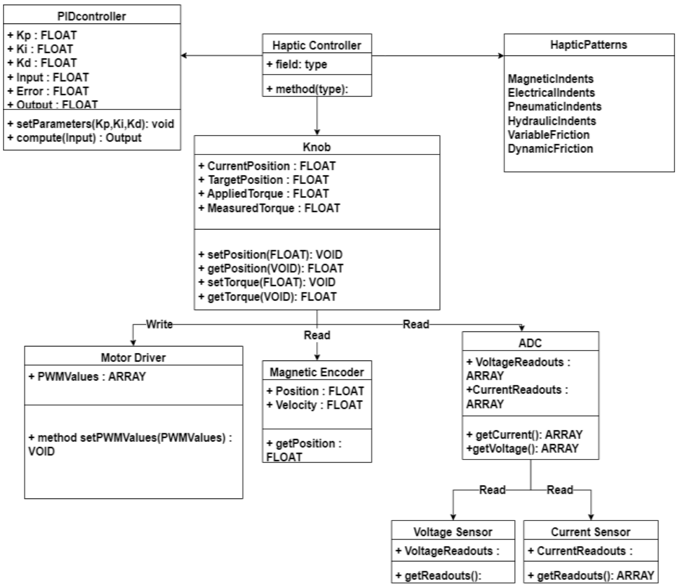

Fig. 10. Simplified UML diagram of Haptic Controller Software

III. User Experience Demonstration and Survey

A. User Experience Demonstration

A user experience demo and survey were conducted to determine:

- If people believe that IoT devices and processes add value to their lives.
- If haptic feedback adds value to IoT devices and processes.
- What type of feedback (haptic/visual/sound based) is preferred by users in specific IoT control processes.

To demonstrate haptic feedback enabled IoT device, 3 different scenarios were prepared:

- User controls ambient sound volume by using experimental platform device. Users were exposed to all haptic, visual and sound feedback modes one by one.
- User controls ambient illumination by using experimental platform device. Users were exposed to all haptic, visual and sound feedback modes one by one.
- User uses experimental device as a space-mouse-like computer peripheral to interact with CAD software (Fusion 360). Only haptic feedback was enabled in this demonstration.

B. User Experience Survey

After the demonstration, an experience survey was conducted over Google Forms platform. 20 men and 17 women participated in the survey. According to the survey results, it has been observed that participants are familiar with the concept of the Internet of Things (IoT) and believe that this technology adds value to human life. It was noticed that all participants own and use at least one IoT-compatible device in their daily lives.

Users were observed to have a more intuitive and understandable experience through haptic feedback compared to visual and auditory feedback (Fig.11). Based on this, it can be predicted that integrating haptic feedback rotary knob applications into IoT and smart home automation applications could improve individuals' interactions in daily life.

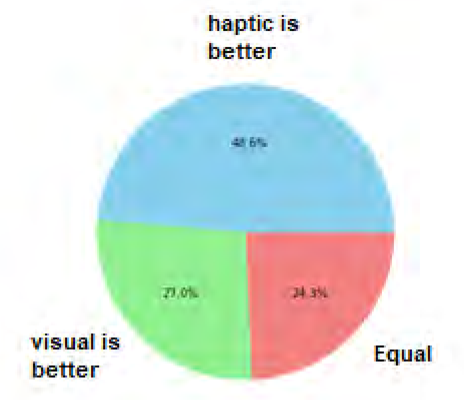

Fig. 11. Comparison of Haptic and Visual Feedback User Experience Intuitivity

IV. Conclusion

This study conducts detailed research on the design and implementation of Internet of Things (IoT)-compatible, haptic feedback-supported human interface devices. The research focuses on the potential of haptic feedback technology to enhance user experience and its integration with IoT. An experimental kit capable of implementing haptic feedback patterns was designed. Tests conducted with this kit demonstrated that user interactions with such systems could be optimized. Surveys and experiments showed that users experienced more intuitive and understandable interactions through haptic feedback compared to visual and auditory feedback. Participants indicated that haptic feedback was more effective, significantly improving user experience. Experiments with IoT-compatible devices revealed that integrating haptic feedback positively influenced user interactions. Haptic feedback interfaces are predicted to enhance user experience, particularly in smart home automation applications. Integrating haptic feedback technology with IoT devices holds significant potential for improving user experience. This integration can lead to more intuitive and satisfying interactions, especially in smart home automation.

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A Fuzzy Systems Approach to Discrete-time Sliding-mode Control for Uncertain Nonlinear Plant Systems

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Abstract—**The stabilization control problem of a class of uncertain nonlinear discrete-time systems via an equivalent Takagi-Sugeno (T-S) fuzzy model has been explored and an innovative design proposed. First the representation of nonlinear system dynamics by equivalent T-S fuzzy model was studied. The global T-S fuzzy model of nonlinear system was transformed into linear uncertain system model, and thus the stabilization control of nonlinear systems was converted into the robust stabilization control problem. Discrete-time sliding mode control approach was employed to guarantee robust stabilization of linear uncertain systems. The stable sliding surface was designed by using Linear Matrix Inequalities (LMI) so as to reduce the influence of the mismatched uncertainties. Then the sufficient condition for the existence of stable sliding surface was derived in terms of LMI. The innovative design of sliding mode control law was derived. Robust controlled stabilization in the closed loop is guaranteed and also the chattering around the sliding surface is considerably reduced. The benchmark illustrative example of controlled backwards motion of a truck-trailer is solved to demonstrate the feasibility and effectiveness range of the proposed design method.**

I. Introduction

MOST of plants in the industry have severe nonlinearities, which makes the research for nonlinear control systems possess considerable practical significance. However, they also pose additional considerable involved difficulties to the theory of general nonlinear systems and the control design methods. In order to overcome these difficulties in the design of controllers for nonlinear plant systems, various innovated schemes have been developed in the last few decades, in particular with regard to the theoretical synergies employed in of fuzzy control technology [1], [4], [8]. In turn, fuzzy control technology can provide fairly simple and yet most efficient solutions to the control of real-world complex dynamical processes which are ill-defined, nonlinear, time-varying, and uncertain, or have available solely qualitative knowledge from domain experts. In spite of the usefulness of fuzzy control, its main drawback comes from the lack of a rigorously sound system-theory based control design methodology [1-8], [17-21].

The famous Taksgi-Sugeno (T-S) class of fuzzy models [1] in which a linear system is adopted as the consequent part of a fuzzy rule has been developed. It can combine the flexibility of fuzzy logic theory and the rigorous mathematical analysis tools in linear system theory into a unified framework to solve the control and design problem of nonlinear system. It has been proved theoretically [23] and confirmed in applications in applications the T-S fuzzy model is a general nonlinear approximation [24] and can approach nonlinear plants with arbitrary accuracy [2]. Therefore the T-S fuzzy model control design techniques can provide novel solutions to nonlinear system control. Thus the T-S fuzzy-model based control technologies were studied extensively as shown by references. A common belief has been established and demonstrated in applications, the T-S fuzzy-model-based control technique is simple and effective in controlling complex nonlinear systems in general [1], [4], [18], [20], and such as electro-mechanic inverted pendulum and truck-trailer [3], [6], and as industrial process plants with chaotic dynamics [5], [7] .

Besides the fundamental stability prerequisite requirement for feedback control technology, the operating robustness is another important requirement for control systems. It is well known the sliding mode control (SMC) is an effective method of robustness control [3], [9], [19], [21] for complex nonlinear and/or time-varying plants. The SMC has a good performance that is the system behavior is insensitive to the internal parameter variations and external disturbances [9-10], It is reason that the SMC is one of preferred projects to study robustness control of uncertain system. At the same time, with the rapid development of computer technologies and chips for distributed processing of signals, it is imperative to realize controllers of state and/or output feedback control systems by using computer [11-16]. Therefore, it is more significant to extend the design method of SMC in continuous systems into the discrete-time control system. Nonetheless, especially the stability analysis and guarantee for the quality properties of fuzzy-system model based control designs are not easy to establish [17-18].

In this synergy based control study, the problem of T-S fuzzy model-based discrete-time sliding mode control for nonlinear system is explored. First studying global T-S fuzzy model and then transforming it into linear uncertain system model. Nonlinear system is remodeled by employing linear

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uncertain system model which come from T-S fuzzy model. SMC method is used to guarantee linear uncertain system robustly stable. In sliding surface design system uncertainties are considered in order to improve system robustness. The sufficient condition for the existence of stable sliding surface in terms of the Linear Matrix Inequalities (LMI) [24] is derived. Therefore the problem of designing sliding surface is indirectly transformed to the problem of solving linear matrix inequalities. Similarly, the design of sliding mode control law is transformed to a discrete-time approximate law method, which guarantees the global stability of closed-loop system. In this way, also chattering around the sliding surface in sliding mode control is being reduced by this design approach. Finally, simulation results for the bench-mark problem of the trailer-truck motion control demonstrate the feasibility and effectiveness of the proposed control design synthesis.

Further this paper is organized as follows. Section II briefly introduces construction of T-S fuzzy model for a class of uncertainty nonlinear discrete-time systems. In Section III, the sufficient condition for the existence of stable sliding surface derived in terms of LMI, and then the sliding mode control law,- which guarantees the global stability of the closed loop system. Simulation results for of the trailer-truck example are presented in section IV. Concluding remarks, the envisaged further research, and references follow thereafter.

II. Construction of T-S Fuzzy Model

Consider following class of nonlinear discrete-time systems:

$$x(k+1)=f(x(k),u(k),d(k)). \tag{1}$$

Notice in there symbols denotes: $x(k)\in\mathbb{R}^n$ is the state vector; $u(k)\in\mathbb{R}^m$ is the control input vector; $d(k)\in\mathbb{R}^q$ is the exterior disturbance vector; and $f(k)$ is nonlinear function which also may involve uncertainties. From the literature it is well known that it is impossible general nonlinear systems to be described by global model within the class of linear systems. It is also well known however, any nonlinear system can be represented by sum or series of local linear system models.

This fact has inspired the Takagi-Sugeno approach for nonlinear system (1) to be represented by fuzzy-rule based system representation of uncertainty nonlinear systems

R^i: If $x_1(k)$ is F_1^i and … and $x_n(k)$ is F_n^i, Then
$$x(k+1)=A_ix(k)+B_iu(k)+H_id(k) \quad i=1,2,\dots,l. \tag{2}$$

In here, symbols denote: $F_j^i\ (j=1\cdots n)$ is a fuzzy subset; l is the number of rules of this T–S fuzzy model; $\mathbb{R}^i$ denotes the ith rule of fuzzy system; A_i, B_i and H_i are the state, control input, and disturbance input appropriate-dimensions matrices corresponding to the ith subsystem. The defuzzified output of the T–S fuzzy system (2) is then inferred [1], [6], [23] as follows:

$$\begin{aligned}x(k+1)&=\frac{\sum_{i=1}^{l}\omega_i(x(k))(A_ix(k)+B_iu(k)+H_id(k))}{\sum_{i=1}^{l}\omega_i(k)}\\&=\sum_{i=1}^{l}\mu_i(x(k))(A_ix(k)+B_iu(k)+H_id(k))\end{aligned} \tag{3}$$

where

$$\omega_i(x(k))=\prod_{j=1}^{n}F_j^i(x_j(k)),$$
$$\mu_i(x(k))=\omega_i(x(k))\Big/\sum_{i=1}^{l}\omega_i(x(k)).$$

Because of

$$\omega_i(x(k))\geq 0,\quad \sum_{i=1}^{l}\omega_i(x(k))\geq 0,$$

The governing fuzzy properties appear as

$$0\leq\mu_i(x(k))\leq 1,\ \sum_{i=1}^{l}\mu_i(x(k))=1. \tag{4}$$

Thus nonlinear system (1) can be described by employing T-S fuzzy model (3).

From (4) we can also get:

$$\mu_j(x(k))=1-\sum_{i=1(i\neq j)}^{l}\mu_i(x(k)). \tag{5}$$

By substituting (5) into (3), T-S fuzzy model (3) can be rewritten in the following form:

$$\begin{aligned}x(k+1)=&\left(\mu_j(x)A_j+\sum_{i=1(i\neq j)}^{l}\mu_i(x)A_i\right)x(k)+\\&\left(\mu_j(x)B_j+\sum_{i=1(i\neq j)}^{l}\mu_i(x)B_i\right)u(k)+\sum_{i=1}^{l}\mu_i(x)H_id(k)\end{aligned} \tag{6}$$

Then defining the expressions

$$\Delta A_0=\sum_{i=1(i\neq j)}^{l}\mu_i(x)(A_i-A_j),\ \Delta B_0=\sum_{i=1(i\neq j)}^{l}\mu_i(x)(B_i-B_j),$$
$$H=\sum_{i=1}^{l}\mu_i(x)H_i,\ A_j=A_0,\ B_j=B_0.$$

yield

$$x(k+1)=(A_0+\Delta A_0)x(k)+(B_0+\Delta B_0)u(k)+Hd(k). \tag{7}$$

Thus, (7) can be seen as an uncertain linear system with nominal matrix A_0, B_0, uncertainties $\Delta A_0, \Delta B_0$ and exterior disturbance $d(k)$. Therefore, the stability problem of system (1) becomes the robust stabilization problem of system (7).

III. Design of Sliding Mode Control

The robust stabilization of uncertain linear system has been attracting much attention [9-16] in recent years hence many significant results have been obtained. Here in this study, the robust stabilization of uncertain linear system has been achieved by employing SMC method. If ΔA_0 is mismatched uncertainty, ΔB_0 and $Hd(k)$ are matched uncertainties in system dynamics (7), then the linear discrete-time uncertain system (7) can be rewritten in the following form

$$x(k+1)=(A+\Delta A)x(k)+B((I+\Delta B)u(k)+\Delta f(k)) \tag{8}$$

where: $x \in \mathbb{R}^n$ is the state vector; $u \in \mathbb{R}^m$ is control input; $\Delta(\cdot)$ denotes uncertainty and so are quantities $B\Delta B = \Delta B_0$, $B\Delta f(k) = Hd(k)$; while $\Delta A = \Delta A_0$. $A = A_0$, $B = B_0$ are known constant matrices with appropriate dimensions. Further, the following adopted assumptions are associated with the system (8).

Assumption 1: The pair (A, B) is controllable, and the input matrix B has full rank, wherein thus it is assumed $B = [B_1 \quad B_2]^T$ and $\det(B_2) \neq 0$.

Assumption 2: Uncertainties ΔA, ΔB and Δf are unknown but have finite Euclidean norms.

From Assumption 1 it follows that the pair (A, B) is the controllability guaranteeing pair, and thus there exists a linear nonsingular transformation

$$z = Mx = \begin{bmatrix} I_{n-m} & -B_1 B_2^{-1} \\ 0 & B_2^{-1} \end{bmatrix} x$$

which transforms the system dynamics (8) into its regular form

$$\begin{bmatrix} z_1(k+1) \\ z_2(k+1) \end{bmatrix} = (\bar{A} + \Delta\bar{A}) z(k) + \bar{B}(I + \Delta\bar{B}) u(k) + \bar{B}\Delta f. \quad (9)$$

That is, the following two equations emerge

$$z_1(k+1) = (A_{11} + \Delta A_{11}) z_1(k) + (A_{12} + \Delta A_{12}) z_2(k), \quad (10)$$

$$z_2(k+1) = (A_{21} + \Delta A_{21}) z_1(k) + (A_{22} + \Delta A_{22}) z_2(k) + + I_m((I + \Delta B_2) u + \Delta f_m), \quad (11)$$

where $z_1 \in \mathbb{R}^{n-m}$ and $z_2 \in \mathbb{R}^m$ are the state vectors, $\Delta(\cdot)$ denotes uncertainties the bounds of which are known.

A. Design of Sliding Surface using the LMI [24]

Traditional design methods of sliding surface include pole placement method and LQR method [9-10]. These methods design sliding surface based on nominal system, which do not possess robustness when system includes mismatched uncertainties. Many literatures have been developed to deal with the problem of designing stable sliding surface for continuous-time systems, Choi 1999 [11], 2003 [12], Kim 2005 [13], Edwards 2004 [14]. Though the literature that have been developed to deal with the problem of designing stable sliding surface for discrete-time systems are few still [3]. This study considers the plant system mismatched uncertainties in designing of discrete-time sliding surface based on [13], and presents a design method for discrete-time sliding surface by employing the LMI to yield improved system robustness.

The linear sliding surface is usually defined [3], [9] as

$$S(z) = Cz = 0$$

or, without loss of generality, as well as

$$S(z) = Cz = [-K \quad I_m] \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = 0, \quad (12)$$

where $C \in \mathbb{R}^{m \times n}$ and $K \in \mathbb{R}^{m \times (n-m)}$. In (12), I_m is $m \times m$ dimension identity matrix. In the sliding mode, $S(z) = Cz = 0$, then

$$z_2 = Kz_1. \quad (13)$$

Then seeing z_2 as dummy input of subsystem (10), substituting (13) into subsystem (10) yields

$$z_1(k+1) = (A_{11} + \Delta A_{11}) z_1(k) + (A_{12} + \Delta A_{12}) K z_1(k) \quad (14)$$

which is a reduced-order $(n-m)$-dynamics system. If the uncertainties in (14) satisfy matching condition, then ΔA_{11} and ΔA_{12} will not appear in Eq. (14). Further, because $(\bar{A}, \bar{B})$ is controllable, then (A_{11}, A_{12}) is controllable as well and the reduced-order subsystem (14) will be stabilized by choosing appropriate K and, at the same time, the sliding surface (12) has been designed.

If the uncertainties in (14) do not satisfy matching condition but ΔA and ΔB are norm-bounded quantities and have foreseeable structure, then the next assumption is well defined hence adopted too.

Assumption 3: Assume that

$$\Delta A_{11} = DF(k)E_1, \ \Delta A_{12} = DF(k)E_2, \quad (15)$$

where D, E_1 and E_2 are known real constant matrices of appropriate dimensions, and $F(k)$ is an unknown matrix function with Lebesque-measurable elements and satisfies $F^T(k)F(k) \leq I$, where I is the identity matrix.

Under the above assumptions, the sliding surface (12), which stabilizes the reduced-order system (14) in the presence of mismatched uncertainties, can be designed in terms of LMIs. In order to show the proof, the following two results of an important Lemma are recalled in here.

Lemma [8]: Given constant matrices D, E and a symmetric constant matrix Y of appropriate dimensions, the following inequality holds true

$$Y + DFE + E^T F^T D^T < 0,$$

where F satisfies $F^T F \leq R$, if and only if for some $\gamma > 0$,

$$Y + \begin{bmatrix} \gamma^{-1} E^T & \gamma D \end{bmatrix} \begin{bmatrix} R & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} \gamma^{-1} E \\ \gamma D^T \end{bmatrix} < 0$$

is satisfied.

The first main result on the asymptotic stability of the reduced-order system with mismatched uncertainties is summarized in the following theorem.

Theorem 1: If there exists a symmetric and positive definite matrix P, some matrix W and some scalar γ such that the following LMI (16) is satisfied

$$\begin{bmatrix} -X & * & * & * \\ A_{11}X + A_{12}W & -X & * & * \\ E_1X + E_2W & 0 & -\gamma I & * \\ 0 & \gamma D^T & 0 & -\gamma I \end{bmatrix} < 0, \tag{16}$$

where $X = P^{-1}$, $W = KP^{-1}$, and $*$ denotes the transposed elements in the symmetric positions. Then the reduced-order discrete-time system (14) is asymptotically stabilizable via the sliding mode surface (12).

Proof: Consider Lyapunov function candidate

$$V(k) = z_1^T(k)Pz_1(k), \tag{17}$$

where P is a positive definite symmetrical matrix. The difference of $V(k)$ is found as

$$\begin{aligned} \Delta V(k) &= V(k+1) - V(k) \\ &= z_1^T(k+1)Pz_1(k+1) - z_1^T(k)Pz_1(k). \end{aligned} \tag{18}$$

Substituting (14) into (18) yields

$$\begin{aligned} \Delta V(k) = z_1^T(k)&[A_{11} + A_{12}K + \Delta A_{11} + \Delta A_{12}K]^T \times \\ &P\left[A_{11} + A_{12}K + \Delta A_{11} + \Delta A_{12}K\right]z_1(k) - \\ &z_1^T(k)Pz_1(k). \end{aligned} \tag{19}$$

If the right hand of (19) is uniformly negative definite for all $z_1(k)$ and for all $k \ge 0$ except at $z_1(k) = 0$, then the reduced-order dynamics (14) is asymptotically stable about its zero-state equilibrium. Therefore, the following inequality is valid.

$$\begin{aligned} &(A_{11} + A_{12}K + \Delta A_{11} + \Delta A_{12}K)^T P \times \\ &(A_{11} + A_{12}K + \Delta A_{11} + \Delta A_{12}K) - P < 0. \end{aligned} \tag{20}$$

By applying Schur Complement Theorem [9] and Assumption 3 to (20), equations (20) are found equivalent to

$$\begin{aligned} &\begin{bmatrix} -P & * \\ (A_{11} + A_{12}K + \Delta A_{11} + \Delta A_{12}K) & -P^{-1} \end{bmatrix} \\ &= \Phi + \begin{bmatrix} 0 & * \\ DF(k)(E_1 + E_2K) & 0 \end{bmatrix} = \Phi + \begin{bmatrix} 0 \\ D \end{bmatrix} F(k)[E_1 + E_2K \quad 0] + \\ &+[E_1 + E_2K \quad 0]^T F^T(k) \begin{bmatrix} 0 \\ D \end{bmatrix}^T < 0. \end{aligned} \tag{21}$$

where

$$\Phi = \begin{bmatrix} -P & * \\ A_{11} + A_{12}K & -P^{-1} \end{bmatrix}.$$

According to Lemma 1, the matrix inequality (21) holds for all $F(k)$ which satisfies $F^T(k)F(k) \le I$ if and only if there exists a constant $\sqrt{\gamma} > 0$ such that

$$\Phi + \begin{bmatrix} (E_1 + E_2K)^T & 0 \\ 0 & D \end{bmatrix} \begin{bmatrix} \gamma^{-1}I & 0 \\ 0 & \gamma I \end{bmatrix} \times \begin{bmatrix} (E_1 + E_2K) & 0 \\ 0 & D^T \end{bmatrix} < 0. \tag{22}$$

Applying the Schur complement to (22) and taking the congruence transformation with $\mathrm{diag}\{P^{-1} \quad I \quad I \quad I\}$ do result in

$$\begin{bmatrix} -P^{-1} & * & * & * \\ A_{11}P^{-1} + A_{12}KP^{-1} & -P^{-1} & * & * \\ E_1P^{-1} + E_2KP^{-1} & 0 & -\gamma I & * \\ 0 & D^T & 0 & -\gamma^{-1}I \end{bmatrix} < 0. \tag{23}$$

Denoting as $X = P^{-1}$, $W = KP^{-1}$ and taking the congruence transformation with $\mathrm{diag}\{I \quad I \quad I \quad \gamma I\}$ yield (16).

Notice the LMI task [24] is readily solved by using the LMI Toolbox of the MathWorks [25].

B. Design of sliding mode controller

In the previous section, when the uncertain system (9) was in the sliding mode, the sliding mode surface was designed to guarantee the asymptotic stability of the reduced order system in terms of LMIs. Next, we should find feedback control law $u(k)$ to drive system state trajectories to arrive at the switch band in limit time and thereafter maintain in the switch band. This means that the control law is designed to guarantee system satisfy the reaching condition. For system (9), employing discrete-time approximate law method [9] we can get sliding mode control law:

$$\begin{aligned} u(k) = &-(C\overline{B}(I + \Delta\overline{B}))^{-1}[C\overline{A}z(k) - Cz(k) + \\ &TqCz(k) + \varepsilon T \operatorname{sgn} S(k) + C\Delta\overline{A}z(k) + C\overline{B}\Delta f_m(k). \end{aligned} \tag{24}$$

Where T is sampling period, $q \in \mathbb{R}^{m\times m}$ and $\varepsilon \in \mathbb{R}^{m\times m}$ are some diagonal matrices respectively with the entries $\varepsilon_i > 0$, $q_i > 0$ $\forall\, i = 1\cdots m$. $0 < (1 - q_iT) < 1$, $\forall\, i = 1\cdots m$ is satisfied also, and thus

$$S(k) = \begin{bmatrix} s_1(k) \\ \vdots \\ s_m(k) \end{bmatrix}, \quad \operatorname{sgn} S(k) = \begin{bmatrix} \operatorname{sgn} s_1(k) \\ \vdots \\ \operatorname{sgn} s_m(k) \end{bmatrix}.$$

Because in (24) there exist uncertain items, this control law cannot be realized in practice. It is necessary to construct a certain control law $u(k)$, adequate to (24) which can guarantee the systems with uncertainties still be robust stabilized. For sake of simplicity, it is assume $\Delta B = 0$ in here, which is realistic since matrix B reflects on known actuators. From Assumption 2 it is known that $\Delta\overline{A}$ and $\Delta f_m(k)$ are bounded. Thus, suppose [9] their upper bound and lower bound are known as follows

$$\begin{aligned} Q_{\min} &\le C\Delta\overline{A}z(k) \le Q_{\max}, \\ W_{\min} &\le \Delta f_m(k) \le W_{\max}, \end{aligned} \tag{25}$$

defining:

$$
\begin{aligned}
&Q_1 = \frac{1}{2}(Q_{\max} + Q_{\min}) \\
&Q_2 = \frac{1}{2}(Q_{\max} - Q_{\min}) = [Q_{21} \quad \cdots \quad Q_{2m}]^T \\
&\bar{Q} = \operatorname{diag}[Q_{21} \quad \cdots \quad Q_{2m}] \\
&W_1 = \frac{1}{2}(W_{\max} + W_{\min}) \\
&W_2 = \frac{1}{2}(W_{\max} - W_{\min}) = [W_{21} \quad \cdots \quad W_{2m}]^T \\
&\bar{W} = \operatorname{diag}\{W_{21} \quad \cdots \quad W_{2m}\}.
\end{aligned} \tag{26}
$$

From above we can get the following theorem:

Theorem 2: For the system (9) satisfying Assumption 2, the following control law is considered:

$$
\begin{aligned}
u(k) = -(C\bar{B})^{-1}\big[&C\bar{A}z(k) - Cz(k) + TqCz(k) + \\
&\varepsilon T\|z(k)\|\operatorname{sgn}Cz(k) + Q_1 + \bar{Q}\operatorname{sgn}Cz(k) + \\
&C\bar{B}(W_1 + \bar{W}\operatorname{sgn}Cz(k))\big],
\end{aligned} \tag{27}
$$

where T, ε, q, S are same as in (24), and the definitions of $Q_1, \bar{Q}, W, \bar{W}$ are in (26). Then the system (9) does satisfy the reaching condition of sliding mode [9].

Proof: The design of sliding-mode controllers for uncertain discrete-time systems must guarantee system dynamics reach switch band in the limited time and when the uncertainties in systems are changed, should assure reaching condition also be satisfied. For this purpose an reinforced inequality reaching condition based on in reference [9] is proposed as follows:

$$
\begin{aligned}
&S(k+1) - S(k) \le -\varepsilon T\|z(k)\|\operatorname{sgn}S(k) - qTS(k), \quad S(k) > 0; \\
&S(k+1) - S(k) \ge -\varepsilon T\|z(k)\|\operatorname{sgn}S(k) - qTS(k), \quad S(k) < 0.
\end{aligned} \tag{28}
$$

Note that in (28) term $\|z(k)\|$ is added, and thus there is $\|z(k)\|$ in control law (27), the purpose of which is to reduce the chattering around sliding surface. The simulation results will show this effect clearly.

Further, it is fairly easy to prove that:

$$
\begin{aligned}
&C\Delta\bar{A}z(k) \le Q_1 + \bar{Q}\operatorname{sgn}S(k), && S(k) > 0 \\
&C\Delta\bar{A}z(k) \ge Q_1 + \bar{Q}\operatorname{sgn}S(k), && S(k) < 0 \\
&\Delta f_m(k) \le W_1 + \bar{W}\operatorname{sgn}S(k), && S(k) > 0 \\
&\Delta f_m(k) \ge W_1 + \bar{W}\operatorname{sgn}S(k), && S(k) < 0
\end{aligned} \tag{29}
$$

From (9), (28) and (29) one can obtain the following formula:

$$
\begin{aligned}
&S(k+1) - S(k) = Cz(k+1) - Cz(k) \\
&= C\bar{A}z(k) + C\Delta\bar{A}z(k) + C\bar{B}(u(k) + \Delta f_m(k)) - Cz(k) \\
&= C\bar{A}z(k) + C\Delta\bar{A}z(k) + C\bar{B}\Delta f_m(k) - Cz(k) - C\bar{B}(C\bar{B})^{-1}[C\bar{A}z(k) - \\
&\quad Cz(k) + TqCz(k) + \varepsilon T\|z(k)\|\operatorname{sgn}Cz(k) + Q_1 + \bar{Q}\operatorname{sgn}Cz(k) + \\
&\quad C\bar{B}(W_1 + \bar{W}\operatorname{sgn}Cz(k))] \\
&= -TqCz(k) - \varepsilon T\|z(k)\|\operatorname{sgn}Cz(k) + [C\Delta\bar{A}z(k) - Q_1 - \\
&\quad \bar{Q}\operatorname{sgn}Cz(k)] + C\bar{B}[\Delta f_m(k) - (W_1 + \bar{W}\operatorname{sgn}Cz(k))].
\end{aligned}
$$

From (12), then one obtains $C\bar{B} = I_m$ and thus also:

$$
\begin{aligned}
&S(k+1) - S(k) = Cz(k+1) - Cz(k) \\
&\begin{cases}
\le -\varepsilon T\|z(k)\|\operatorname{sgn}S(k) - qTS(k) \le 0, & S(k) > 0 \\
\ge -\varepsilon T\|z(k)\|\operatorname{sgn}S(k) - qTS(k) \ge 0, & S(k) < 0
\end{cases}
\end{aligned}
$$

It is therefore that system (9) satisfies reaching condition (28).

IV. Simulation Study

To illustrate the effectiveness of proposed approach, the benchmark control problem of trailer-truck docking motion control is considered. A discrete-time nonlinear kinematic model of the truck-trailer [6] is considered as follows:

$$
\begin{aligned}
&x_1(k+1) = (1 - v\frac{k}{L})x_1(k) + v\frac{k}{l}u(k), \\
&x_2(k+1) = x_2(k) + v\frac{k}{L}x_1(k), \\
&x_3(k+1) = x_3(k) + vk\sin(x_2(k) + v\frac{k}{2L}x_1(k)),
\end{aligned}
$$

In here: l is the length of the truck; L is the length of the trailer; k is the sampling time-instant; and v is the constant speed of the backward movement.

This system can be presented as following T-S model:

Rule1: If $z(k) = x_2(k) + \frac{vk}{2L}x_1(k)$ is about 0 *[rad]*,

Then $x(k+1) = A_1x(k) + B_1u(k)$;

Rule2: If $z(k) = x_2(k) + \frac{vk}{2L}x_1(k)$ is about $\pm\pi$ *[rad]*,

Then $x(k+1) = A_2x(k) + B_2u(k)$.

where $v = -0.1m/\sec$, $l = 0.087m$, $L = 0.13m$, $k = 0.5\sec$, and g= $0.106/\pi$. In addition, also there are:

$$
A_1 = \begin{bmatrix} 1 - \frac{vk}{L} & 0 & 0 \\ \frac{vk}{L} & 1 & 0 \\ \frac{(vk)^2}{2L} & vk & 1 \end{bmatrix} = \begin{bmatrix} 1.3846 & 0 & 0 \\ -0.3846 & 1 & 0 \\ 0.009615 & -0.05 & 1 \end{bmatrix},
$$

$$
B_1 = \begin{bmatrix} \frac{vk}{L} & 0 & 0 \end{bmatrix}^T = \begin{bmatrix} -0.5747 & 0 & 0 \end{bmatrix}^T,
$$

$$
A_2 = \begin{bmatrix} 1 - \frac{vk}{L} & 0 & 0 \\ \frac{vk}{L} & 1 & 0 \\ \frac{g(vk)^2}{2L} & gvk & 1 \end{bmatrix} = \begin{bmatrix} 1.3846 & 0 & 0 \\ -0.3846 & 1 & 0 \\ 0.00032458 & -0.001688 & 0 \end{bmatrix},
$$

$$
B_2 = B_1 = [-0.5747 \quad 0 \quad 0]^T.
$$

The membership function is chosen as follows:

$$\mu_1(z(k))=(1-\frac{1}{1+\exp\{-3[z(k)-\frac{\pi}{2}]\}})\times\frac{1}{1+\exp\{-3[z(k)+\frac{\pi}{2}]\}},$$

$$\mu_2(z(k))=1-\mu_1(z(k)),\ z(k)=x_2(k)+v\tfrac{\bar{k}}{2L}x_1(k).$$

Then global fuzzy T-S model can be obtained as follows:

$$x(k+1)=\mu_1(A_1x(k)+B_1u(k))+\mu_2(A_2x(k)+B_2u(k)).$$

According to (7), above T-S fuzzy model can be transformed into linear uncertain system model as follows:

$$x(k+1)=(A_1+\Delta A)x(k)+(B_1+\Delta B)u(k),$$

where

$$\Delta A=\mu_2(A_2-A_1)=\mu_2\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ -0.00929 & 0.0483 & 0\end{bmatrix},$$

$$\Delta B=\mu_2(B_2-B_1)=0$$

Taking the transforming matrix as

$$M=\begin{bmatrix}0 & 0 & 1\\ 0 & 1 & 0\\ -1.74 & 0 & 0\end{bmatrix},$$

yields

$$\bar{B}=MB=[0\quad 0\quad 1]^T,$$

$$\bar{A}=MA_1M^{-1}=\begin{bmatrix}1 & -0.05 & -0.0055\\ 0 & 1 & 0.221\\ 0 & 0 & 1.3846\end{bmatrix},$$

$$\Delta\bar{A}=M\Delta AM^{-1}=\mu_2\left[\begin{array}{cc|c}0 & 0.048 & 0.0053\\ 0 & 0 & 0\\ \hline 0 & 0 & 0\end{array}\right]$$

$$=\left[\begin{array}{c|c}\Delta A_{11} & \Delta A_{12}\\ \hline \Delta A_{21} & \Delta A_{22}\end{array}\right],$$

$$\Delta A_{11}(k)=DF(k)E_1=\mu_2\begin{bmatrix}0 & 0.048\\ 0 & 0\end{bmatrix},$$

$$\Delta A_{12}(k)=DF(k)E_2=\mu_2\begin{bmatrix}0.0053\\ 0\end{bmatrix},$$

where $F(k)=\mu_2(k),\quad 0\le\mu_2(k)\le 1$, and $F^T(k)F(k)\le 1$ is satisfied.

Further, following (12), it can be readily can calculated

$$C=[-K\quad I]=[-17.3061\quad 8.8775\quad 1.0000].$$

The control law (27), where there are

$$Q_{\min}=0,\quad Q_1=\bar{Q}=0.0246\|x(k)\|$$

upon taking $1-Tq=0.5,\quad T=0.5,\quad \varepsilon T=0.5$, has been employed in the

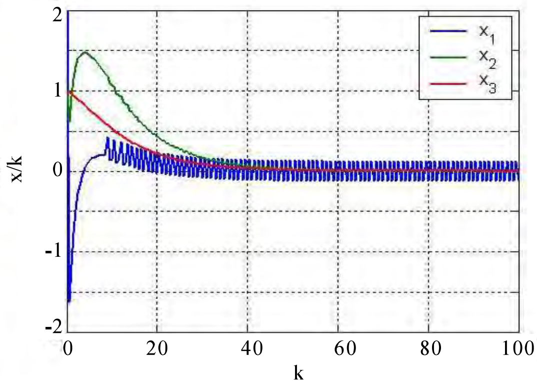

Fig. 1 Plant state responses with no $\|z(k)\|$ in control (27)

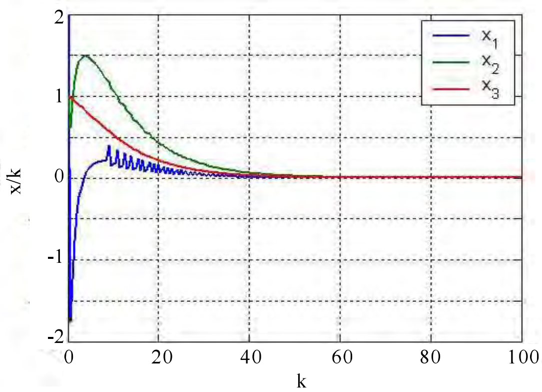

Fig.2 Plants state responses under control law (27)

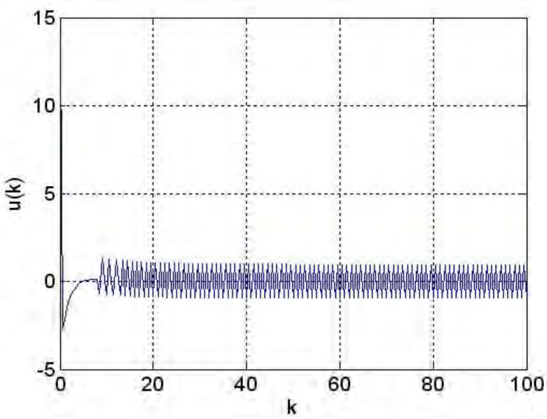

Fig.3 Plant system control input $u(k)$ with no $\|z(k)\|$ in control law (27)

closed-loop motion control of the truck-trailer plant [6]. Simulation results with initial state vector $x(0)=[2\quad 1\quad 1]^T$ are shown in Figures 1, 2 and 3.

Figures 1 and 3 present the system state responses and control input $u(k)$ with no $\|z(k)\|$ in control law (27). While Figures 2 and 4 present the system state responses and control input $u(k)$ with the proposed sliding control law (27). Apparently, from these simulation results it can concluded both statements:

(i) motion of the truck-trailer is stabilized quickly; and

(ii) chattering around the sliding surface obviously is being considerably reduced by adding term $\|z(k)\|$ in the reaching condition (28).

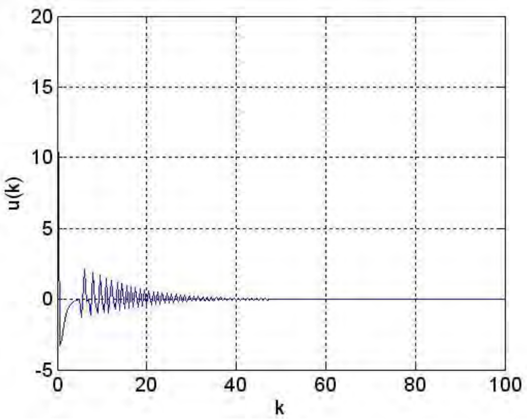

Fig.4 Plant system control input $u(k)$ with control law (27)

Thus the simulation results confirmed on the benchmark truck-trailer motion control the proposed discrete-time hybrid-control scheme is not only feasible but rather effective in controlling complicated nonlinear system dynamics. Furthermore, it has also demonstrated that the phenomenon of chattering, which accompanies the sliding-mode control strategy, has been reasonably ameliorated in the truck-trailer motion control.

V. CONCLUDING REMARKS

This paper proposes another control design technique for nonlinear control systems of complex plants possessing uncertainties. A linear uncertain system model is used to describe nonlinear plant dynamics. Thus the stability problem of nonlinear systems becomes the robust stabilization problem of linear uncertain dynamical systems. Discrete-time sliding mode control approach is employed in order to guarantee robust stabilization of linear uncertain plant system.

The design of sliding mode controller is presented, which drives system state trajectories to arrive at the switch band in limit time and thereafter maintain in the switch band and the chattering around sliding surface is reduced effectively also. In design of sliding surface mismatched uncertainties were considered in order to improve system robustness. The stable sliding surface is readily designed by solving linear matrix inequalities by means of the LMI toolbox of Matlab [25].

It should be noted however, simulation experiments have also shown that when uncertainties appear to be very large, the feasible solution for linear matrix inequalities may not be obtained [17]. Then other approaches like adaptive fuzzy tracking control [18], [20] and robust H-inf control under arbitrary switching [19], [21] should be employed.

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Machine Learning 2
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Artificial Intelligence architectural, regulatory and business framework for telecom networks

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***Abstract*—The new level of complexity introduced in the IMT-2020 networks, has revolutionized the concept of designing, operation and maintenance of telecommunication systems. Relying solely on human intervention is no longer feasible, making AI/ML models indispensable part of every architecture. The paper concentrates on three main enablers for AI/ML efficient deployment. It presents the AI/ML architectural frameworks introduced by ITU-T and ETSI, which are essential as a basis for technological development, deployment and interoperability. The business profitability of AI/ML implementation has been established through numerous industry collaborations and practical deployments by telecommunications operators. Statistical reports point the downward trend in CAPEX and OPEX expenses, in parallel with increased revenue growth and improved customer satisfaction scores. Furthermore, the paper explores the legislative landscape governing AI in telecommunications. The EU's AI Act, along with regulatory initiatives in the USA and China, emphasizes ethical standards and security measures, ensuring responsible and secure AI deployment.**

Keywords—AI, ENI, ETSI, EU's AI Act, IMT-2020, ITU, ML

I. INTRODUCTION

The concept of next-generation networks, introduced through the presentation of 6G, brings about significant innovations and increased complexity in their development, deployment, and maintenance [1]. In addition, to the standard requirements for increased data throughput and reduced latency , which are inherent to each network generation, IMT-2020 concept introduces native heterogeneity in the access network (AN), personalization of services and complex procedures for QoS management. The introduced level of complexity is too great for network operation and management (OAM) to rely solely on human intervention. The concept of abstracting complexity and improving performance is inherent to AI/ML models. The significant advancement of these models in recent years has popularized their usage, making them an indispensable part of every technological development framework. There are already practical and theoretical implementations of AI models in various segments of telecommunications networks. Furthermore, the readiness of operators and vendors to implement AI/ML in next-generation networks can be observed from the presented whitepapers [2]-[4]. Consequently, this leads to a significant reduction in CAPEX and OPEX costs for OAM. Forecast analysis predict a Compound Annual Growth Rate (CAGR) of 41.4% throughout the upcoming decade from 2022 to 2031. The most recent survey conducted by NVIDIA regarding AI's impact in the telecommunications sector, reports that a significant 56% of the respondents recognize the pivotal importance of AI in their business achievements, with an overwhelming 90% already actively involved in the deployment of AI technologies [5]. Business use-cases and the development of user applications are the primary drivers of technological demands. The survey ranks customer experience as the primary reason for AI adoption, at 48%, followed by the drive for expense reduction at 35%. Company reports for AI functionalities implementation demonstrate revenue increase and downturn in expenses. The predicted ROI is approximately five years.

In order to have successful and effective deployment of AI/ML functions in the telecommunication networks, a standardization framework must be constructed. This is crucial for providing interoperability and continuity among different vendors. To cope with this challenge, ITU-T and ETSI already issued several recommendations, suggesting architectural frameworks which encompass QoS management, QoS-QoE translation, definition of internal and external interfaces, resource and fault management and etc. ITU-T presented their recommendations in the Y series – ITU-T Y.3115 [6], ITU-T Y.3170 [7], ITU-T Y.3172 [8], ITU-T Y.3177 [9], ITU-T Y.3182 [10] and others. The heart of the recommendations lies in the architectural framework described in ITU-T Y.3172. In parallel, ETSI introduced the Experimental Networked Intelligence Industry Specification Group (ENI ISG) and its AI architectural framework named by the group – Experimental Networked Intelligence (ENI) [11]. The recommended architecture and the internal/external interfaces are depicted through several documents: ENI ETSI 002 [12], ENI ETSI 003 [13], ENI ETSI 004 [14] and ENI ETSI 005 [15]. The following in the sequence is ENI ETSI 006 [16], representing a Proof of Concept framework. The aim of the last segment is to provide a technical feasibility study of the proposed solutions in practical environment. To date, 22 PoCs have been conducted with successful results [17].

However, the implementation of the AI/ML functions in the architectural framework of the new-generation networks comes with many security issues and considerations. The pillars of AI/ML models operation are the data sets and their integrity. The telecommunication systems are described as critical infrastructure, which operates based on sensitive personal data, and data linked to one's behavior and preferences. Given that,

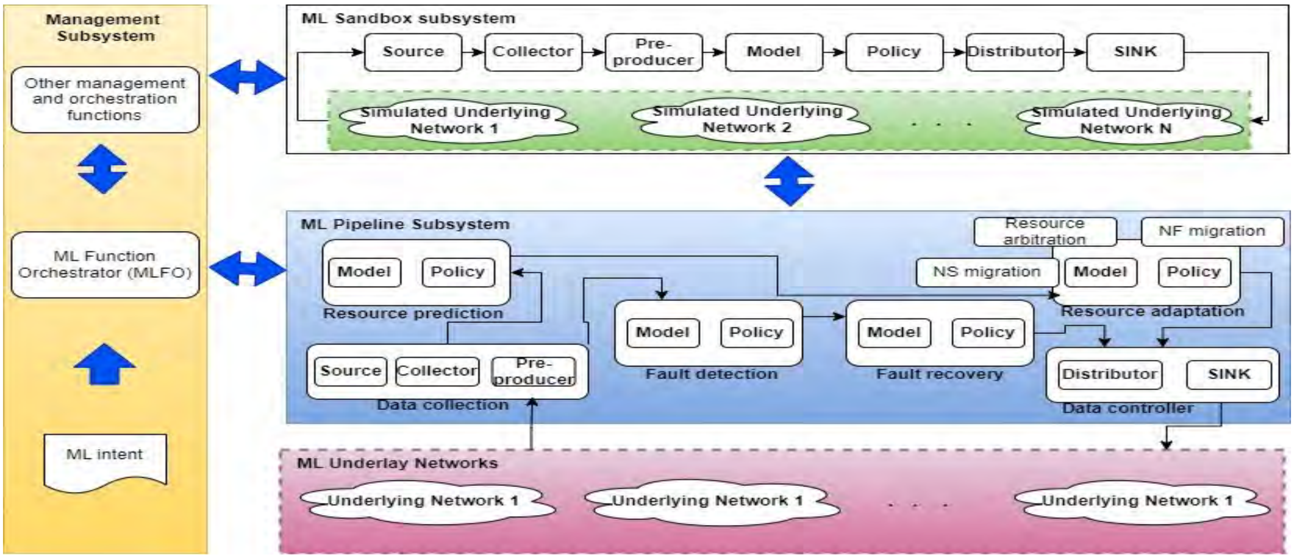

Fig. 1 ITU-T Y.3177 framework recommendation for Resource and Fault management

the data sets must be handle with utmost care, implementing security mechanisms which will guarantee the privacy of the individuals in compliance with General Data Protection Regulation (GPDR). The EU introduced the most detailed and comprehensive legislative framework - AI Act, covering numerous aspects of the AI integration and implementation. The rest of the paper is organized as follows. Section II describes the ITU-T and ETSI architectural frameworks, which form the basis for integration of AI/ML functions in the telecommunication networks.Section III presents the business use cases, practical AI implementations and the reported results and forecasted trends. Section IV presents the different legislative directions, placing security and safety frames for implementation of the AI/ML models. Finally, Section V concludes the paper.

II. ITU-T AND ETSI AI ARCHITECTURAL FRAMEWORKS

Networks from the new-generation are natively heterogenic with variety of AN technologies and QoS requirements, which translate in different demands and interfaces in the core network, thus forming the network slicing architecture. As described before, AI/ML functions are incorporated in the classical telco architecture for the mitigation of the introduced complexity.

A. ITU-T Y series AI/ML Framework

ITU-T Y.3115 provides a high-level description of the different domains in the telecommunication network [6]. A domain is defined as a set of entities that are physically or logically connected for a given purpose. At the top of the architecture is the Business Management domain, which is responsible for direct communication with customers and monitoring SLA levels. This serves as the bridge between customer experience lingo and network orchestration and management parameters. Next in line is the Network service O&M domain, accountable for end-to-end network service control. Following this is the Network management layer, which consists of multiple Management domains, usually representing different network segments such as the access network (AN), core network (CN), and transport network. Lastly, the Network function layer usually encompasses multiple domains referring to different network segments. This level is characterized by intra-layer and inter-domain interaction.

Going from top to bottom, ITU-T Y.3170 specifies high-level and functional requirements for QoS assurance in ML integrated networks [7]. The model suggest that QoS data of all network segments (UE, AN, CN) should be collected and pre-processed, before the ML models can derive QoS anomaly detection and anomaly prediction. Given the output, the QoS policy decisions are enforced on management and user plane accordingly.

ITU-T Y.3172 outlines the challenges for AI/ML integration in four categories: managing network heterogeneity, unifying the development roadmap between network and ML functions, cost-effective and seamless integration in telco network architecture and minimizing the impact on O&M procedures [8]. In order to address the potential issues and to create an interoperability platform, the recommendation specifies a generalized architectural framework defined on the premises of five key enablers - enablers for data correlation sourced from technological heterogeneity, enablers for deployment, requirements related to interaction between interfaces of different architectural components, requirements for declarative language specifications and management requirements for architectural components.

As described before, the multi-domain approach requires a support of data correlation between data sets originating from different domains in the network. This is due to the multi-level dependencies of a given parameter linked with different network functions (NFs) deployed in separate network segments. Additionally, the ML architecture should support distributed instantiation of ML functionalities and data transfers between domains, as required. In addition, this aligns with the requirements from deployment enablers, which suggest flexible architecture where the ML function

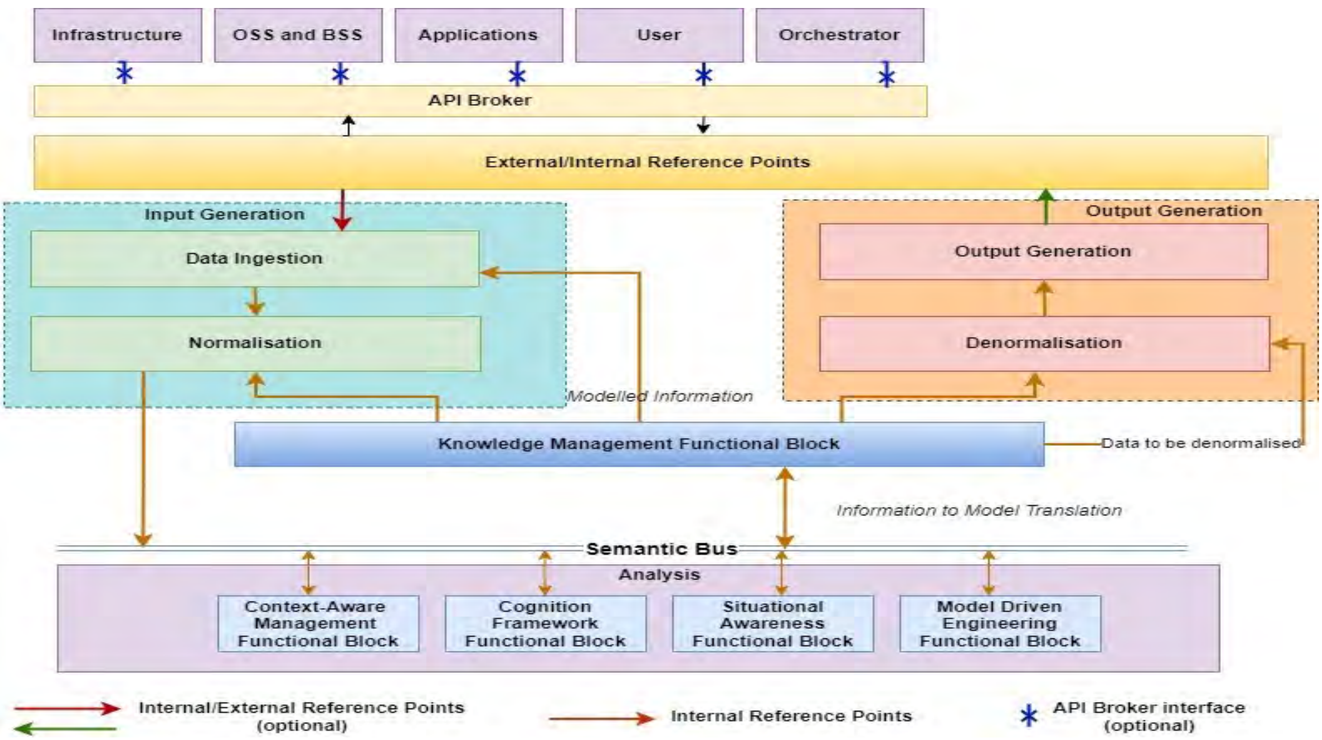

Fig. 2 ETSI ENI Architectural Framework

placements is dependent on resources and parameter constraints. This introduces a transparence between data sources and ML functions deployment.

The framework creation is induced from the interoperability and compatibility challenges. Different segments of the network can be deployed from different vendors and additionally different services demand different inter-domains interaction. As a result, the recommendation suggest a declarative specification, which will make the underlay network architecture agnostic of the serving ML applications. The ML architecture should provide dynamic specification of data sources, ML models, output targets and parameter constraints.

Finally, the management requirements are placed in order to ensure network stability, performance monitoring, resource orchestration, fault detection and legislative compliance.

Training, updating and scaling interventions performed in the ML domain, should be completely transparent to the live network. These requirements are sublimed and illustrated in their intrinsic form in Figure 1 (ML Sandbox subsystem block).

One of the most emphasized and important management feature, aiming at efficient O&M and contorolled implementation of regulatory legislation is presented as fault and recovery function in ITU-T Y.3177 recommendation [10]. All of the presented blocks adhere to the All of the outlined components conform to the architectural prerequisites outlined in ITU-T Y.3172 – Figure 1. On highest level, the model is divided in two pipelines – Resource management and Fault management pipelines. The sandbox is a crucial part of the framework, used for simulation and improvement of the ML model. It is particularly vital for Fault Management as the anticipated number of faults at the production level is not suitable for training and refinement. As illustrated, the Fault Management consists of two functions – fault detection and fault recovery. The efficiency of this pipeline is greatly determined of the simulation sandbox data. The Resource Management pipeline is divided between resource prediction and resource adaptation. The first is used for data gathering and AI/ML prediction to guide resource allocation strategies. The latter is presented through multistage decision function aiming at optimal resource slicing and it can be carried in reactive or proactive manner. It involves resource arbitration (optimal resource allocation across network slices), network function migration (efficient migration of vNFs/cNFs) and network slice reconfiguration (scaling physical nodes).

B. *ETSI ENI framework*

Parallel to the recommendations presented by ITU-T, ETSI derived the ENI architectural framework, providing unified, distributed platform using AI/ML functions to address next-generation network issues [15]. It is designed as a policy-driven closed-loop model, with dynamical network adaptation on changing inputs. Unlike ITU's modular architecture, ENI is designed as an isolated segment with an API interface for the external systems or functions. The later are termed as Assisted System (AS). ENI operates in two modes – "recommendation mode" for suggesting actions and "management mode" for issuing command. There is a possibility for a hybrid mode. The architecture, illustrated in Figure 2, consists of three blocks. The fist block, input processing, includes two functions – data ingestion and normalization. Data ingestion is responsible for collection and preprocessing of data from various sources, while the normalization function ensures that the data format is compatible with ENI's internal system. The second block, analysis is divided among several functions. Knowledge management function utilizes mathematical models for representing facts and information entropy. The Context Aware Management function derives rules for a subset of entities in the AS based on the current state. The brain of the ENI system is the context management function, which interprets processed data, considering context and objectives. Real time monitoring of the environment and decision making based on triggers is performed by the Situational Awareness function. The translation from decisions to recommendations or commands suitable for the external AS is performed by the Model-Driven Engineering function. Finally, The Output Generation block consists of deformalizing and output generation, performing invers operations to those defined in the Input Processing.

III. Standardization and Regulation

With the exploding popularity and widespread of AI, the regulatory bodies across the world started to focus their attention to the standardization and regulation of the usage of such models.

In April 2021, the European Commission proposed the 1st European regulatory framework for AI. After period of 2 years, in December 2023, and agreement for AI framework was reached with the member states of the European Parliament [18]. This resulted with official final adoption of the EU AI Act on 13 March 2024. The act is categorizing the AI usage in four categories: unacceptable (banned use – Art.5), high risk (Art.5 and Art.6), limited risk and minimal risk. The Act defines administrative fines, for non-compliance with the prohibition of AI practices referred to in Article 5 (Prohibited AI Practices) [19].

In the USA, there is AI regulative but mainly it is defined on state level, i.e. no strict regulation is imposed on federal level. According to Stanford University, between 2016 and 2022, 14 states passed legislation. . However, on federal level only 9 AI legislations passed out of 88 proposed [20]. An important step towards the AI regulative was the executive order (EO) on the "Safe, Secure, and Trustworthy Development and Use of AI" issued by US President Joe Biden on 30 October 2023 [21].

Chinese legislation is mainly divided in two segments – legislation for government AI systems and legislation for the private sector [22]. Government AI systems face looser restrictions, allowing practices like social scoring. In 2021 China issued the first act for regulation on recommendation algorithms, requiring alignment with social and ethical values and avoidance of inducing user addiction. On July 13, 2023, the Chinese government published the finalized rule for regulating Generative AI models. The document is named as "Interim Measures for Management of Generative Artificial Intelligence Services), which is effective as of August 15, 2023 [23].

Although the evidence suggests that regulations in the telecommunications sector will be largely similar, at the time of writing this paper, we will adhere to the well-defined parameters outlined in the EU's AI Act. With the definition of high-risk AI systems provided, it can be inferred that a significant portion of the envisioned use cases in telecommunications will fall into this category. The telecommunications are classified as critical digital infrastructure. The main business driver – "profiling" is considered as high-risk category, regarding Article III in the Act, referring to the definitions provided in Article 4, point (4) of Regulation (EU) 2016/679 or Article 3, point (4) of Directive (EU) 2016/680 or Article 3, point (5) of Regulation (EU) 2018/1725. The legislation about the radio equipment is specified under the category of critical infrastructure (Annex I, point (6)). Annex IV defines the need for a detailed documentations for the SW packages and the APIs which are part of the ML functionalities. The owners/provides of high-risk AI systems shall be responsible that their product is fully compliant with all of the requirements specified with the Union harmonization legislation, referenced in Section A of Annex I. The risk management system should be utilized as a measure of compliance for the high-risk AI systems, where testing is carried out against prior defined thresholds, parameters and metrics. Access of the ML functions to CRM system, CDR/EDR records, deep package inspection (DPI) systems and customer care systems (Chatbots) should be regulated and compliant in regards with Article 9(1) of Regulation (EU) 2016/679 and the Union of national law, if they specific use cases are not forbidden by the EU's Act. The risk management systems must be able to identify and cope with the risk of biased and discriminatory results based on the biometric data, such as social status, race, sex, ethnicity or disabilities. The data management should be in accordance with the General Data Protection Regulation ("GPDR"), introduced in 2016 [24]. The regulation states that processing of personal data is permitted only if there is a legitimate bases for the actions, such as consent from the data subject, contractual agreement or some of the points explicitly defined in Article 6 from the GPDR document. The chatbots used as a first line customer care service, are often designed as general-purpose AI systems (GPAIS). Due to the nature of these models, which implementation is not strictly linked to a specific purpose, there is a special design criteria regulation, specified in Annex XI and Annex XIII. Apart for the internal controls and risk management systems, the provider of ML functions is subjected to external control by the responsible regulatory body. Article 12 requires that every high-risk AI system must provide automatic record ('logs') keeping functionality, throughout their lifetime.

The presented regulation will shape the use cases and business models that will rely on AI systems. Moreover, it should ensure fair market competition and interoperability between the ML functions and network interfaces.

IV. Business – aims, opportunities and realizations

The main drivers behind every commercially available technology are the business use cases and opportunities. The emerging of the AI/ML models opened the doors for many new business models, profit avenues and savings. Many companies have already started implementation of such models in different segments of their networks and business portfolio, aligning with the forecasted growth. A plethora of potential use cases can already be found in numerous whitepapers and recommendations. The Body of European Regulators for

Electronic Communications (BEREC) classifies AI use cases into six main areas: network and capacity planning and upgrades; channel modeling, prediction, and propagation; dynamic spectrum sharing (DSS); quality of service (QoS) optimization and traffic classification; security optimization and threat detection; fraud detection and prevention [25]. While other whitepapers and reports may introduce different nomenclature, the grouping is generally consistent. The aforementioned classification is more formal and technical. The AI/ML services that can be presented closer to the end consumers are introduced through Customer Care services – chatbots and personalized content and application optimization through AI/ML.

Beginning with the RAN segment, Nokia and NVIDIA announced their collaboration to revolutionize technology which is a sublimation of Nokia Cloud RAN and NVIDIA powered AI [26]. NVIDIA Grace CPU Superchip for Layer 2+ processing will be used to enhance Nokia's energy efficient In-Line Layer 1 accelerator for the Cloud RAN segment. Additionally, NVIDIA GPUs will be used for AI applications and vRAN acceleration.

The intelligence and automation are equally important in the rest of the telecommunication network. The optimization can be executed separately in different segments of the network, but the ultimate goal is to achieve end-to-end service optimization. This is the only way to guarantee desirable level of QoS. This is termed as zero-touch operation. The first official group was formed by ETSI - Zero-Touch Network and Service Management (ZSM) in December 2017, consisting of many renewed telco companies: Nokia, Ericsson, NTT, Huawei, Amdocs, ZTE and many others [27], [28]. The idea behind the group was to create a framework and standardization, making the variety of vendor specific solutions interoperable. Nokia already reported an increased operational efficiency by 80% in a proof-of-concept exercise with one of the leading North American operators, while using Nokia's Self-Organizing Network software (SON). The software is ML driven and it is responsible for cognitive automation and orchestration in network, using concepts like clustering, classification and reinforcement learning. One of the most successful implementations of the concept is TANGO (Telco Advanced Next-Generation OSS) by SK Telecom, launched in April 2019 [29]. TANGO presents an AI-assisted network operating system, which provides total integrated OSS for operators. It aggregates data from different network segments, which are then correlated and analyzed in parallel, with the help of AI/ML models. The preliminary projection suggests that the CAPEX and OPEX incurred during the implementation of TANGO will be recouped within five years. Furthermore, a projected additional 40% reduction in costs is anticipated over the subsequent five years. In addition, the marker research report by POLARIS values zero-touch provisioning market at 2,772.13 million USD in 2022, with expected CAGR of 10.6%, reaching forecasted worth of 7,544.15 million USD by 2032 [30].

NTT and Huawei, among other leading companies, are spearheading the development of versatile language models designed to serve various applications across diverse sectors. These models bear resemblance to the well-known ChatGPT, offering similar capabilities in natural language understanding and generation across a wide range of applications. NTT announced the commercial availability of its proprietary Japanese LLM – "tsuzumi" aiming at operational efficiency and digital transformation, starting from March 2024 [31]. One of the primary features of NTT's model is its lightweight design. It is available in two versions: an ultra-lightweight version with parameter size of 600 million and a lightweight version with parameter size of 7 billion, which is only a fraction of the size of Open AI's GPT-3's, size of 175 billion. Its smaller size allows efficient single GPU or even CPU deployment, reducing training and maintenance costs, leading to faster ROI. "Tsuzumi" score of 81.3% on the Rakuda benchmark, surpasses GPT-3.5, making it suitable for customer care in telecommunications. On a different note, Huawei has introduced specialized models, NET4AI and AI4Net, designed for telecommunications [32]. NET4AI enables AI-as-a-service for next-gen networks, while AI4Net emphasizes intelligent operations to improve network performance, resource management, security, user experience, and privacy.

As previously presented, the aggressive implementation of AI/ML models and functionalities in the telecommunication networks not only ensures a technological evolution in line with the latest advancements, but also a reduction in CAPEX/OPEX expenses and revenue growth. According to GVR reports, the AI in telecommunication market size was valued at USD 1.45 billion in 2022 and it is forecasted with CAGR of 28.2% from 2023 to 2030 [33]. The largest revenue share, accounting for 34.8% in 2022, was in North America. However, the fastest CAGR in the aforementioned period is forecasted for the Asia Pacific region. The technological and economical investments in China and India are the main responsible factors for the growth. HAI-AI index report (2024) states that China dominates the AI patent scene, with 61.1% of all patents reported in 2022 [34]. USA comes in second place, with just 20.9%. However, the USA leads in investments in the private AI sector with $67.2 billion USD, which is approximately 8.7 times higher than China, the second highest investor in this segment. In general, according to the McKinsey survey, 42% of surveyed companies and organizations report cost reduction after implementing AI, and 59% report revenue increase [35]. Moreover, the adoption of AI, segmented by industry, shows the highest percentage – 44% in the category of product and/or service development within the technology, media, and telecom sectors. Additionally, the aforementioned sectors, along with financial services, emerged as clear leaders in the hiring of AI-related roles in 2023. Finally, the results from the Gtinux market data report (2024) suggest that AI/ML driven predictive maintenance can reduce 30-40% of the maintenance expenses for telecommunications companies [36]. The analytical capabilities provided by the AI models for behavior prediction based on customer data, can potentially reduce the churn rates by 10-15%. The conducted surveys show that more than 75% of the telecom companies will invest in AI systems in the following 3 years.

V. Conclusion

This paper presents a comprehensive examination of AI/ML initiatives within the development, operation, and maintenance procedures of telecommunication networks. With the imperative necessity to manage the complexity of IMT-2020 networks, standardization bodies such as ITU-T and ETSI are devising architectural frameworks that encompass all network segments, including AI/ML integration. These proposed frameworks outline methods for enforcing quality of service (QoS) and security policies, monitoring procedures and operations procedures. Regulatory efforts, exemplified by the EU's AI Act, the USA's Executive Order, and China's initiatives to regulate Generative AI, are aimed at designing a secure framework for ethical and responsible deployment of AI/ML. This is particularly crucial in the telecommunications sector, where the majority of AI/ML models operate with customers' personal and sensitive information, thereby categorizing them as high-risk systems. Integration of AI/ML models in telecommunications networks not only drives technological advancement but also reduces CAPEX/OPEX expenses and fosters revenue growth. As evidenced by market forecasts and industry case studies, these advancements not only enhance operational efficiency but also significantly improve customer experiences, positioning AI/ML technologies as pivotal drivers of innovation and profitability within the telecommunications sector.

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Bitcoin Price Prediction Using Machine Learning Algorithms

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Abstract— **Bitcoin, being the first decentralized digital cryptocurrency, has received significant attention and recognition, and it's now a popular stock market asset. However, precise price prediction is severely constrained by its high volatility and quick changes. Cryptocurrency prices have been predicted using traditional statistical and economic models, there is a growing need for more advanced and reliable prediction tools. This paper gives a comprehensive overview of machine learning and deep learning techniques in predicting Bitcoin prices. Our research emphasizes the improved accuracy and precision of Long Short-Term Memory models, leading to the use of multiple attributes and previous pricing to generate more accurate forecasts. By researching past, Bitcoin price data, the Long Short-Term Memory model can highlight important and relevant features that are utilized for developing more accurate predictions about future Bitcoin prices. An extensive dataset of Bitcoin prices was used to evaluate machine learning models and the results show the accuracy for predicting Bitcoin prices, resulting in high variance scores of 0.9544 for training and 0.9579 for testing. The conclusion of this paper indicated that Long Short-Term Memory machine learning models perform better than any other approaches. The Long Short-Term Memory model is used by investors and trading professionals to identify potential in the cryptocurrency market since this machine learning model can recognize persistent patterns in time series data.**

Keywords— Machine Learning (ML), Bitcoin prices, Long Short-Term Memory (LSTM)

I. Introduction

The financial ecosystem has changed tremendously over the last few years with the development and implementation of the newest technology based on cryptocurrency. Bitcoin was established as the first and most well-known digital currency. It was initially invented in 2008 by an individual known as Satoshi Nakamoto. Leveraging blockchain technology to provide security and transparency, Bitcoin is a peer-to-peer electronic payment software system that enables users to execute transactions without any requirement for third parties. Since its launch, Bitcoin has revolutionized the exchange of finances by enabling a global and decentralized network of transactions avoiding established banking institutions.

The significance of Bitcoin in the global financial system has increased along with its popularity. Bitcoin has since become a well-known payment method, accepted by both individual and institutional investors. Nonetheless, there is a lot of volatility in this market and prices can change quickly and without warning.

Several variables and factors, such as technical developments, economic and political events, could influence the unpredictability of the value of Bitcoin. In consideration of Bitcoin's unique qualities and the quickly modifying cryptocurrency ecosystem, traditional financial models frequently discover it hard to predict the price oscillations of the cryptocurrency. There is a more interest in using machine-learning techniques like recurrent neural networks and long short-term memory networks.

These deep learning models are suitable for forecasting the future value of Bitcoin because they are especially well-suited for analyzing the sequential and unpredictable nature of time-series data. Researchers can get significant insights into potential price patterns by using the effectiveness of these models, restricting the risks associated with Bitcoin's underlying unpredictability.

The rest of the paper is organized as follows: Section II summarizes the related work, Section III explains the experimental setup, and Section IV presents and elaborates the results, while Section V concludes the paper.

II. Related work

Bitcoin's highly volatile nature, driven by various factors including political and economic changes, makes precise price predictions challenging. Numerous studies have utilized machine learning techniques, especially LSTM networks, which are outstanding at handling dependencies in time-series data, to address these kinds of problems. These models from different research projects use historical data and other indicators in an effort to generate more precise Bitcoin price predictions and help in creating profitable trading strategies.

The authors in [1] attempts to develop a model for forecasting for Bitcoin values using LSTM networks, a type of RNN. Bitcoin's high volatility, which is impacted by many previously unidentified variables such as political and economic changes, makes precise forecasting difficult.

Considering LSTM is so pleasant at handling dependencies that persist in time-series data, it is employed in this study. Although the Root Mean Square Error (RMSE) indicates that the model predicts Bitcoin prices rather precisely, it remains subject to enhancement. With the goal to better account for the inherent uncertainties and increase prediction accuracy, subsequent work seeks to modify the model through changes to LSTM layers, including dropout techniques, optimizing the number of epochs, and investigating sentiment evaluation.

Bitcoin's distributed nature makes it an internationally recognized payment mechanism, but its extreme volatility raises challenges for investors [2]. Using Recurrent Neural Networks and Long Short-Term Memory algorithms, this research attempts to forecast Bitcoin prices. Using an analysis of sequential information from the Kraken exchange, such as volume of transactions, hashing rate, and Google search trends, the research demonstrates how accurately these models expect changes in the price of Bitcoin. Preprocessing and cleaning data ensures accuracy before training and testing the models. The results provide valuable information about important factors that contribute and predict future pricing movements. In the future, the model will be enhanced by expanding the dataset, investigating alternative neural network architectures, integrating additional variables, applying the model for other crypto currencies, and creating the best trading strategies for dealing with Bitcoin's volatility.

III. Experimental Setup

A. Dataset Analysis

` Time-series data is composed of observations or measurements gathered in consecutive order across time. These observations record daily Bitcoin trading data in the dataset represented in Fig. *1*, each row is an overview of different trade parameters for a single day. This type of data is critical for studying trends, and patterns, and forecasting future values based on past behavior.

attribute	*description*
date	The specific day the data was recorded.
open	The price of Bitcoin at the start of the trading day
high	The highest price that Bitcoin reached during the trading day.
low	The lowest price that Bitcoin fell to during the trading day.
close	The price of Bitcoin at the end of the trading day.
Adjusted close	The closing price adjusted for any corporate actions like dividends, stock splits, etc.
volume	The total number of Bitcoin units traded during the day.

Fig. 1 Dataset analysis

The "Date" attribute serves as the temporal basis, enabling the long-term tracking of Bitcoin's price and volume. This temporal component is critical for evaluating trends, seasonal patterns, and sudden shifts in Bitcoin's behavior. At the start of each trading day, the "Open" price reveals the first sense of the market. The "High" price shows peak activity within a day, displaying the highest price that traders were prepared to pay for Bitcoin, indicating the highest moment of demand. As a representation of high daily volatility, the "Low" price denotes the lowest point of market confidence. This is important information for comprehending risk and possible fluctuations in prices. The "Adjusted Close" ensures consistency in financial analysis by regularly matching the closing price. The "Volume" data shows how active the market is on a particular day, large volumes are frequently caused by major events in the market.

B. Dataset Visualization

a. Analysis of Year 2016

Both visualizations analyze stock prices month by month across many measures, providing valuable information into the stock's behavior over the year. The first graph on Fig. *2* compares the stock's opening and closing prices by month, with blue bars representing opening prices and orange bars showing closing values. In most months, the closing price is slightly higher than the opening price, indicating that the stock's worth increased as the month progressed. Additionally, June, July, and December had significantly higher starting and closing prices than other months, implying increased trading activity happenings during these periods.

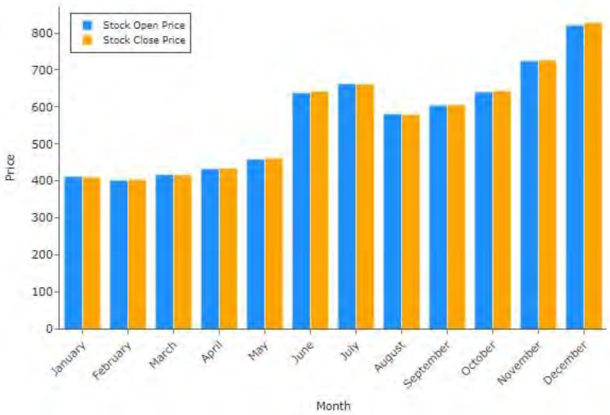

Fig. 2 Monthwise Comparison between Stock Open and Close Price 2016, a comprehensive analysis of the opening and closing prices of a stock for each month of the year, illustrating the stock's performance trends and fluctuations over time. The blue bars represent the stock's opening prices, while the orange bars represent the closing prices.

The second graph on Fig. *3* provides a comprehensive month-by-month review of the peak and lowest prices of Bitcoin stock in 2016. The red-colored bars represent the lowest prices seen, and the blue bars display the highest prices reached throughout each month. The following graph delivers knowledge on the year-over-year variations in Bitcoin pricing. June and December have been recognized months for their significant price fluctuations, ranging from the highest to the lowest. For example, in December, the price reached a peak that exceeded 430, and the low was slightly within 400, indicating significant market instability. However, months like February and March had a narrower gap between high and low prices, suggesting times during trade that were less volatile and more consistent.

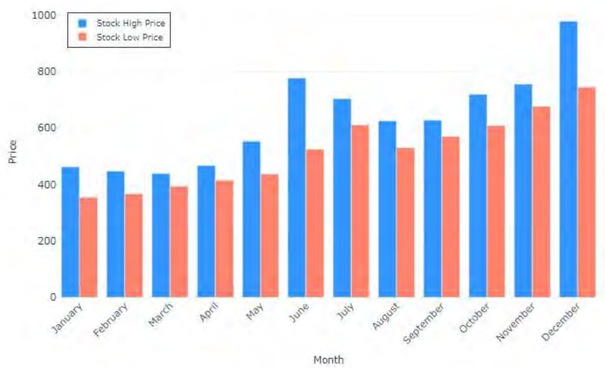

Fig. 3 Monthwise High and Low Stock Prices – 2016, a detailed analysis of the highest and lowest prices of a Bitcoin for each month in 2016. The blue bars represent the stock's highest prices within each month, while the red bars indicate the lowest prices.

b. Analysis of Year 2021

A corresponding evaluation has been carried out for the last year of the record, 2021 represented on Fig. *4*. April and October are the months with the highest peaks, while July and August have the biggest drops, which correspond to the biggest price fluctuations during these times. It seems that closing prices have usually exceeded opening prices throughout the duration of the year indicating the value of Bitcoin has been generally increasing.

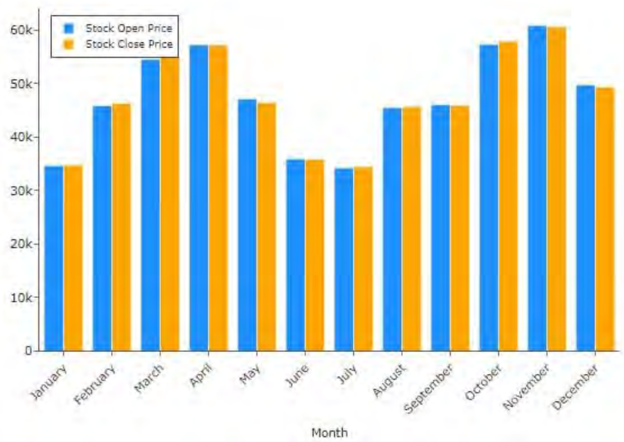

Fig. 4 Monthwise Comparison between Stock Open and Close Price 2021, a comprehensive analysis of the opening and closing prices of a stock for each month of the year, illustrating the stock's performance trends and fluctuations over time. The blue bars represent the stock's opening prices, while the orange bars represent the closing prices.

The stock data reveals important fluctuations during the year visually on Fig. *5*. The first quarter indicates a robust rising pattern that peaks in April. However, the mid-year period of May to July reveals a drop, probably caused by market corrections or uncertainty. There is an impressive comeback in the latter quarter, especially in October and November, and a minor decline in December.

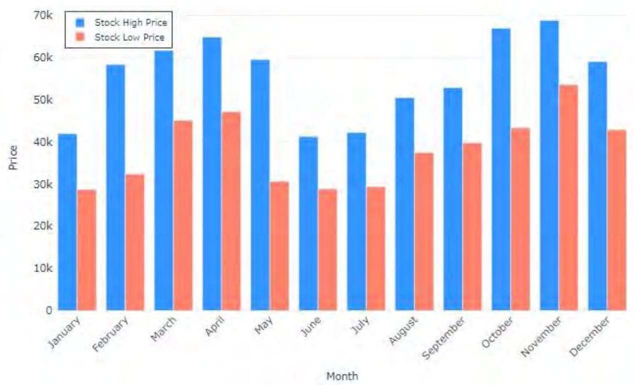

Fig. 5 Monthwise High and Low Stock Prices – 2021, a detailed analysis of the highest and lowest prices of a Bitcoin for each month in 2021. The blue bars represent the stock's highest prices within each month, while the red bars indicate the lowest prices.

The Fig. *6* shows the historical behavior of Bitcoin values from 2015 until 2022, demonstrating high volatility. From 2015 to 2016, the price rise of Bitcoin was consistent; however, during the major spikes in 2017 and 2020–2021, it experienced exponential growth. However, due to regulation and volatility in the markets after 2021, the price of Bitcoin experienced significant fluctuations. Substantial instability can be observed in the price trajectory of Bitcoin from 2015 to early 2022, with times of rapid increases and decreases. From around 2017, the price increased consistently until taking an unexpected turn in 2020 and peaking in 2021. Based on past data, the LSTM model utilized here attempts an effort to forecast these patterns while considering the significant fluctuation of the bitcoin market.

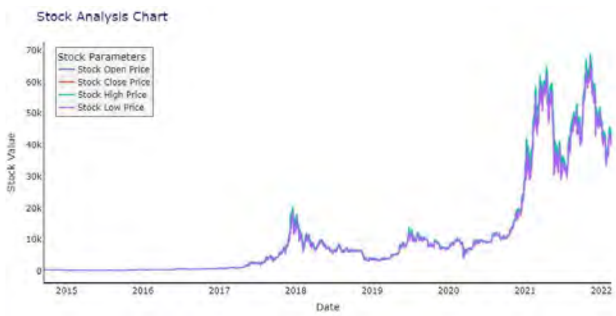

Fig. 6 Historical analysis of bitcoin values from 2015-2022, highlighting its extreme volatility and significant market fluctuations. The analysis shows that while Bitcoin experienced steady growth from 2015 to 2016, it underwent exponential spikes in 2017 and again in 2020-2021, reaching all-time highs. These peaks were followed by sharp corrections, reflecting the unpredictable and highly volatile nature of the cryptocurrency market.

C. Preparing Data for Training and Testing

a. Preparing Data for Training and Testing

The necessary dataset must be selected in order to generate data for training an LSTM model for predicting Bitcoin values. Here, the emphasis is on learning the model using a year's worth of data. Including a long period of data could result in noise and fluctuation that might reduce the model's ability to learn, especially when you consider the huge fluctuations in the price of Bitcoin over time (from $200 in 2015 to $15,000 in 2018 and then $3,000 in 2019). A full year of data is selected in order to avoid this, leading to a more reliable and targeted dataset that yet is able to identify important overall trends and patterns. The primary variable for this study is the Close Price of Bitcoin, and the time index is the Date. This selection simplifies the problem by focusing on predicting the closing price, which is the final trading price for each day.

b. Normalization

We should normalize the data before providing it into the model constructed with LSTM. Normalization scales the dataset's values into a range, avoiding larger numerical values from overpowering smaller ones. This is essential for time-series data such as Bitcoin prices, in which price ranges could vary significantly. In this case, the normalization method of selection is MinMaxScaler. The following equation (1) is applied by this scaler to convert each value in the dataset: are the minimum and maximum values in the dataset, correspondingly. By scaling all values to a range between 0 and 1, this transformation maintains the pattern of distribution and relationships of the initial data set without altering any of its basic characteristics. MinMaxScaler is especially important in this kind of situation since Bitcoin price data fluctuates significantly, and scaling ensures the model will interpret this data accurately.

$$X_{scaled} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (1)$$

X – is the original data value

X_{max}, X_{min} – are the maximum and minimum values in dataset

c. Model architecture

To accurately represent the temporal relationships inherent in Bitcoin price data, the model employs a single Long Short-Term Memory layer having ten units. The activation function of ReLU is applied in this layer to add non-linearity and improve the predictive ability of the model to identify complicated patterns. The Dense layer, composed of a single neuron, takes the output from the LSTM layer and utilizes it to predict the final price of Bitcoin. The model is constructed using the Adam optimizer, which is known for being suitable for flexible learning, and Mean Squared Error (MSE), a relevant loss function for regression tasks. This architecture aims to accurately predict Bitcoin prices through integrating sequential data patterns with strong optimization techniques.

d. Data Splitting And Preparation for Time-Series Prediction

The dataset was split into two sets: training and testing, with 60% used for training and 40% reserved for testing to ensure that the model can generalize to new data. The LSTM model has been utilized to predict time series by transforming the input data into sequences of previous observations. The model analyzes the closing prices of the last 15 days of Bitcoin to predict the price of the next day since a time step of 15 was selected. This method enables the model to identify the temporal interactions and underlying patterns of the data, which are essential to successful time series forecasting.

IV. RESULTS

This section will present the measurements results from the experimental setup described in Section III.

Metric	Training Data	Testing Data
RMSE (Root Mean Squared Error)	2021.34	1872.88
MSE (Mean Squared Error)	4,085,802.47	3,507,675.38
MAE (Mean Absolute Error)	1578.24	1439.86
Explained Variance Score	0.9544	0.9579
R^2 Score	0.9530	0.9570
Mean Gamma Deviance (MGD)	0.00207	0.00145
Mean Poisson Deviance (MPD)	90.44	70.37

Fig. 7 Performance on training and testing data, the performance metrics provides comprehensive evidence that the model effectively captures the underlying patterns in the Bitcoin price data. The metrics used to evaluate the model's performance include Root Mean Squared Error (RMSE), Mean Squared Error (MSE), Mean Absolute Error (MAE), Explained Variance Score, R^2 Score, Mean Gamma Deviance (MGD), and Mean Poisson Deviance (MPD).

The model includes strong performance across different metrics used for evaluation, as seen by the Fig. 7. The training and testing sets' RMSE, MSE, and MAE scores approximately correspond, indicating that the model is not over fitting and that it generalizes well to new data. Outstanding predictive performance is illustrated by the model's high calculated variance scores (0.9544 for training and 0.9579 for testing) and values of R2 (0.9530 for training and 0.9570 for testing), which indicate the model incorporates most of the variation in Bitcoin prices. The low mean gamma and Poisson deviance values confirm that the model's predictions are closely comparable to the actual Bitcoin price distribution, with lower scores suggesting higher precision. In general, the model has excellent predictive ability, little variance from actual values, good generalization, and good accuracy across training and testing datasets.

Three lines are presented Fig. *8* in the comparison plot: the model's predictions on the training dataset, which should closely match the actual prices; the model's predictions on test data that has not yet been seen, which demonstrates that the model is able to generalize to new data; and the Original Close Price (blue), which corresponds to actual Bitcoin closing prices over time.

Fig. 8 Comparison between original and predicted close price, three lines representing different aspects of the model's performance in predicting Bitcoin closing prices over time.

The comparison graphic represents three lines that indicate various characteristics of the model's ability to predict Bitcoin closing prices over time.

- **Original Close Price (blue line):** The blue line shows the actual historical Bitcoin closing prices from March 2021 to February 2022, which provides the starting point against that the model's forecasts are evaluated.

- **Train projected Close Price (red line):** This line represents the model's projected Bitcoin prices utilizing the training dataset. Ideally, the red line should be very similar to the blue line, indicating that the model has learned the patterns in the historical data.

- **Test Predicted Close Price (green line):** The green line represents the model's predictions on a separate testing dataset not used for training. The green line's closeness to the blue line illustrates the model's ability to generalize well to new, previously unseen data while remaining accurate in predicting Bitcoin prices over time.

Overall, the alignment of expected and real prices in both the training and testing datasets indicates the model's robustness, predictive accuracy, as well as potential to generalize successfully, with little divergence from actual price patterns.

Additional data preprocessing tasks, such as scaling or normalizing the input data, could enhance the model's performance. For additional enhancement of the model, experimented with more complicated structures such as Bidirectional LSTMs or GRUs, which may identify time-dependent variables more effectively. More effective results can also be achieved by fine-tuning the LSTM model's hyper parameters, including the number of layers, units per layer, and learning rate. Avoiding over fitting may be achieved by implementing techniques like regularization and dropout into implementation. In addition, using cross-validation for a more reliable evaluation and testing with alternative loss functions adaptable to financial data could boost forecast accuracy.

V. CONCLUSION

This research indicates that Long Short-Term Memory models improve established techniques to forecast Bitcoin values because of their ability to capture complex time-dependent patterns in sequential data. Across training and testing datasets, the LSTM model highlights excellent predictive performance with high variability scores and low variance metrics, successfully managing the volatility of Bitcoin and providing useful data for investors. Future research could investigate further data processing techniques like scaling or normalization, experiment with more complex architectures like Bidirectional LSTMs or GRUs, and modify hyperparameters to further enhance model performance. The process of regularization and dropout techniques may help prevent overfitting and exploring various loss function adapted to financial data and performing cross-validation may improve prediction accuracy. These enhancements will help create more reliable and accurate forecasting devices, which might advance the field of Bitcoin prediction while enabling improved financial sector making choices.

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A Comparison of Gradient Boosting Algorithms: XGBoost, CatBoost, and LightGBM

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***Abstract*—Gradient boosting methods are powerful algorithms that find use-cases in many predictive modeling applications due to their ability to quickly and efficiently learn from high-dimensional data while simultaneously achieving high accuracies. We present an exploration of the three most popular gradient boosting algorithms: XGBoost, CatBoost, and LightGBM. The emphasis is placed on the theoretical foundations, starting from the fundamental principles of non-gradient boosting algorithms, the addition of gradient descent for optimization in parameter and function space, the classic Friedman gradient boosting algorithm and Newton boosting; before getting into the unique approaches each of the three algorithms takes with regards to handling overfitting, data sparsity, categorical features, computational performance and scalability. These algorithms are then applied to three separate datasets: the Default of Credit Card Clients dataset, and the Adult (Census Income) dataset, both from the UC Irvine Machine Learning Repository; as well as the Fraud Detection with Vesta dataset from the IEEE-CIS Fraud Detection competition on Kaggle. We give detailed methodologies for preprocessing and feature selection for each dataset, followed by performance evaluation of the algorithms using both default hyperparameters, and optimized hyperparameters.**

***Index Terms*—Keywords—Gradient boosting algorithms, XGBoost, CatBoost, LightGBM, machine learning**

I. Introduction

As data science has become a prominent discipline in academia and industry [1], driven in part by the growing abundance of computing power and the growing data availability from the increased adoption of the Internet [2], different types of algorithms have been discovered to be well suited to different tasks. Transformer models have found use in large language models [3], convolutional neural networks in vision tasks [4], and gradient boosting methods have evolved into powerful techniques for tabular data and predictive modeling problems [5]. We focus explicitly on the three most widely adopted gradient boosting algorithms according to industry surveys [6]. The first part of the paper reviews the theoretical evolution of regular boosting algorithms, through gradient based approaches, to the algorithms in modern libraries, in this case XGBoost [5], CatBoost [7], and LightGBM [8]. The three datasets are then presented, one balanced between categorical and numerical variables, and two of which are heavy on numerical variables, although with vastly different sizes, along with information about their contents, examination and justification of the steps taken with regard to preprocessing and feature selection. The base versions of all three algorithms, that is, with default parameters, are evaluated for their accuracy on the corresponding dataset. Finally, their hyperparameters are optimized using different approaches for the different combinations of algorithm and dataset, followed by a final evaluation. At the end, we give a few concluding remarks based on the insights gained during the paper, and compare our conclusions to those of previous work on the matter.

II. Theory of Boosting Algorithms

The motivation for boosting algorithms is a procedure that combines the outputs of multiple "weak" classifiers to produce a powerful "committee" (ensemble) [9]. The concept is built on the idea of weighted training sets, where each example has an associated weight $w_j \geq 0$.

Starting with equal weights of 1, a weak learner is trained to generate a hypothesis which will optimize some loss function. The weight of each data point of the training set is adjusted according to the loss incurred by that point. This process continues iteratively until K hypotheses have been generated, where K is an input to the boosting algorithm [10].

The final ensemble allows the hypotheses to vote, weighted by how well each hypothesis performed on its training set. For binary classification and regression the hypothesis function of the entire ensemble is:

$$\hat{f}(\mathbf{x}) = \sum_{i=1}^{K} z_i \hat{f}_i(\mathbf{x}) \tag{1}$$

A. Gradient Boosting

For regression and classification of factored tabular data, a derivative method of boosting is used, referred to as gradient boosting, or sometimes gradient boosting machines (GBM). Rather than assigning a greater weight to examples that incur greater loss, gradient boosting works by adding new hypotheses which pay attention to the gradient between the right answer and the answers given by the previous hypothesis [11].

B. Optimization in Parameter Space

We are trying to model an underlying distribution $y = f(x)$ by minimizing the loss function $L(y, f(x))$ [11] [12]:

$$\hat{f}(x) = \underset{f(x)}{\arg\min}\ \mathbb{E}_{x,y}[L(y, f(x))] \tag{2}$$

As the functional space of $f(x)$ is infinite-dimensional, the search space is limited to a family of functions $f(x, \theta), \theta \in \mathbb{R}^d$. The problem is simplified to finding the optimal set of parameters, which we approximate with $\hat{\theta}$, which is a cumulative sum of the current, as well as previous iterative evaluations:

$$\hat{\theta} = \underset{\theta}{\arg\min}\ E_{x,y}[L(y, f(x))] = \sum_{i=1}^{M} \theta_i \tag{3}$$

After defining an initial approximation of the optimal parameters $\hat{\theta} = \hat{\theta}_0$, the gradient of the loss function is calculated at every iteration of the algorithm at the value of the current cumulative approximation:

$$\nabla L_\theta(\hat{\theta}) = \left[\frac{\partial L(y, f(x,\theta))}{\partial \theta}\right]\Bigg|_{\theta=\hat{\theta}} \tag{4}$$

The current iterative approximation $\hat{\theta}_i$ is set to be equal to the negative of the value of the calculated gradient $\nabla L_\theta(\hat{\theta})$, and is then added to the the cumulative approximation. After a number of iterations, the process stops, yielding a model function $f(\hat{x}) = f(x, \hat{\theta})$.

C. Optimization in Function Space

In boosting algorithms, optimization is done directly in function space [12], i.e. we find better estimates of $\hat{f}$ using a cumulative sum of functions that is updated at each one of M iterations:

$$\hat{f}(x) = \sum_{i=0}^{M} \hat{f}_i(x) \tag{5}$$

Similarly, the search space is restricted by choosing a function $\hat{f}(x) = h(x, \theta)$ belonging to a specific family, called a base-learner. Additionally, the parameter for the optimal step size ρ is calculated at each iteration. The equations for the k-th iteration are the following:

$$\hat{f}_k = \hat{f}_{k-1} + \rho_k h(x, \theta_k) \tag{6}$$

$$(\rho_k, \theta_k) = \underset{\rho,\theta}{\arg\min}\ \mathbb{E}_{x,y}\ [L(y_i, \hat{f}_{k-1}(x_i) + \rho h(x_i, \theta))] \tag{7}$$

For arbitrary loss functions and base-learners, the parameters could be difficult to calculate. For this reason, the function $h(x, \theta_k)$ at step k is chosen through the least squares method to get the base-learner to match the negative gradient of the loss function as closely as possible:

$$g_{ik}(x) = -\left[\frac{\partial L(t_i, \hat{f}_{k-1}(x_i))}{\partial f(x_i)}\right] \tag{8}$$

$$\theta_k = \underset{\theta}{\arg\min}\ \sum_{i=1}^{N} (g_{ik} - h(x_i, \theta))^2 \tag{9}$$

$$\rho_k = \underset{\rho}{\arg\min}\ \sum_{i=1}^{N} L(y_i, \hat{f}_{k-1}(x_i) + \rho h(x_i, \theta_k)) \tag{10}$$

D. Friedman's Gradient Boosting Algorithm

With this in mind, the classic gradient boosting algorithm by J. Friedman can be defined. The inputs to the algorithm are an input dataset $(x_i, y_i), i = 1, \ldots, n$, the number of iterations M, a differentiable loss function $L(y, f(x))$, a base-learner $h(x, \theta)$ belonging to some class of algorithms, like a decision tree, with certain hyperparameters [11].

The first step of the algorithm is an initialization of the approximation function $\hat{f}_0$ to some constant value. Following that, the next step is the iterative part of the algorithm: for all iterations, the negative gradient $g_{ik}(x)$ is computed. Through least squares minimization, we fit the function $h_k(x, \theta)$. This process yields the minimized argument θ_k. Finally, the parameter ρ_k is minimized, which allows us to update the model, $\hat{f}_k = \hat{f}_{k-1} + \rho_k h(x, \theta_k)$. This process is repeated M times, after which the final model is $\hat{f}_M$.

A similar, though more refined method is Newton boosting, which also takes the Hessian $\hat{h}_{ik}$ into account for the least squares minimization, rather than just the gradient [13].

E. XGBoost

XGBoost is a performant and scalable gradient tree boosting algorithm. The library that implements it is consistently ranked among the top most used libraries in Kaggle user surveys. There are multiple properties of XGBoost that differentiate it from other gradient tree boosting algorithms [5].

First among them is the minimization of a regularized learning objective, a kind of generalized loss function that includes a penalty term $\Omega(f) = \gamma T + \frac{1}{2}\lambda \|w\|^2$ that grows with model complexity, where T is the number of leaves, w is the vector of leaf weights, and γ and λ are constant coefficients. The loss function part is minimized using a variant of Newton boosting. The purpose of the regularized learning objective is to avoid overfitting by yielding simpler models [5].

Beyond that, XGBoost features some important optimizations to its split-finding algorithm, notably weighted quantile sketching and sparsity awareness. With weighted quantile sketching, approximations of the quantiles of the data distribution are generated and then used as candidates for splits, greatly reducing the processing time of the split finding algorithm. Sparsity awareness implies the split finding algorithm adopts a default direction through the tree, learned from the data, which allows it to process sparse datasets, while simultaneously greatly increasing the performance of the algorithm [5].

XGBoost employs several other performance optimizations, such as column blocks for parallel learning, which reduces the cost of sorting the data and makes the quantile finding step, as well as the binary search in histograms, faster to execute, while also allowing parallelization of the split finding process. Cache-aware access reduces the computational complexity of the split finding algorithm when the gradient statistics do not fit into CPU cache. Block compression and sharding increase IO throughput when data does not fit in main memory [5].

F. CatBoost

CatBoost is another gradient tree boosting algorithm that is popular amongst data scientists, optimized primarily for dealing with categorical data. Specifically, the way CatBoost deals with categorical variables depends on their cardinality, i.e. how many possible values the variables can take. Low cardinality variables are encoded as one-hot vectors, whereas high cardinality variables are encoded using ordered target statistics [14].

Ordered target statistics are based on the idea that in a preprocessing step, categories can be converted into target statistics, i.e. simple statistical models of the variable. While this can cause target leakage, CatBoost has a unique solution to this issue called ordered boosting, which also helps the algorithm to deal with overfitting [14].

Ordered boosting is based on generating random permutations of the data, and training the k-th model in the ensemble only up to the k-th instance in the permutation. Additionally, when calculating the k-th residual, only models trained on the first $k - 1$ instances in the permutation are used. This makes sure that the residual of an instance does not include information from that instance [7].

In terms of performance enhancements, CatBoost builds the trees symmetrically, meaning that each split is chosen based on the same splitting criteria, which reduces the execution time of the trained ensemble [15].

G. LightGBM

LightGBM is a variation of gradient tree boosting that is explicitly focused on achieving high performance, with a low memory footprint, all the while not compromising on model accuracy [8].

Leaf-wise growth is the tree growing strategy of choice for LightGBM, targeting splits with higher gain, despite the potential for overfitting [8].

Histogram-based algorithms group continuous features into discrete bins, making the gain calculations of each split have time complexity proportional to the number of bins, rather than the number of instances, all with a single preprocessing operation with complexity linearly proportional to the number of instances. This has the added benefit of needing to store less data in memory [8].

The two main techniques behind the performance of LightGBM are gradient-based one side sampling (GOSS) and exclusive feature bundling (EFB). GOSS takes advantage of the fact that instances with larger gradients will contribute more to information gain. Specifically, it takes into account instances with large gradients, and samples a fixed portion of the instances with small gradients during the training process. EFB exploits the exclusivity (or near exclusivity) of some features in sparse feature spaces to bundle them together with minimal information loss. Together, these features greatly accelerate the training of the model [8].

III. DATASETS

The first of the three datasets we used for the purpose of training and evaluation is the Default of Credit Card Clients dataset [16] from the UC Irvine Machine Learning Repository. It consists of 23 integer features, and a binary target variable (whether the borrower will succeed to meet the payment obligations on their debt). The dataset has 30000 instances, with no missing values.

The second dataset we use is also from the UCI Machine Learning Repository, and is known as both the Adult dataset, as well as the Census Income dataset [17]. It has 14 features, of which 8 are categorical, while the others are integers. The target is a binary categorical variable that indicates whether an individual's annual income is greater or lesser than \$50000. It has 48842 instances, with three of its features having missing values.

The final dataset is the Fraud Detection with Vesta Dataset [18] that is used as part of a Kaggle competition. This dataset is by far the biggest of the three, with 432 features, with 399 being floating point, 4 being integer, and 31 being categorical features, as well as 1097231 instances. Of the 432 features, 414 have missing values.

We trained and tested models on the datasets with all their features, as well as with feature selection. The only exception was the third dataset, which could not be used without performing any feature selection due to compute constraints posed by the large number of features.

IV. PREPROCESSING, FEATURE SELECTION AND HYPERPARAMETER OPTIMIZATION

As the Default of Credit Card Clients dataset is fairly small and contains no missing values, no preprocessing was done. The data was separated into a 70-30 split between training and testing. We ranked the features using a Random Forest classifier and selected the top five: PAY_0, ID, AGE, BILL_AMT1, and LIMIT_BAL, with importances of 0.093430, 0.070524, 0.057626, 0.054095, and 0.051085, respectively, as shown in Figure 1. The hyperparameters of all three algorithms for this dataset were optimized using grid search.

The Census Income dataset has missing values, so we used the forward fill method from the pandas library to deal with them. Additionally, the dataset contained duplicate categories for the target variable, i.e. both ”<=50K.” and ”<=50K”, as well as ”>50K.” and ”>50K”, which we collapsed into only the two categories ”<=50K” and ”>50K”. Afterwards, we performed an 80-20 train-test split on the data. Recursive feature elimination was used, with a Random Forest classifier as a base model, to reduce the number of features to 10. Figure 2 shows the four worst performing features of the fourteen, according to the Random Forest base classifier: race, sex, native-country, and education. We performed hyperparameter optimization on all three algorithms using Bayes search, and noted no improvement over baseline performance.

The Fraud Detection with Vesta dataset was dealt with differently from the other two due to its size. The Kaggle tournament entry has many Jupyter notebooks with sections

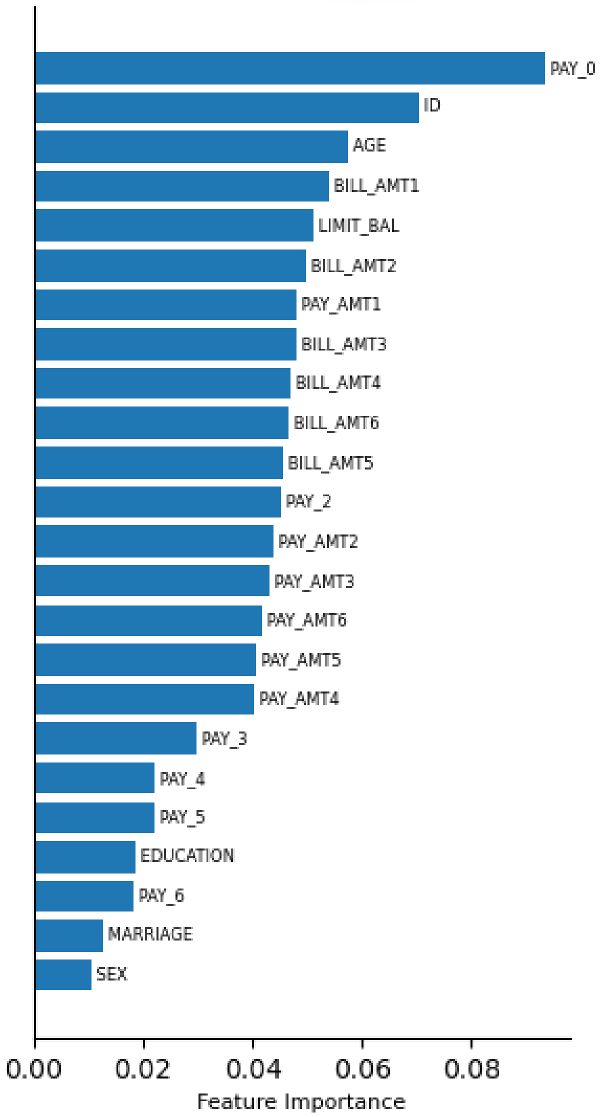

Fig. 1. Random Forest feature ranked feature importances of the Default of Credit Card Clients dataset

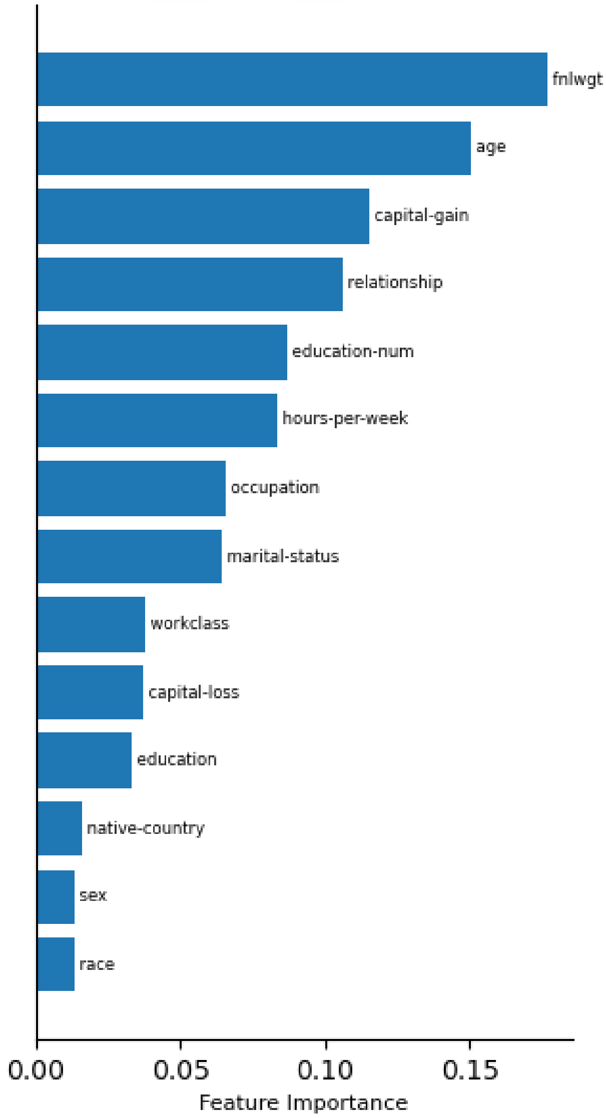

Fig. 2. Random Forest feature ranked feature importances of the Census Income dataset

on EDA, data cleaning, and feature engineering, one of which [19] we used for the purposes of this paper. The first step was the concatenation of the "transaction" and "identity" datasets, both training and test, into "merged" training and test datasets. Then, all columns with over 70% missing data were dropped. The categorical and numerical features were separately imputed, with most frequent value imputation, and median value imputation, respectively. High cardinality features were dropped. The final steps before feature selection were standardization and one-hot encoding of the categorical features, after which we were able to perform principal component analysis and reduce the dataset to 10 principal components, illustrated in Figure 3. Due to the highly imbalanced distribution of values of the target variable, where only around 3% of the labels were fraudulent, we used Synthetic Memory Oversampling (SMOTE) from the library imblearn to resample the dataset and get a balanced distribution of the target variable. All hyperparameters for all three algorithms were optimized by successively chaining multiple grid search calls, each with different parameters.

V. Evaluation

For the Default of Credit Card Clients dataset, applying all three gradient boosting algorithms, without feature selection or hyperparameter optimization, yields 81.02% accuracy for XGBoost, 81.93% for CatBoost, and 81.77% for LightGBM. After selecting the top features and optimizing each of the models' hyperparameters, we got 86.1% for XGBoost, 84.2%

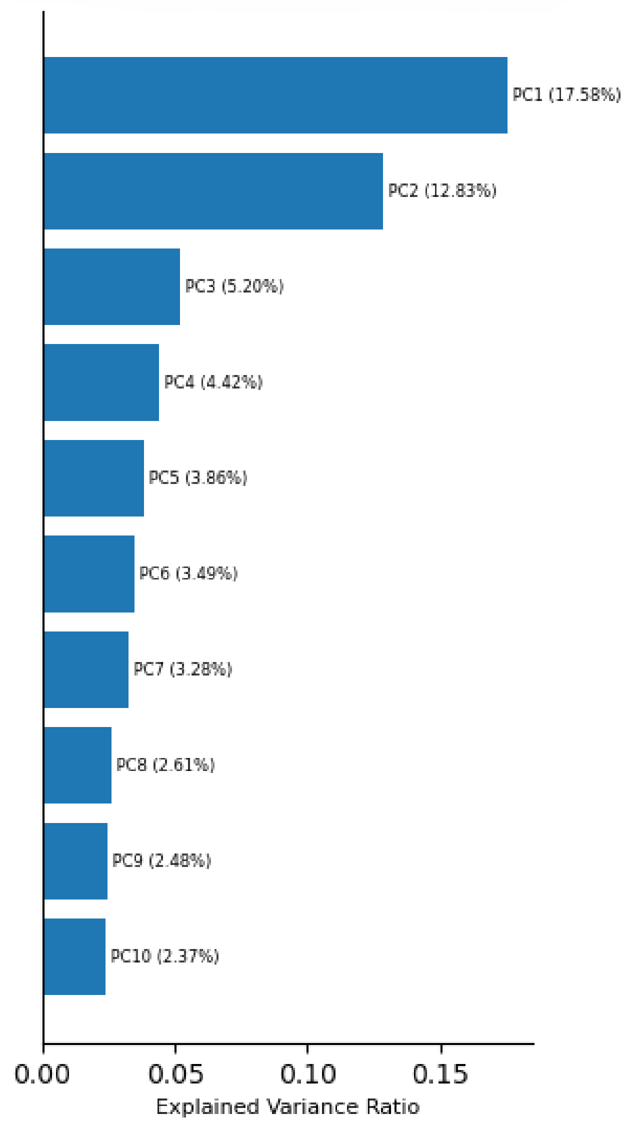

Fig. 3. Explained variance ratios of each principal component of the Fraud Detection with Vesta dataset

for CatBoost, and only a minor improvement for LightGBM, with 82% (Figure 4).

Next, for the Census Income dataset, with all features included, the default parameter versions of the algorithms achieve accuracies of 87.47% for XGBoost, 87.65% for CatBoost, and 87.76% for LightGBM. Post feature selection and hyperparameter optimization, they hover around the same values, in fact slightly worsening, with 87.26% for XGBoost, 87.55% for CatBoost, and 87.54% for LightGBM (Figure 5).

Finally, for the Fraud Detection dataset we have the greatest increase in performance. As mentioned before, we didn't evaluate the performance of any of the algorithms on the base version of the dataset, rather only on the reduced version obtained through PCA. Moreover, as the values of the target variable

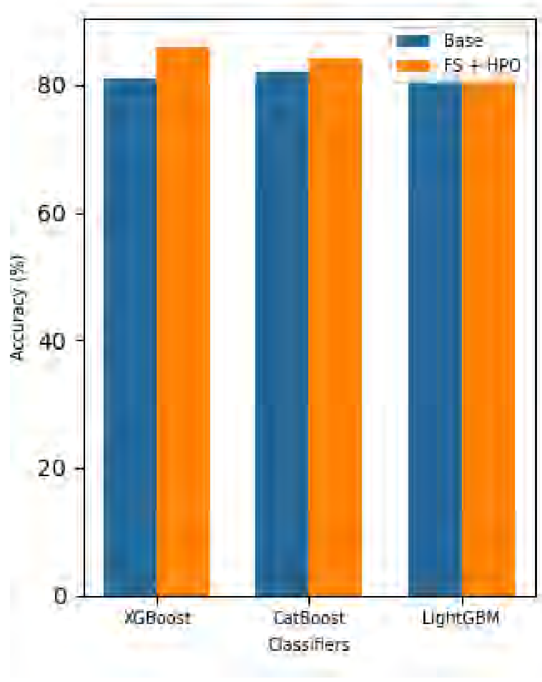

Fig. 4. The three algorithms evaluated on the Default of Credit Card Clients dataset

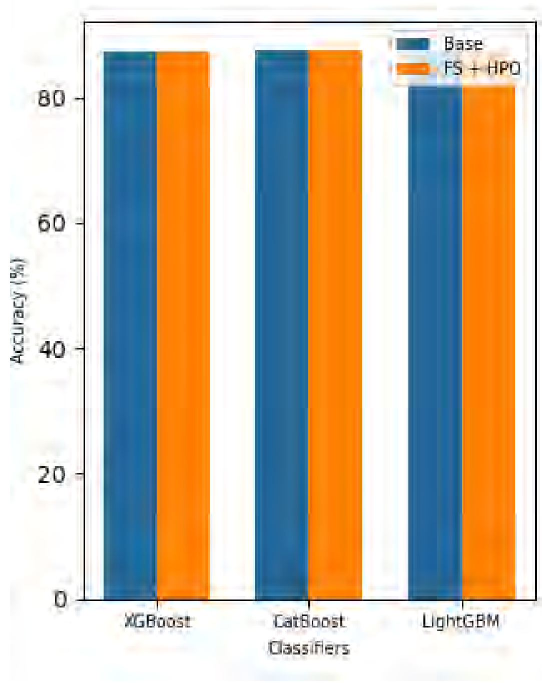

Fig. 5. The three algorithms evaluated on the Adult (Census Income) dataset

in the test set were not provided directly, and could only be accessed by making a submission of the model predictions, we evaluated the performance of the models using 5-fold cross-validation on the test set. The scores achieved were 81.92% for XGBoost, 79.74% for CatBoost, and 81.36% for LightGBM.

After optimizing the hyperparameters of each algorithm, the scores were noticably improved, with 89.33% for XGBoost, 80.21% for CatBoost, and 92.36% for LightGBM (Figure 6).

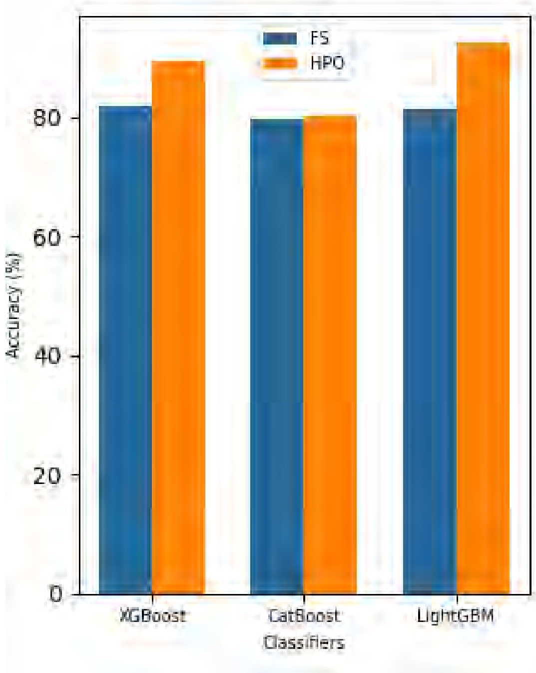

Fig. 6. The three algorithms evaluated on the Fraud Detection with Vesta dataset

VI. Conclusion

To summarize the findings, the three most popular gradient boosting algorithms, despite differences in their approaches, tend to achieve similar levels of accuracy in classification across different datasets. Additionally, as depicted in Figure 7, our results indicate that the necessity of feature selection and hyperparameter optimization is dataset dependent, with the algorithms finding little to no increase in accuracy when compared to default parameters on some datasets, and greatly increasing their accuracy on others.

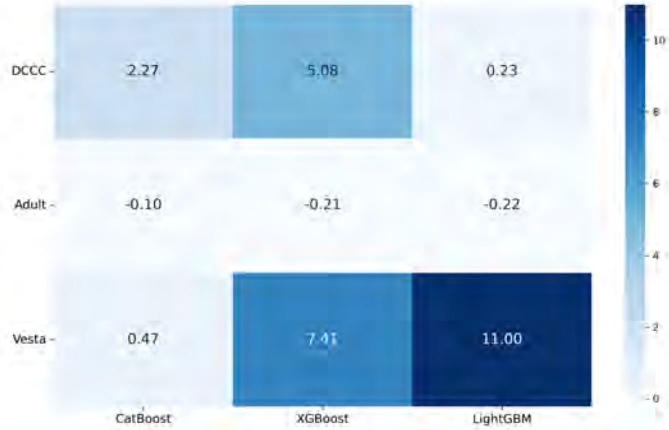

Fig. 7. Heatmap showing the change in accuracy following feature selection and hyperparameter optimization for all three algorithms, on all datasets

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Analyzing Telecom Customer Churn using Machine Learning

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***Abstract*—Predicting customer churn is a critical challenge in the telecommunications industry, with significant implications for business strategy and revenue. This study presents an analysis of various machine learning models to identify at-risk customers. The research evaluates the predictive performance of Decision Tree, Logistic Regression, Support Vector Machine (SVM), K-Nearest Neighbors (KNN), Random Forest, and XGBoost algorithms. The models are assessed using a dataset preprocessed through feature encoding, scaling, and selection, identifying the top 15 most informative features. Performance metrics such as accuracy, balanced accuracy, precision, F1 score, recall, and ROC_AUC are calculated to compare the effectiveness of each model under default parameters, reduced feature set, and after hyperparameter tuning via Random Search Cross-Validation. The results indicate that ensemble methods, particularly the XGBoost classifier with hyperparameter optimization, outperforms individual classifiers, offering a robust solution for churn prediction. The study also highlights the efficiency of using a reduced feature set without significantly compromising model performance, suggesting a streamlined approach for practical application. These insights provide a valuable contribution to the predictive analytics field and offer a strategic asset for telecom companies in their customer retention efforts.**

Keywords— Customer churn prediction, Ensemble Machine Learning, Feature Selection Optimiziation.

I. INTRODUCTION

In the competitive landscape of the telecommunications industry, customer attrition, or churn, poses a significant threat to the sustainability and profitability of service providers. Churn, which occurs when subscribers discontinue their services, can result in considerable revenue loss and increased marketing costs as companies strive to replace lost customers. Consequently, the ability to predict and preemptively address customer churn has become a strategic imperative for telecom operators [1].

Recent advancements in machine learning (ML) offer promising solutions to this challenge by enabling sophisticated analytical capabilities that can uncover complex patterns in customer behavior and predict potential churn. This paper explores the application of supervised ML algorithms to predict churn within a telecom company. By leveraging a dataset encompassing a range of customer attributes and service details, we aim to develop a predictive model that forecasts churn with high accuracy and provides insights into key determinants of customer retention.

Our research is driven by the premise that predictive analytics, powered by ML, can transform the traditional approach to churn management. Through this study, we aim to demonstrate the predictive power of ML algorithms and provide actionable insights that telecom companies can leverage to devise targeted retention strategies and enhance customer loyalty.

II. DATASET AND ANALYSIS

A. Dataset

We used a publicly available dataset for this research obtained from the Telco Customer Churn data collection, which is hosted on Kaggle platform [2], and originates from a sample provided from IBM [3]. This dataset encapsulates the interactions and service usage of 7043 customers from a hypothetical telecommunications company based in California in the third fiscal quarter. The dataset comprises various customer attributes and service subscription details, which are important for analyzing the churn phenomenon. The dataset is composed of multiple features, each representing a specific aspect of customer information given in Table 1.

The dependent variable of interest, ‘Churn’, denotes whether a customer has terminated their subscription within the last month, with possible responses being Yes or No. The dataset not only provides a granular view of the service to which the customers are subscribed, such as phone lines, internet, and various subsidiary services, but also encompasses critical account information, including tenure, contractual agreements, payment modalities, and financial charges. Furthermore, it includes demographic data points, such as gender, age bracket, and familial status, which are essential for a nuanced demographic analysis in the context of churn.

B. Analysis

The goal of this analysis is to harness predictive modeling to anticipate customer churn, thereby enabling the formulation of targeted customer retention strategies. By leveraging the comprehensive data provided, this study seeks to generate actionable insights that can guide telecom companies in their efforts to mitigate churn and enhance customer engagement.

The exploratory data analysis conducted in this study serves as a preliminary step to understand the underlying structure and patterns within the Telco Customer Churn dataset. To identify key factors that contribute to customer churn and inform the subsequent data processing and modeling phase.

Table 1. Feature and their description

Feature Name	Description
customerID	A distinct identifier for each customer.
gender	The customer’s gender, categorized as Female or Male.
SeniorCitizen	A binary indicator reflecting whether the customer is aged 65 or above.
Partner	A binary indicator of whether the customer has a life partner.
Dependents	A binary indicator of whether the customer has dependents.
tenure	The duration, in months, of the customers relationship with the company.
PhoneService	A binary indicator of the customer's subscription to phone service.
MultipleLines	The customer's subscription status to multiple telephone lines.
InternetService	The type of internet service availed by the customer.
OnlineSecurity	The customer's subscription status to online security services.
OnlineBackup	The customer's subscription status to online backup services.
DeviceProtection	The customer's subscription status to device protection plans.
TechSupport	The customer's subscription status to technical support services.
StreamingTV	The customer's subscription status to streaming TV services.
StreamingMovies	The customer's subscription status to streaming movie services.
Contract	The term of the customer's service contract.
Paperless billing	A binary indicator of the customer's preference for paperless billing.
PaymentMethod	The method by which the customer completes payments.
MonthlyCharges	The monetary cost billed to the customer monthly.
TotalCharges	The aggregate monetary cost billed to the customer.

The target variable, ‘Churn’, exhibits a class imbalance with approximately 26.6% of customers having canceled their subscriptions as shown on Figure 1 [5]. This imbalance underscores the necessity for careful consideration of evaluation metrics beyond accuracy, such as balanced accuracy, precision, recall, F1 score, and the ROC-AUC score, which provide a more nuanced assessment of model performance across imbalanced classes. The gender distribution within the dataset is nearly balanced, with a slight majority of male customers (50.5%). In contrast, the proportion of senior citizens is relatively low at 16.2%, suggesting that the majority of the customer base is younger. The presence of a partner and dependents among customers is almost evenly split, with a slight majority not having a partner (51.7%) and a significant majority not having dependents (70.2%).

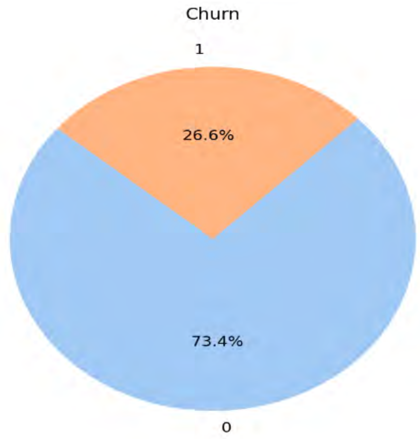

Figure 1 Churn Distribution.

Many customers have subscribed to phone services (90.3%). However, the presence of multiple lines among these customers does not show a significant difference in churn rates. Internet service type distribution reveals that customers with fiber optic service are more likely to churn than those with DSL or no-internet service, highlighting the potential impact of service quality or pricing on customer retention.

The analysis of additional services such as online security, online backup, device protection, and tech support indicates that customers lacking these services exhibit higher churn rates. This pattern extends to streaming services, where customers without streaming TV or movies tend to churn more frequently. Notably, the type of contract is a strong indicator of churn, with customers on month-to-month contracts showing a higher propensity to churn compared to those on longer-term contracts. Customers who have adopted paperless billing and those who use electronic checks as their payment method are more prone to churn. These findings may reflect a segment of customers who are more comfortable with digital services and potentially more sensitive to service dissatisfaction or competitive offers.

This analysis has revealed several features with significant differences in churn rates, as seen on the Figure 2, including the type of internet service, contract length, and billing practices. These features warrant closer examination in the predictive modeling phase and suggest potential areas for targeted customer retention strategies.

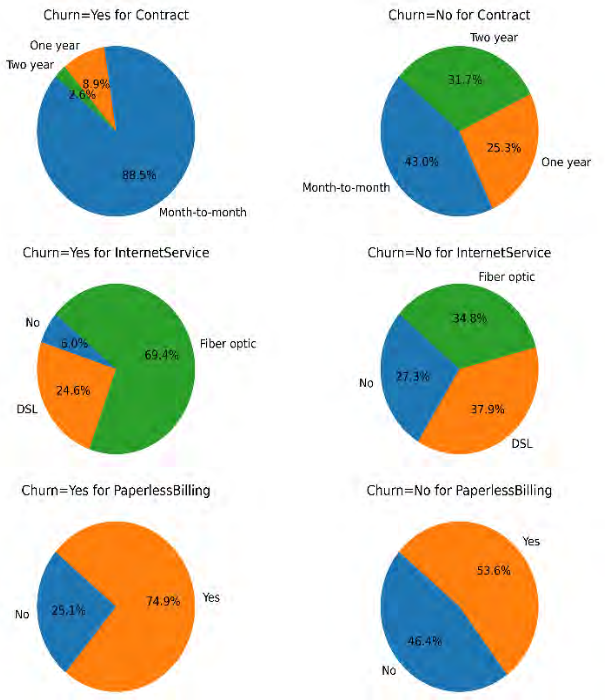

Figure 2 Additional Services and Contract Distribution

To develop our predictive models, we employed both individual classifier approaches and ensemble techniques. The individual classifier approach involved the use of several machine learning algorithms, each with its own theoretical underpinnings and assumptions:

- **Decision Tree Classifier**: A non-parametric supervised learning method ideal for classification and regression tasks. It operates by recursively partitioning data into subsets based on the feature that results in the maximum information gain at each decision node. The end result is a tree-like model of decisions as shown on Figure 3, where each path from root to leaf represents a classification rule. One of the key advantages of decision trees is their interpretability, as they can mimic human decision-making processes. However, they can be prone to overfitting, especially when they grow too complex [4].

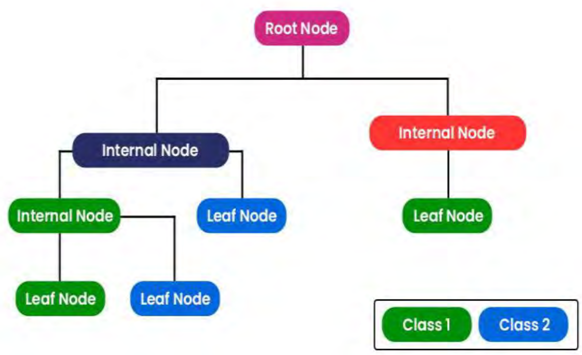

Figure 3 Decision Tree basic structure.

- **Logistic Regression**: Logistic regression is used for binary classification rather than regression. It predicts the probability of the target variable belonging to a particular class using a logistic function, which is an S-shaped curve that can take any real-valued number and map it into a value between 0 and 1. Logistic Regression is robust to noise and provides probabilities that can be used to interpret model predictions in terms of odds ratios.

- **Support Vector Machine Classifier (SVM)**: SVM is a powerful algorithm that works well for both linear and non-linear classification. It aims to find the optimal separating hyperplane that maximizes the margin between different classes, seen on the Figure 4. In cases where the data is linearly inseparable SVM uses kernel functions to project the data into higher-dimensional spaces where a hyperplane can be used to separate the classes. SVMs are effective in high-dimensional spaces and are versatile due to the different kernels that can be applied [4].

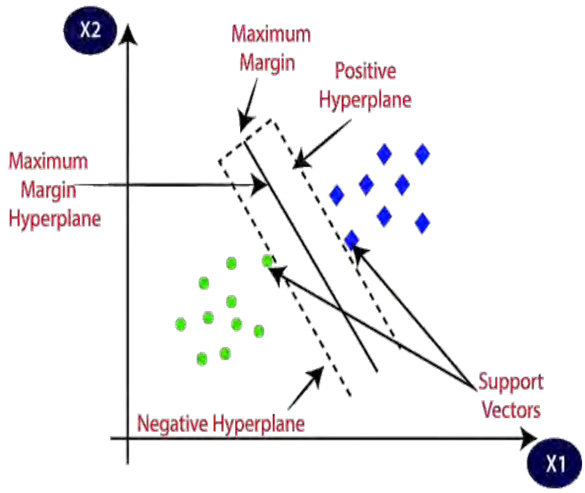

Figure 4 Support Vector Machine.

- **k - Nearest Neighbor Classifier (KNN)**: KNN is an instance-based learning algorithm that classifies instances based on the majority vote learning of the k-nearest neighbors in the feature space. It is a type of a lazy learning, where the generalization of the training data is delayed until a query is made to the system. This model is simple and effective but can become computationally expensive as the size of the data grows, and it may suffer from the curse of dimensionality in high-dimensional spaces.

- **Random Forest Classifier**: Random Forest is an ensemble learning method that builds upon the simplicity of decision trees and enhances their performance. It constructs a multitude of decision trees during training and outputs the mode of the classes (for classification) as the final prediction. By aggregating the predictions of individual trees, random forest reduces the risk of overfitting and is able to capture complex relationships in the data [7].

- **XGBoost Classifier**: XGBoost stands for Extreme Gradient Boosting and is an advanced implementation of gradient-boosted decision trees. It is designed for speed and performance, utilizing both hardware optimization and software algorithmic enhancements. XGBoost provides regularizations to prevent overfitting and is capable of handling missing data. It works by sequentially adding predictors that correct the predecessors' errors, with each new model being fitted on the residual errors of the last prediction.

Prior to applying these algorithms, the data was processed through feature encoding, feature scaling, and data splitting. Categorical values were encoded to numerical values to facilitate computation, while numerical features were standardized to have a mean of zero and standard deviation of one. The dataset was then split into 80%-20% training and testing set, respectively.

Feature selection was performed using the SelectKBest technique to identify the top 15 features that are most predictive of churn. This step is crucial to improve model efficiency and effectiveness by reducing dimensionality and focusing on the most relevant predictors [8].

III. Experimental Results

A. Evaluation Metrics

The following section will detail the results obtained from applying these methods, including the performance metrics and comparative analysis of the six different machine learning models applied to the task of predicting customer churn. The models were evaluated using a comprehensive set of metrics [9] to provide a thorough understanding of their predictive capabilities. The evaluation metrics include:

- Accuracy: The proportion of true results (both true positives and true negatives) among the total number of cases examined. It is calculated as:

$$\text{Accuracy} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{TN} + \text{FP} + \text{FN}}$$

- Balanced Accuracy: The average recall obtained on each class. It is used to deal with imbalanced datasets and is calculated as:

$$\text{Balanced Accuracy} = \frac{\text{Sensitivity} + \text{Specificity}}{2}$$

where, sensitivity is the "true positive rate" – the percentage of positive cases the model is able to detect; and specificity is the "true negative rate" – the percentage of negative cases the model is able to detect.

- Precision: The ration of true positives to all positive results predicted tby the classifer. It is calcualted as:

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}}$$

- F1 Score (F1): The harmonic mean of precision and recall, providing a balance between the two in cases where one may be more imporatnt then the other. It is calculated as:

$$\text{F1 Score} = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}}$$

- Recall: The ratio of true positives to the sum of true positives and false negatives. It is calculated as:

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}}$$

- ROC-AUC: The area under the receiver operating characteristic curve, a graphical plot that illustrates the diagnostic ability of a binary classifier system as its discrimination threshold is varied. It is a value between 0 and 1, where 1 represents a perfect model and 0.5 represents a model with no discriminative ability.

The models were trained and evaluated twice: first using all available features, and then using a subset of the top 15 features selected through the SelectKBest technique. Additionally, hyperparameter tuning was performed on the models (Logistic Regression, Random Forest, and XGBoost) using Random Search Cross-Validation to optimize their parameters.

B. Results with Default Parameters (All Features)

The initial set of experiments was conducted using all the features with default model parameters. The results are summarized in Table 2.

Table 2: Model Performance with Default Parameters (All Features)

Metrics	Decision Tree	Logistic Reg	SVM	KNN	Random Forest	XGBoost
Accuracy	0.7292	0.7789	0.7341	0.6837	0.7860	0.7796
Bal accuracy	0.6586	0.6831	0.5000	0.5244	0.6811	0.6844
Precision	0.4909	0.6067	0.0000	0.3301	0.635688	0.6081
F1	0.4993	0.5351	0.0000	0.2367	0.531882	0.5373
Recall	0.5080	0.4786	0.0000	0.1844	0.4572	0.4812
ROC-AUC	0.6586	0.6831	0.5000	0.5244	0.6811	0.6844

C. Results with Default Parameters (Top 15 Features)

The models were then trained using only the top 15 features, that were selected using the SelectKBest technique. The results are summarized in Table 3.

Table 3: Model Performance with Default Parameters (Top 15 Features)

Metrics	Decision Tree	Logistic Reg	SVM	KNN	Random Forest	XGBoost
Accuracy	0.7086	0.7818	0.7896	0.7512	0.7810	0.7661
Bal accuracy	0.6471	0.6927	0.6835	0.6583	0.6820	0.6727
Precision	0.4573	0.6084	0.6477	0.5375	0.6153	0.5728
F1	0.4849	0.5505	0.5360	0.4956	0.5333	0.5183
Recall	0.5160	0.5026	0.4572	0.4598	0.4705	0.4732
ROC-AUC	0.6471	0.6927	0.6835	0.6583	0.6820	0.6727

D. Results after Hyperparameter Tuning (All Features)

Hyperparameters tuning was performed on Logistic regression, Random Forest, and XGBoost models using all features. The results are summarized in Table 4.

Table 4: Model Performance after Hyperparameter Tuning (All Features)

Metrics	Logistic Reg	Random Forest	XGBoost
Accuracy	0.7867	0.7938	0.7988
Bal accuracy	0.6918	0.6856	0.7095
Precision	0.6267	0.6640	0.6531
F1	0.5495	0.5396	0.5782
Recall	0.4893	0.4545	0.5187
ROC-AUC	0.6918	0.6856	0.7095

The comparison of results seen on Figure 5 indicates that hyperparameter tuning generally improved the performance of the models. Notably XGBoost with hyperparameter tuning achieved the highest accuracy and balanced accuracy among all configurations. The use of only 15 features did not significantly diminish model performance, suggesting that these features capture the most relevant information for predicting churn.

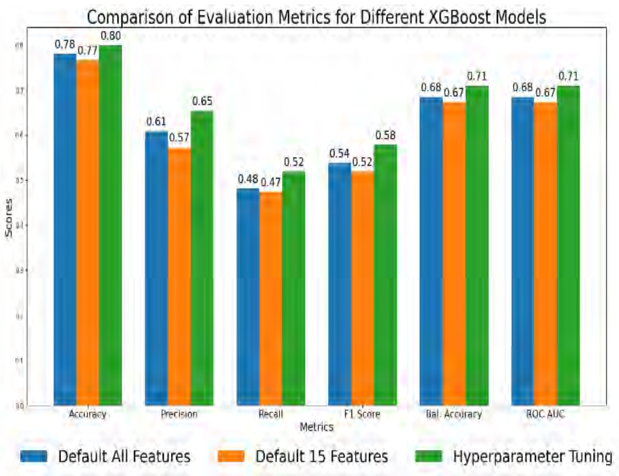

Figure 5: Comparison of the XGBoost model with all metrics.

On the Figure 6, the confusion matrix offers a detailed evaluation of the XGBoost model's performance in predicting customer churn post-hyperparameter tuning. It accurately identifies 930 non-churning and 194 churning customers but misclassifies 103 non-churning as churners and 180 churning as non-churners. While proficient at identifying non-churners, the model struggles with false negatives indicating in recognizing all churning customers. This assessment underscores the model's strengths and areas requiring improvement in discriminating between churning and non-churning customers.

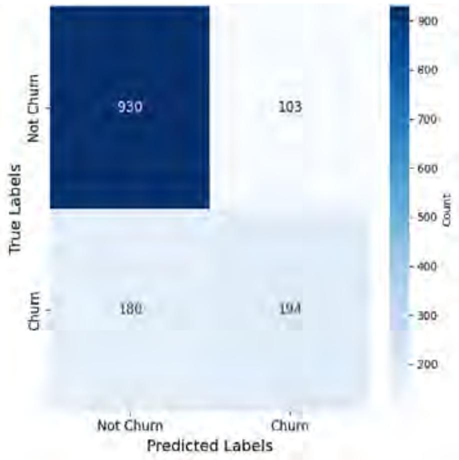

Figure 6: Confusion Matrix XGBoost - Hyperparameter tuned.

IV. Conclusion

The objective of this study was to develop a predictive model for customer churn that could assist telecom companies in identifying at-risk customers and formulating effective retention strategies [10]. Through the application of various machine learning algorithms, both individually and in ensemble, we sought to determine the most effective approach for this classification task.

The experimental results revealed several key findings. Initially, when all features were used, the Random Forest and XGBoost classifiers demonstrated superior performance in terms of accuracy and balanced accuracy compared to other models like Decision Tree, Logistic Regression, SVM, and KNN. This outcome can be attributed to the ensemble methods ability to reduce overfitting and capture complex patterns in the data. Upon reducing the features set to the top 15 most significant features, as determined by the SelectKBest technique, there was a negligible decrease in performance for most models. This suggests that these selected features retain the essential information required for churn prediction, and that a more parsimonious model could be just as effective as one using the full features set. Notably, the SVM classifier showed a marked improvement in balanced accuracy with the reduced feature set, indicating that feature selection can have a positive impact on the performance of certain models.

The application of hyperparameter tuning to the Logistic Regression, Random Forest, and XGBoost models further refined their performance, XGBoost benefited from this optimization, achieving the highest accuracy and balanced accuracy across all models and configuration tested. This underscores the importance of hyperparameter tuning in the development of predictive models and its potential to significantly enhance model accuracy.

In conclusion, the study demonstrates that machine learning can be a powerful tool in predicting customer churn. The XGBoost classifier, with hyperparameter tuning, emerged as the most effective model in this study. However, the relatively strong performance of models with only top 15 features indicates that a simpler model could be nearly effective, which has implications for computational efficiency and ease of model interpretation.

Future work could explore the integration of additional data sources, the application of more sophisticated feature selection methods, and the deployment of these models in a real-world setting to validate their predictive power. Additionally, the development of a cost-sensitive model that takes into account the financial implications of false positives and false negatives could provide a more nuanced approach to customer retention strategies.

This study contributes to the growing body of knowledge on the application of machine learning in the telecommunication industry and provides a foundation for further research and practical applications in the area of churn prediction.

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ЗДРУЖЕНИЕ ЗА ЕЛЕКТРОНИКА ТЕЛЕКОМУНИКАЦИИ АВТОМАТИКА И ИНФОРМАТИКА НА РЕПУБЛИКА МАКЕДОНИЈА

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Dynamic Graphs, Networks-of-Networks with Faulty Inter-network Connections, Pinning-control Synchronization Coordinator: Coincidences and Confluences

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***Abstract*—Investigation of large network-of-networks system structures is an appealing timely research topic, in particular when of permanent and recoverable faults may occur in coupling node connections within different networks. For the modeling of such a multi-network structure, in this paper, the coupling terms in the same network and those among different networks are described separately in order to distinguish clearly the multi-network feature. A dimension-transformation matrix is used where needed to deal with the mismatched dimensions of nodes in different networks. A synchronization decentralized control infrastructure beyond traditional feedback is designed via the theory of pinning control schemes. A sufficient stability condition under the pinning control is derived that guarantees convergence to a steady-state operating synchronization while overall multi-network structure remains technically stable. Simulation results for a bench-mark case-study of three coupled networks of node systems of notoriously complex nonlinear dynamics demonstrate control strategy employing pinning control theory can enforce stabilized synchronization despite any faults.**

***Index Terms*—Complex dynamic networks; Chaos dynamics; Decentralized node controls; Controlled synchronization; Faults; Interconnection edges; Networks of dynamic networks; Pinning control coordinator; Supervisory control beyond feedback.**

I. Introduction

IN THEIR recent article Wang et al. (2022) rightly argued that a new era begins focused on exploration of the symbiotic autonomous systems (SAS; Wang Y., 2018) and complex multi-network systems (CMNS; Gormanchian et al., 2021; Chen G., 2022) from synergies of artificial intelligence (AI) advances and some human-intelligence-in-the-loop beyond the traditional feedback (Siljak and Zecevic, 2005; Zecevic and Siljak, 2010). Indeed, a new scientific investigation era of networked systemic structures has emerged (Lin et al., 2024; Zhu et al., 2023) following the discoveries of small-worlds of Watts-Strogatz (1998) and scale-free networks of Brabasi-Albert (1999), both being advanced follow up developments built upon random graphs[10] of Erdos-Renyi (1960) and the early graph dynamics [2] of Aizerman and co-authors (1977). Ever since studies of complex dynamical networks do expand via new discoveries in complex network-like systemic structures [19-20], [22-23], [26], [28], [46], [48], [51]. And so do the application oriented investigations of complex dynamic network-like systems such as artificial neural networks, brain neuronal networks, communication and computer networks, electric power grids, social networks, etc. to name a few.

Nowadays, it is well known the functionality of complex dynamic networks depend heavily on both convergence to stable operating equilibrium and synchronization dynamics. Therefore about two decades both controlled stabilization and synchronization became the main research endeavors world-wide and considerable advances in the applications and the theory and of complex networks have been achieved [6],[23]. In particular, idea and concept of pinning control of Chen and co-authors (2002-2004) [15], [30] have appeared amazingly effective and yielded a research direction with impressive results (e.g., see [5], [6], [19], [27-29], [31], [38]).

Unlike the topology of a single network (e.g., see [4], [5], [18], [29], [40] and references therein), systemic structure of networks of coupled networks does have a great influence on overall dynamics (e.g., see [11], [12], [14], [21], [39], [41] and references therein). The change of the node connecting edge between any two networks will have a great impact on the stability of the whole network, thus affecting overall network stability and synchronization too. Due to the interaction among networks, the failure of a node in the network will not only affect its own network, but also lead to a kind of chain reaction, resulting in multiple network failure. In real-world networks, after some time of the self-adjustment (e.g. biological network has the ability to self-recovery) or the certain artificial intervention (e.g. traffic network congestion will be diverted by traffic police), some networks coupling connection failures can return to normal working condition. Therefore the inter-network faults can be either permanent and/or recoverable faults. Thus, studies of the problem of multi-network synchronization control in the presence of both recoverable and permanent faults among networks, operating within a multi-network, have profound importance [14], [9],

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[21], [32], [37]. Studies of clustering synchronization control in complex networks are already fairly mature now. On the other hand, it should be noted controlled multi-network synchronization and cluster synchronization involve similar underlying issues [21], [39]. Thus the study of multi-network can be combined with the characteristics of multi-network model coupling and learned from the cluster synchronization research models as well as the respective methods [28], [39] .

In particular, the pinning controller is designed and the gain of the controller is adjusted, the clustering synchronization of complex network is realized in work [14]. But the coupling strength of the network appears large, which does not seem realistic. In [13], the coupling control strategy is adopted to adjust the coupling strength by means of adaptation, and clustering synchronization of network can be realized under a relatively weak coupling. In [19], based on the pinning control scheme, the clustering synchronization of network is realized by the intermittent control method. Due to influence from the environment, human factors inclusive, the coupling strength of nodes in a complex network may change randomly with time and so can inter-network connections [14]. Recoverable failure that is the random and unpredictable is due to interference or attack among networks. In [37], random variables are used to describe the random variation of coupling strength, a class of neural network synchronization control problem is studied. In [11], the problem of complex network synchronization with nonlinear stochastic distribution is studied. The stochastic variation of nodes is represented by introducing the random variables with Bernoulli distribution, which seems reasonable; however, the connections among nodes are not considered. In [12], the cascade failures caused by the attack on complex network are studied; investigation is rightly carried out from the occurrence to the propagation of the process underlying the evolution dynamics [14]. But it is not studied from the control point and does not consider the recoverability of node connection failures. In [32], the complex dynamic network in the case of fault is studied. The nodes in the network are randomly switched between all connections and failures that possibly may occur. The failure time ratio is designed to synchronize the network.

In the existing literature, not many researches do report on the *multi-network* settings, i.e. the *network-of-networks*, of the operating synchronization when inter-connection failures occur [28]. It appears as if the present literature does not consider the coupling interconnection edge may be subject to deliberate interference, failure, or even attacked hence concept of connective stability [30] seems ignored. Thus investigating categories of *recoverability* and/or *permanent* faults among nodes of different sub-networks within multi-networks seems timely and thus of considerable importance. However, the issue of controlled synchronization of multi-networks to a stable operating equilibrium, unlike that of networked control systems [38], is much more involved [28-30]. Hence complex networks and multi-networks are to be driven to the stable operating equilibrium in a similar way as the recurrent neural networks with time-varying delays need [15], [45].

In this paper, the multi-network mathematical model is used to study the synchronization control problem in network-of-networks by considering both the *recoverable* and the *permanent* faults of the interconnection and possibly the inter-network connecting link. Bernoulli-distribution probabilistic variable is employed to capture the change events between failure and recovery or vice-versa. On the theoretical grounds of pinning control [4-8], sufficient conditions for controlled synchronization within respective multi-network structure are derived here. By relying on concepts and ideas of Lyapunov stability [49], sufficient conditions for synchronization within the respective network are found. These derived results are verified to be correct by means of simulation experiments on a case-study network-of-networks example comprising a four-node Lorenz hyper-chaotic sub-network as well as one Rossler and one Chen sub-networks both having three nodes.

Further, this paper is written as follows. In Section II, there are explored the system models for multi-networks with two types of inter-network failures as well as certain mathematical preliminaries. Section III presents the main results on pinning control design for network synchronization and its asymptotic property. These results are verified in Section IV by means of numerical and simulation results for a complex multi-network case-study. Then concluding remarks and references follow.

II. On Networks-of-Networks And Inter-network Connection Faults

The underlying systems theory requires certain preliminary mathematical modeling for networks of complex networks as well as some specific mathematical issues to be addressed first. Then exploration of multi-network systemic structures and dynamic graphs with inter-network faults or failures can be carried out to the full and can reveal essential differences in comparison with standard dynamic networks.

A. On Mathematical Models of Network-of-Networks with Inter-network Connection Faults

Let consider r dynamical networks, and suppose the k -th network is composed of N_k nodes whose associated dynamic systems have dimensions n_k. Also, networks where both *permanent* and *recoverable* faults of coupled nodes among different networks may occur are encompassed in this study. Thus the i -th node in the k -th network are modeled by:

$$\left\{\begin{aligned} \dot{x}_i^k(t) &= f^k(x_i^k(t)) + \sum_{j=1,j\neq i}^{N_k} a_{ij}^{kk}(x_j^k(t)-x_i^k(t)) \\ &\quad + \sum_{l=1,l\neq k}^{r}\sum_{j=1}^{[\alpha N_l]}(m_{ij}^{kl}(t)+a_{ij}^{kl})(\Gamma^{kl}x_j^l(t)-x_i^k(t)) \\ &\quad + \sum_{l=1,l\neq k}^{r}\sum_{j=[\alpha N_l]+1}^{N_l}\delta_{ij}^{kl}(t)a_{ij}^{kl}(\Gamma^{kl}x_j^l(t)-x_i^k(t)), \\ &\quad i=1,2,...,N_k,\ k=1,2,...,r. \end{aligned}\right. \tag{1}$$

Quantities in here, denote: $t\in\mathbb{R}^+$ is the independent variable of time; $x_i^k(t)=(x_{i1}^k(t),x_{i2}^k(t),\cdots,x_{in_k}^k(t))^{\mathrm{T}}\in\mathbb{R}^{n_k}$ is the state vector of node i in the k -th network; $f^k(\cdot):\mathbb{R}^{n_k}\to\mathbb{R}^{n_k}$ is a nonlinear vector-valued function of a given node, describing functional dynamics of nodes. Matrix $A_{kk}=(a_{ij}^{kk})\in\mathbb{R}^{N_k\times N_k}$ describes the coupling configuration, representing topological structure and coupling strength of the k-th network, where $a_{ij}^{kk}>0$ if there is a healthy connection edge between nodes 'i' and 'j' $(i\neq j)$ and $a_{ij}^{kk}=0$ if otherwise; $A_{kl}=(a_{ij}^{kl})\in\mathbb{R}^{N_k\times N_l}$ is the matrix of external connections. Real-valued constant α represents the proportion of nodes where failures occurrence $[\alpha N_l]$ represents the number of nodes in which *permanent* faults occur, while $N_l-[\alpha N_l]$ represents the number of nodes in which *recoverable* faults occur. Variable $m_{ij}^{kl}(t)$ represents the fault signal pointing to connection problem between the l-th and the k-th sub-network. Quantity Γ^{kl} is a chosen suitable dimension-transformation matrix, highlighted in the sequel.

Further, a random variable $\delta_{ij}(t)$ is employed to describe the probabilistic events of connection failure and recovery in considered network systemic structure (1), namely:

$$\delta_{ij}^{kl}(t)=\begin{cases}1 & \text{Connection edge is operational,}\\ 0 & \text{Connection edge is faulty or failed.}\end{cases}\tag{2}$$

Assumption 1 [28]***:*** Probabilistic events of connection failure or malfunctioning $\delta_{ij}^{kl}(t)$ obeys the Bernoulli distribution hence the equalities $\operatorname{Prob}\{\delta_{ij}^{kl}(t)=1\}=\bar{\delta}_{ij}^{kl}$, $\operatorname{Prob}\{\delta_{ij}^{kl}(t)=0\}=1-\bar{\delta}_{ij}^{kl}$, where $\bar{\delta}_{ij}^{kl}$ is the probability that the connection will not fail, are satisfied.

Suppose that connection edge of network (1) is represented as follows:

$$\begin{aligned}a_{ii}^{kk}=&-\sum_{j=1,j\neq i}^{N_k}a_{ij}^{kk}-\sum_{l=1,l\neq k}^{r}\sum_{j=1}^{[\alpha N_l]}(m_{ij}^{kl}(t)+a_{ij}^{kl})\\&-\sum_{l=1,l\neq k}^{r}\sum_{j=[\alpha N_l]+1}^{N_l}\delta_{ij}^{kl}(t)a_{ij}^{kl},\ i=1,2...,N_k,k=1,...,r.\end{aligned}\tag{3}$$

Then, network (1) can be described [28], [31] as

$$\begin{cases}\dot{x}_i^k(t)=f^k(x_i^k(t))+\sum_{j=1}^{N_k}a_{ij}^{kk}x_j^k(t)\\ \qquad+\sum_{l=1,l\neq k}^{r}\sum_{j=1}^{[\alpha N_l]}(m_{ij}^{kl}(t)+a_{ij}^{kl})\Gamma^{kl}x_j^l(t)\\ \qquad+\sum_{l=1,l\neq k}^{r}\sum_{j=[\alpha N_l]+1}^{N_l}\delta_{ij}^{kl}(t)a_{ij}^{kl}\Gamma^{kl}x_j^l(t)\\ i=1,2,...,N_k,k=1,2,...,r.\end{cases}\tag{4}$$

B. Mathematical Preliminaries: Definitions and Assumptions

Certain assumptions and definitions are in order to present.

***Definition 1* [38], [39]:** If the expectation property

$$\lim_{t\to\infty}E\left\{\sum_{i=1}^{N_k}\|x_i^k(t)-s^k(t)\|^2\right\}=0,\ i=1,...,N_k,k=1,2,...,r,\tag{5}$$

where $s^k(t)$ represents a *solution* for an isolated node system in the k-*th* network and applies for each of the multi-network nodes, then the multi-network system dynamics (4) is said to be *asymptotically Lyapunov stable in the mean-square sense*.

In Definition 1, it is important to note the solution of an isolated node

$$\dot{s}^k(t)=f^k(s^k(t))\text{ and }s^k\in\mathbb{R}_0^{+\infty}\to\mathbb{R}^n\tag{6}$$

may represent any kind of *steady-state operation*. That is, (6) may be an *equilibrium state*, a *regular periodic orbit*, a *chaotic orbit*, or *a trajectory converging to a random steady-state evolution* that may not have analytical description [28].

Definition 2: Suppose $A=(a_{ij})\in\mathbb{R}^{m\times n}$, $B=(b_{ij})\in\mathbb{R}^{p\times q}$. Then the following Kronecker product matrix is obtained

$$A\otimes B=\begin{pmatrix}a_{11}B & a_{12}B & \cdots & a_{1n}B\\ a_{21}B & a_{22}B & \cdots & a_{2n}B\\ \vdots & \vdots & \ddots & \vdots\\ a_{m1}B & a_{m2}B & \cdots & a_{mn}B\end{pmatrix}\in\mathbb{R}^{mp\times nq},\tag{7}$$

which satisfies essential properties:

(i) $(A+B)\otimes C=A\otimes C+B\otimes C$;

(ii) $(A\otimes B)^{\mathrm{T}}=A^{\mathrm{T}}\otimes B^{\mathrm{T}}$.

Assumption 2 [28]***:*** There exists a constant $\theta_k>0$, such that the nonlinear function $f^k(\cdot)$ of the k-th node dynamics satisfies

$$(x-y)^{\mathrm{T}}(f^k(x)-f^k(y))\leq\theta_k(x-y)^{\mathrm{T}}(x-y),\ \forall x,y\in\mathbb{R}^{n_k}\tag{8}$$

Assumption 3 [28]***:*** Changes in coupling connection edges are assumed to be bounded, and solely occurrence of possible coupling faults among different networks are considered.

Assumption 4 [28]***:*** Interconnections $0<\underline{m}_{ij}^{kl}\leq m_{ij}^{kl}(t)\leq\bar{m}_{ij}^{kl}$ are assumed to have edges $m_{ij}^{kl}(t)$ that satisfy update rates

$$\dot{m}_{ij}^{kl}(t)=-\beta e_i^k(t)^{\mathrm{T}}\Gamma^{kl}s^l(t),\tag{9}$$

with $i=1,2,...,N_k$, $j=1,2,...,N_l$, $k,l=1,2,...,r$, where $\underline{m}_{ij}^{kl}$ and $\bar{m}_{ij}^{kl}$ are the upper and lower bounds of $m_{ij}^{kl}(t)$ while β is a positive constant.

Assumption 5 [28]***:*** Suppose sets $V=\{i_1,i_2,...,i_N\}$ and $V_{pin}=\{i_1,i_2,...,i_l\}$ are defined such as to constitute the set the *total* nodes and the selected *pinned* nodes, respectively, for the controlled multi-network (3). Thus all nodes in $V\setminus V_{pin}$ are accessible from the pinned node set V_{pin}; i.e., for any node $i\in V\setminus V_{pin}$, always a node $j\in V_{pin}$ can be found, such that there is a functional path from node 'j' to node 'i'.

Assumption 6 [28]***:*** When a node has a recoverable fault, the external coupling connected to the node is assumed disconnected but the connection is resumed at the same time, thus $\delta_{i1}^{kl}(t)=\delta_{i2}^{kl}(t)=\cdots=\delta_{iN}^{kl}(t)=\delta_i^{kl}(t), i=1,2,...,N$, while the internal couplings are assumed not affected. In here, $\delta_i^{kl}(t)$ is also assumed to obey Bernoulli distribution and to satisfy $\operatorname{Prob}\{\delta_i^{kl}(t)=1\}=\bar{\delta}_i^{kl}$, $\operatorname{Prob}\{\delta_i^{kl}(t)=0\}=1\text{-}\bar{\delta}_i^{kl}$ (where $\bar{\delta}_i^{kl}$ is the probability that the connection will not fail).

Assumption 7 [28]***:*** There exist non-negative bounded functions $s^k(t), s^k(t), s^k(t)$.

C. Error Dynamics under a Supervisory Control Design

Assumptions 4 and 5 enable to re-write the multi-network system model (4) as follows:

$$\begin{cases} \dot{x}_i^k(t) = f^k(x_i^k(t)) + \sum_{j=1}^{N_k} a_{ij}^{kk} x_j^k(t) \\ \quad + \sum_{l=1,l\neq k}^{r} \sum_{j=1}^{[\alpha N_l]} (m_{ij}^{kl}(t) + a_{ij}^{kl}) \Gamma^{kl} x_j^l(t) \\ \quad + \sum_{l=1,l\neq k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} \delta_i^{kl}(t) a_{ij}^{kl} \Gamma^{kl} x_j^l(t) \\ i = 1,2,...,N_k, k = 1,2,...,r. \end{cases} \tag{10}$$

The supervisory synchronization controller to be designed is assumed under the principles of pinning control theory of Guangrong Chen [5], [7]. Therefore the i -th node in the k -th network is described by means of the equations

$$\begin{cases} \dot{x}_i^k(t) = f^k(x_i^k(t)) + \sum_{j=1}^{N_k} a_{ij}^{kk} x_j^k(t) \\ \quad + \sum_{l=1,l\neq k}^{r} \sum_{j=1}^{[\alpha N_l]} (m_{ij}^{kl}(t) + a_{ij}^{kl}) \Gamma^{kl} x_j^l(t) \\ \quad + \sum_{l=1,l\neq k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} \delta_i^{kl}(t) a_{ij}^{kl} \Gamma^{kl} x_j^l(t) + u_i^k(t), \\ i = 1,2,...,N_k,\ k = 1,2,...,r, \end{cases} \tag{11}$$

Inspired by the theory of pinning control schemes [5], [7], [15], [31], the class of controllers

$$\begin{cases} u_i^k(t) = -\sum_{j=1}^{N_k} h_{ij}^{kk}(t) s^k(t) - \sum_{j=[\alpha N_l]+1}^{N_l} h_{ij}^{kl} \Gamma^{kl} s^l(t) - d_i^k e_i^k(t), \\ \dot{h}_{ij}^{kk}(t) = e_i^k(t)^{\mathrm{T}} s^k(t),\ \dot{h}_{ij}^{kl}(t) = e_i^k(t)^{\mathrm{T}} \Gamma^{kl} s^l(t), \qquad i \in \phi_k, \\ \qquad u_i^k(t) = -d_i^k e_i^k(t), \qquad i = \tilde{\phi}_k - \phi_k, \end{cases} \tag{12 a}$$

are taken into consideration [28] where: $h_{ij}^{kk}(t)$ and $h_{ij}^{kl}(t)$ are some one-dimensional variables while d_i^k represent feedback control gains that satisfy rule

$$\begin{cases} d_i^k > 0, i = 1,...,l_k, \\ d_i^k = 0, i = l_k + 1,...,N_k. \end{cases} \tag{12 b}$$

Furthermore, for dynamic networks and multi-networks it is proposed to distinguish the concepts of an *inter-acting* node and an *intra-acting* node at this point of present explication. Node 'i' is said to be the inter-acting node if it belongs to the set ϕ_k; in contrast, 'i' is said to be an intra-acting node if it belongs to $\tilde{\phi}_k - \phi_k$. These conceptualizations imply that an inter-acting node can receive information from the other network clusters, whereas an intra-acting node can only exchange information within the same network cluster.

Next, suppose the synchronization errors of node 'i' in the k -th network are defined as

$$e_i^k(t) = x_i^k(t) - s^k(t). \tag{13}$$

Then the system model of error dynamics for the multi-network (11) can be derived in the form:

$$\begin{cases} \dot{e}_i^k(t) = f^k(x_i^k(t)) - f^k(s^k(t)) + \sum_{j=1}^{N_k} a_{ij}^{kk} e_j^k(t) \\ \quad + \sum_{l=1,l\neq k}^{r} \sum_{j=1}^{[\alpha N_l]} (m_{ij}^{kl}(t) + a_{ij}^{kl}) \Gamma^{kl} e_j^l(t) \\ \quad + \sum_{l=1,l\neq k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} \delta_i^{kl}(t) a_{ij}^{kl} \Gamma^{kl} e_j^l(t) + \sum_{j=1}^{N_k} a_{ij}^{kk} s^k(t) \\ \quad + \sum_{l=1,l\neq k}^{r} \sum_{j=1}^{[\alpha N_l]} (m_{ij}^{kl}(t) + a_{ij}^{kl}) \Gamma^{kl} s^l(t) \\ \quad + \sum_{l=1,l\neq k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} \delta_i^{kl}(t) a_{ij}^{kl} \Gamma^{kl} s^l(t) + u_i^k(t), \\ i = 1,2,\cdots,N_k, k = 1,...r. \end{cases} \tag{14}$$

Lemma 1 **[22]:** If node 'i' is an intra-acting node, namely, $i \in \tilde{\phi}_k - \phi_k$, then the following results hold:

$$\begin{aligned} &\sum_{k=1}^{r} \sum_{j=1}^{N_k} a_{ij}^{kk} s^k(t) = 0,\ \sum_{l=1,l\neq k}^{r} \sum_{j=1}^{[\alpha N_l]} (m_{ij}^{kl}(t) + a_{ij}^{kl}) \Gamma^{kl} s^l(t) = 0, \\ &\sum_{l=1,l\neq k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} \delta_i^{kl}(t) a_{ij}^{kl} \Gamma^{kl} s^l(t) = 0, \\ &i = 1,...,N_k, k = 1,...,r. \end{aligned} \tag{15}$$

Lemma 2 **[22]:** For a symmetric matrix $M = (m_{ij})_{N\times N}$ and $D = \mathrm{diag}(d_1,\cdots,d_q,0,\cdots,0)_{N\times N}$, $i = 1,2,\cdots,q (1 \le q \le N)$, suppose

$$M - D = \begin{bmatrix} A - \tilde{D} & C \\ C^{\mathrm{T}} & M_q \end{bmatrix}, \tag{16}$$

where M_q is the minor matrix of M obtained by removing its first q row-column pairs, and where:

$A = (a_{ij})_{q\times q}$, $a_{ij} = a_{ji} = m_{ij}, i, j = 1,2,...,q$, $C = (c_{ij})_{q\times(N-q)}$, $c_{ij} = m_{ij}$, $i = 1,2,...,q$, $j = q+1,...,N$, $M_q = (m_{q_{ij}})_{(N-q)\times(N-q)}$, $m_{q_{ij}} = m_{q_{ji}} = m_{i+q,j+q}, i, j = 1,2...,N-q$.

If $d_i > \lambda_{\max}\left(A - CM_q^{-1}C^{\mathrm{T}}\right)$, then $M - D < 0$ is equivalent to $M_q < 0$.

Lemma 3 **[6], [9]:** (*Gerschgorin Disc Theorem*) Let matrix $A = (a_{ij})_{n\times n}$ be a complex matrix and let $R_i(A) = \sum_{j=1,j\neq i}^{n} |a_{ij}|, 1 \le i \le n$ represent the deleted absolute row sums of A. Then all the eigenvalues of A are located in the union of the following n discs:

$$G(A) = \bigcup_{i=1}^{n} \{z \in C : |z - a_{ii}| \le R_i(A)\}. \tag{17}$$

Remark 2: If A is a real-valued symmetric matrix, it follows from Lemma 1 that the eigenvalues λ of A satisfy

$$\min_{1\le i\le n}(a_{ii} - R_i(A)) \le \lambda \le \max_{1\le i\le n}(a_{ii} + R_i(A)). \tag{18}$$

Lemma 4 **[9], [27]:** Let assume that A, B are $N \times N$

Hermitian matrices and $\alpha_1 \ge \alpha_2 \ge ... \ge \alpha_N$, $\beta_1 \ge \beta_2 \ge ... \ge \beta_N$, $\gamma_1 \ge \gamma_2 \ge ... \ge \gamma_N$ are the eigenvalues of matrices A, B, and $A + B$, respectively. Then $\alpha_i + \beta_N \le \gamma_i \le \alpha_i + \beta_1$ hold true.

Now the main results can be presented.

III. Main Innovated Results

A sufficient asymptotic stability condition ought to be derived for the considered multi-networks assuming they may happen to have both *permanent* fault and *recoverable* fault in connection-coupled nodes among different networks [38]. Though, the concepts and ideas of Lyapunov stability theory from [30] ought be employed as applied to networks [35-36], [38] and synchronization of networks [18-20], [26], [50-51].

Theorem 1: Under the Assumptions 1-5, the controlled multi-network (11) with the controller system (12 a, b) can accomplish the desired synchronization *if* the following inequality

$$\Theta - D + A^s < 0 \tag{19}$$

is satisfied, where:

$$D = \mathrm{diag}(d_1^1 I_{n_1}, ..., d_{N_1}^1 I_{n_1}, d_1^2 I_{n_2}, ..., d_{N_2}^2 I_{n_2}, ..., d_1^r I_{n_r}, ..., d_{N_r}^r I_{n_r});$$

$$\Theta = \mathrm{diag}(\theta_1 I_{N_1 \times n_1}, ..., \theta_r I_{N_r \times n_r}); \; A^s = \frac{A + A^{\mathrm{T}}}{2};$$

$$A = \begin{bmatrix} \tilde{A}_{11} & \tilde{A}_{12} & \cdots & \tilde{A}_{1r} \\ \tilde{A}_{21} & \tilde{A}_{22} & \cdots & \tilde{A}_{2r} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{A}_{r1} & \tilde{A}_{r2} & \cdots & \tilde{A}_{rr} \end{bmatrix}, \; \tilde{A}_{kk} = \bar{A}_{kk} \otimes I_{n_k}, \; \tilde{A}_{kl} = \bar{A}_{kl} \otimes \Gamma^{kl}, \text{ when}$$

$$j = 1, 2, ..., [\alpha N_l];$$

$$(\bar{A}_{kl})_{ij} = \bar{m}_{ij}^{kl} + a_{ij}^{kl}, \text{ when } j = [\alpha N_l] + 1, ...N_l;$$

$$(\bar{A}_{kl})_{ij} = \bar{\delta}_i^{kl} a_{ij}^{kl}, \; (\bar{A}_{kk})_{ij} = a_{ij}^{kk}, \; i, j = 1, 2, ..., N_k, k = 1, 2, ..., r.$$

Proof [28]. Finding appropriate composite Lyapunov function is the crucial task of the problem in the synthesis of multi-network systems. In this case Lyapunov function candidate is built by using component Lyapunov-like quadratic forms:

$$V_1(t) = \frac{1}{2} \sum_{k=1}^{r} \sum_{i=1}^{N_k} e_i^k(t)^{\mathrm{T}} e_i^k(t), \tag{20}$$

$$V_2(t) = \frac{1}{2} \sum_{k=1}^{r} \sum_{i \in \phi_k} \sum_{l=1, l \ne k}^{r} \sum_{j=1}^{[\alpha N_l]} \frac{(m_{ij}^{kl}(t) + a_{ij}^{kl})^2}{\beta}, \tag{21}$$

$$V_3(t) = \frac{1}{2} \sum_{k=1}^{r} \sum_{i \in \phi_k} \sum_{l=1, l \ne k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} (h_{ij}^{kl}(t) - \bar{\delta}_i^{kl} a_{ij}^{kl})^2, \tag{22}$$

$$V_4(t) = \frac{1}{2} \sum_{k=1}^{r} \sum_{i \in \phi_k} \sum_{j=1}^{N_k} (h_{ij}^{kk}(t) - a_{ij}^{kk})^2. \tag{23}$$

Thus, composite Lyapunov function candidate is given as

$$V(t) = V_1(t) + V_2(t) + V_3(t) + V_4(t). \tag{24}$$

Next, the differential operator of the first time-derivative of Lyapunov function (20), conveniently denoted as $\ell V_1(t)$, is calculated. Due to Assumptions 1 and 2 as well as Lemma 1, and supported by Lemmas 3 and 4, one can calculate:

$$\begin{aligned}
\ell V_1(t) &= \sum_{k=1}^{r} \sum_{i=1}^{N_k} e_i^k(t)^{\mathrm{T}} \dot{e}_i^k(t) \\
&= \sum_{k=1}^{r} \sum_{i \in \phi_k} e_i^k(t)^{\mathrm{T}} [f^k(x_i^k(t)) - f^k(s^k(t)) + \sum_{j=1}^{N_k} a_{ij}^{kk} e_j^k(t) \\
&+ \sum_{l=1, l \ne k}^{r} \sum_{j=1}^{[\alpha N_l]} (m_{ij}^{kl}(t) + a_{ij}^{kl}) \Gamma^{kl} e_j^l(t) + \sum_{l=1, l \ne k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} \delta_i^{kl}(t) a_{ij}^{kl} \Gamma^{kl} e_j^l(t) + \sum_{j=1}^{N_k} a_{ij}^{kk} s^k(t) \\
&+ \sum_{l=1, l \ne k}^{r} \sum_{j=1}^{[\alpha N_l]} (m_{ij}^{kl}(t) + a_{ij}^{kl}) \Gamma^{kl} s^l(t) - \sum_{j=1}^{N_k} h_{ij}^{kk}(t) s^k(t) - d_i^k e_i^k(t)] \\
&+ \sum_{k=1}^{r} \sum_{i \in \phi_k} e_i^k(t)^{\mathrm{T}} \left[\sum_{l=1, l \ne k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} \delta_i^{kl}(t) a_{ij}^{kl} \Gamma^{kl} s^l(t) - \sum_{l=1, l \ne k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} h_{ij}^{kl} \Gamma^{kl} s^l(t) \right] \\
&+ \sum_{k=1}^{r} \sum_{i \in \tilde{\phi}_k - \phi_k} e_i^k(t)^{\mathrm{T}} \left[f^k(x_i^k(t)) - f^k(s^k(t)) + \sum_{j=1}^{N_k} a_{ij}^{kk} e_j^k(t) - d_i^k e_i^k(t) \right] \\
&\le \sum_{k=1}^{r} \sum_{i \in \phi_k} e_i^k(t)^{\mathrm{T}} \left[(\theta_k - d_i^k) e_i^k(t) + \sum_{j=1}^{N_k} a_{ij}^{kk} e_j^k(t) + \sum_{l=1, l \ne k}^{r} \sum_{j=1}^{[\alpha N_l]} (m_{ij}^{kl}(t) + a_{ij}^{kl}) \Gamma^{kl} e_j^l(t) \right. \\
&\left. + \sum_{l=1, l \ne k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} \delta_i^{kl}(t) a_{ij}^{kl} \Gamma^{kl} e_j^l(t) \right] \\
&+ \sum_{k=1}^{r} \sum_{i \in \phi_k} e_i^k(t)^{\mathrm{T}} \left[\sum_{j=1}^{N_k} a_{ij}^{kk} s^k(t) + \sum_{l=1, l \ne k}^{r} \sum_{j=1}^{[\alpha N_l]} (m_{ij}^{kl}(t) + a_{ij}^{kl}) \Gamma^{kl} s^l(t) - \sum_{j=1}^{N_k} h_{ij}^{kk}(t) s^k(t) \right] \\
&+ \sum_{k=1}^{r} \sum_{i \in \phi_k} e_i^k(t)^{\mathrm{T}} \left[\sum_{l=1, l \ne k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} \delta_i^{kl}(t) a_{ij}^{kl} \Gamma^{kl} s^l(t) - \sum_{l=1, l \ne k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} h_{ij}^{kl} \Gamma^{kl} s^l(t) \right] \\
&+ \sum_{k=1}^{r} \sum_{i \in \tilde{\phi}_k - \phi_k} e_i^k(t)^{\mathrm{T}} \left[(\theta_k - d_i^k) e_i^k(t) + \sum_{j=1}^{N_k} a_{ij}^{kk} e_j^k(t) \right].
\end{aligned} \tag{25}$$

Similarly, by calculating differential operators of the first time-derivative of (21)-(23), one can establish results:

$$\ell V_2(t) = -\sum_{k=1}^{r} \sum_{i \in \phi_k} \sum_{l=1, l \ne k}^{r} \sum_{j=1}^{[\alpha N_l]} (m_{ij}^{kl}(t) + a_{ij}^{kl}) e_i^k(t)^{\mathrm{T}} \Gamma^{kl} s^l(t), \tag{26}$$

$$\ell V_3(t) = \sum_{k=1}^{r} \sum_{i \in \phi_k} \sum_{l=1, l \ne k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} (h_{ij}^{kl}(t) - \bar{\delta}_i^{kl} a_{ij}^{kl}) e_i^k(t)^{\mathrm{T}} \Gamma^{kl} s^l(t), \tag{27}$$

$$\ell V_4(t) = \sum_{k=1}^{r} \sum_{i \in \phi_k} \sum_{j=1}^{N_k} (h_{ij}^{kk}(t) - a_{ij}^{kk}) e_i^k(t)^{\mathrm{T}} s^k(t). \tag{28}$$

Next, the combined consideration of the above four results yields the first time-derivative of the composite Lyapunov function, conceptualized by means of (25)-(28), as follows:

$$\ell V(t) = \ell V_1(t) + \ell V_2(t) + \ell V_3(t) + \ell V_4(t). \tag{29}$$

Hence the following end result is readily found as follows:

$$\begin{aligned}
\ell V(t) &= \sum_{k=1}^{r} \sum_{i \in \phi_k} e_i^k(t)^{\mathrm{T}} \left[(\theta_k - d_i^k) e_i^k(t) + \sum_{j=1}^{N_k} a_{ij}^{kk} e_j^k(t) \right. \\
&\left. + \sum_{l=1, l \ne k}^{r} \sum_{j=1}^{[\alpha N_l]} (m_{ij}^{kl}(t) + a_{ij}^{kl}) \Gamma^{kl} e_j^l(t) + \sum_{l=1, l \ne k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} \delta_i^{kl}(t) a_{ij}^{kl} \Gamma^{kl} e_j^l(t) \right] \\
&+ \sum_{k=1}^{r} \sum_{i \in \phi_k} e_i^k(t)^{\mathrm{T}} \left[\sum_{l=1, l \ne k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} \delta_i^{kl}(t) a_{ij}^{kl} \Gamma^{kl} s^l(t) - \sum_{l=1, l \ne k}^{r} \sum_{j=[\alpha N_l]+1}^{N_l} \bar{\delta}_i^{kl} a_{ij}^{kl} \Gamma^{kl} s^l(t) \right] \\
&+ \sum_{k=1}^{r} \sum_{i \in \tilde{\phi}_k - \phi_k} e_i^k(t)^{\mathrm{T}} \left[(\theta_k - d_i^k) e_i^k(t) + \sum_{j=1}^{N_k} a_{ij}^{kk} e_j^k(t) \right].
\end{aligned} \tag{30}$$

The calculation of the expected value of (30) does yield:

$$E\{\ell V(t)\}=\sum_{k=1}^{r}\sum_{i\in\phi_k}e_i^k(t)^{\mathrm{T}}\Bigg[(\theta_k-d_i^k)e_i^k(t)+\sum_{j=1}^{N_k}a_{ij}^{kk}e_j^k(t)$$
$$+\sum_{l=1,l\neq k}^{r}\sum_{j=1}^{[\alpha N_l]}(m_{ij}^{kl}(t)+a_{ij}^{kl})\Gamma^{kl}e_j^l(t)+\sum_{l=1,l\neq k}^{r}\sum_{j=[\alpha N_l]+1}^{N_l}\bar{\delta}_i^{kl}a_{ij}^{kl}\Gamma^{kl}e_j^l(t)\Bigg] \quad (31)$$
$$+\sum_{k=1}^{r}\sum_{i\in\bar{\phi}_k-\phi_k}e_i^k(t)^{\mathrm{T}}\Bigg[(\theta_k-d_i^k)e_i^k(t)+\sum_{j=1}^{N_k}a_{ij}^{kk}e_j^k(t)\Bigg]$$

Thus, by virtue of Assumption 2, one can establish

$$\sum_{k=1}^{r}\sum_{i\in\phi_k}e_i^k(t)^{\mathrm{T}}[(\theta_k-d_i^k)e_i^k(t)+\sum_{j=1}^{N_k}a_{ij}^{kk}e_j^k(t)$$
$$+\sum_{l=1,l\neq k}^{r}\sum_{j=1}^{[\alpha N_l]}(m_{ij}^{kl}(t)+a_{ij}^{kl})\Gamma^{kl}e_j^l(t)+\sum_{l=1,l\neq k}^{r}\sum_{j=[\alpha N_l]+1}^{N_l}\bar{\delta}_i^{kl}a_{ij}^{kl}\Gamma^{kl}e_j^l(t)]$$
$$\leq\sum_{k=1}^{r}\sum_{i\in\phi_k}^{N_k}e_i^k(t)^{\mathrm{T}}\left[(\theta_k-d_i^k)e_i^k(t)\right]+\sum_{k=1}^{r}\sum_{i\in\phi_k}^{N_k}e_i^k(t)^{\mathrm{T}}\sum_{j=1}^{N_k}a_{ij}^{kk}e_j^k(t) \quad (32)$$
$$+\sum_{k=1}^{r}\sum_{i\in\phi_k}^{N_k}\sum_{l=1,l\neq k}^{r}\sum_{j=1}^{[\alpha N_l]}|e_i^k(t)|^{\mathrm{T}}(\bar{m}_{ij}^{kl}+a_{ij}^{kl})\Gamma^{kl}|e_j^l(t)|$$
$$+\sum_{k=1}^{r}\sum_{i\in\phi_k}^{N_k}\sum_{l=1,l\neq k}^{r}\sum_{j=[\alpha N_l]+1}^{N_l}e_i^k(t)^{\mathrm{T}}\bar{\delta}_i^{kl}a_{ij}^{kl}\Gamma^{kl}e_j^l(t),$$

where $|e_i^k(t)|=(|e_{i1}^k(t)|,|e_{i2}^k(t)|,\cdots,|e_{in_k}^k(t)|)^{\mathrm{T}}\in\mathbb{R}^{n_k}$. Then combining results (30) and (31) does yield

$$E\{\ell V(t)\}\leq|e(t)|^{\mathrm{T}}(\Theta-D+A^s)|e(t)| \quad (33)$$

where:

$$|e(t)|=(|e_1^1(t)|^{\mathrm{T}},...,|e_{N_1}^1(t)|^{\mathrm{T}},|e_1^2(t)|^{T},...,$$
$$|e_{N_2}^2(t)|^{\mathrm{T}},...,|e_1^r(t)|^{\mathrm{T}},...,|e_{N_r}^r(t)|^{\mathrm{T}})^{\mathrm{T}}.$$

It is therefore that, whenever inequality (19) is satisfied, then the expectation the first time-derivative of Lyapunov function is $E\{\ell V(t)\}<0$, that is negative definite, which implies asymptotic stability of the error dynamics of the controlled network system. Thus the synchronization in the mean-square sense for the multi-network (11) under the pinning control (12 a, b) is guaranteed asymptotically stable. □

Remark 3: It should be noted, whenever inequality (19) is satisfied, so are satisfied inequalities implied by Lemmas 2 and 3 as well as Remark 2.

Theorem 1 guaranteed the synchronization in general multi-network structure is feasible by employing the pinning control (12 a, b). Therefore, given the validity of the adopted Lemmas 1-4, one can conclude: (i) At least one design algorithm for the gains of pinning control (12 a) is feasible too hence it can be found; and (ii) The pinning control (12 a, b), provided it does exist, then it does govern the multi-network (4) or the network-of-networks systemic structure (1) by operating as an acting supervisory coordinator [33], [35].

One such design algorithm via network node manipulation, in the view of right-hand matrices in the inequality (19), has been derived as follows [14-16]. For this purpose, the nodes taken are reordered as outlined below: The inter-acting nodes that are subject to control are adopted as the first q nodes, while the remaining nodes are left uncontrolled. In this way a control selection is designed. At the same time the matrix

$$G=(\mathrm{g}_{ij})_{N\times N}=\Theta+A^s \quad (34)$$

is constructed. Therefore, instead of equality (15) in Lemma 2, the following result is obtained:

$$G-\tilde{D}=\begin{bmatrix}B-\tilde{D} & C\\ C^{\mathrm{T}} & G_q\end{bmatrix}. \quad (35)$$

In here quantities denote: $B=(b_{ij})_{q\times q},b_{ij}=b_{ji}=g_{ij},i=1,...,q$, gains $\tilde{D}=\mathrm{diag}(d_1,\cdots,d_q)$, $C=(c_{ij})_{q\times(N-q)}$, $c_{ij}=g_{ij}$, $i=1,...,q,$, $j=q+1,q+2,...,N$. In (35) G_q is the minor of matrix G by removing its first q row-column pairs.

Next, the effect influence of the control node selection is discussed. For this purpose, let it be defined and denoted:

$$-a_{ii}^{kk}=\sum_{j=1,j\neq i}^{N_k}a_{ij}^{kk}+\sum_{l=1,l\neq k}^{r}\sum_{j=1}^{N_l}a_{ij}^{kl}=\mathrm{Degin}(k_i), \quad (36)$$
$$\sum_{j=1,j\neq i}^{N_k}a_{ji}^{kk}+\sum_{l=1,l\neq k}^{r}\sum_{j=1}^{N_l}a_{ji}^{kl}=\mathrm{Degout}(k_i). \quad (37)$$

In here, $\mathrm{Degin}(k_i)$ and $\mathrm{Degout}(k_i)$ denote the in-degree and the out-degree of a given node vertex 'i', respectively.

In order to ensure G is negative definite always, Eq. (34) must yield diagonal elements less than zero. Theorem 1 still remains satisfied if the nodes whose diagonal elements are bigger than zero are being kept as controlled ones. Matrix G has diagonal elements determined by equation

$$G_{ii}^k=\theta_k+a_{ii}^{kk}=\theta_k-\mathrm{Degin}(k_i) \quad (38)$$

Note that the smaller the in-degrees of a vertex is, then the more easily the diagonal element may be greater than zero. Thus pining-control candidate nodes ought to be selected among some vertices with very small in-degree values. It should be noted though, some vertices with very small in-degrees are also bound to receive very little information from all the other vertices; therefore it is unlikely these be readily controlled by other nodes. Thus it is necessary to apply additional control effort with other nodes in order to achieve desired controlled synchronization of the considered network.

From Lemma 2, whenever (19) is satisfied, if (37) and (38) are also satisfied

$$G_q<0, \quad (39)$$
$$d_i>\lambda_{\max}\left(B-CG_q^{-1}C^{\mathrm{T}}\right), \quad (40)$$

then the multi-network (11) is globally synchronized under the given pinning controllers (12 a. b).

By virtue of Lemma 3 and Remark 2, one can readily establish the arbitrary eigenvalue $\lambda\leq\max(\mathrm{G}_{q_{ii}}+\sum_{j=1,j\neq i}^{N}G_{q_{ij}})$ of the matrix G is such that λ is less than the largest row sum of G_q. Thus the smaller the largest row sum of G_q is, the matrix is more likely to be negative definite when the largest row sum of the matrix G_q is small. The matrix G_q is more likely to be negative definite when there are subject to control all the nodes for which the row-sum of the matrix G nodes has greater value. By means of (34) and (35), one finds that the row-sum of matrix G is given as follows:

$$\theta_k + \frac{\text{Degout}(k_i) - \text{Degin}(k_i)}{2} \tag{41}$$

It is also apparent, the greater the difference out-degree and in-degree for a given node is, the more likely the row-sum of the matrix G is greater than zero.

In turn, it is readily concluded the network is more likely to reach synchronization if the vertices with large out-degrees are being pinned for controller infrastructure. For, the vertices with large out-degrees can influence many other vertices in the multi-network structure. These findings yield the below summarized algorithm for the pinned-node design selection scheme.

Pinned-Node Selection Scheme Algorithm

(1) All inter-acting nodes are controlled and the total number is denoted as q_0.

(2) In the remaining nodes, the nodes with diagonal elements of matrix G that are greater than zero are controlled via the remaining nodes, and the total number is denoted as q_1.

(3) All remaining nodes are sorted by the row sum of matrix descending order, let $q = q_0 + q_1$.

(4) Calculate whether the matrix G_q is negative definite. If G_q is not negative definite, let $q = q+1$, go to step (3); otherwise, go to calculate feedback control gains by using inequality (40) via maximal eigenvalue of resulting matrix in the right-hand side; *Stop*.

IV. A Case-Study Example And Simulation Results

A complex systemic structure possessing three directional networks, namely ***r* =3**, is taken as an example for numerical simulation in order to clearly illustrate what functioning the above presented theoretical results imply. The network-of-networks structure is shown in Figure 1. The number of nodes in each network is ***N₁=4, N₂=3, N₃=3,*** respectively.

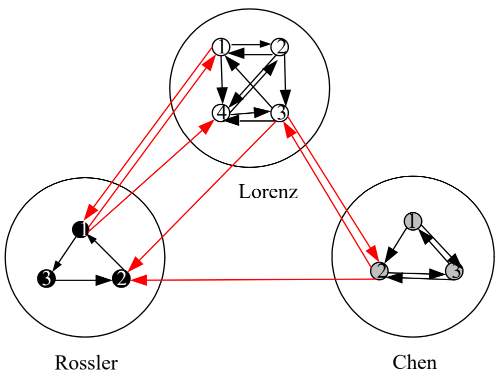

Fig. 1 Topological structure of the benchmark multi-network

The nodes in the first network are selected to represent the four-dimensional hyper-chaotic Lorenz system. The nodes in the second network are chosen to construct three-dimensional Rossler system. The nodes in the third network are selected to create a three-dimensional Chen system [28]. The respective mathematical models are presented further below.

Nodes absorbing hyper-chaotic Lorenz dynamic system are described by equations:

$$\begin{aligned}
\dot{x}_1(t) &= 10(x_2(t) - x_1(t)) + x_4(t), \\
\dot{x}_2(t) &= 28x_1(t) - x_2(t) - x_1(t)x_3(t), \\
\dot{x}_3(t) &= x_1(t)x_2(t) - 8/3x_3(t), \\
\dot{x}_4(t) &= -x_1(t)x_3(t) + 13/10x_3(t).
\end{aligned}$$

Nodes absorbing Rossler dynamic system are described by equations:

$$\begin{aligned}
\dot{x}_1(t) &= -x_2(t) - x_3(t), \\
\dot{x}_2(t) &= x_1(t) + 0.2x_2(t), \\
\dot{x}_3(t) &= x_1(t)x_3(t) - 5.7x_3(t) + 0.2.
\end{aligned}$$

Nodes absorbing Chen dynamic system are described by equations:

$$\begin{aligned}
\dot{x}_1(t) &= 35(x_2(t) - x_1(t)), \\
\dot{x}_2(t) &= -7x_1(t) + 28x_2(t) - x_1(t)x_3(t), \\
\dot{x}_3(t) &= -3x_3(t) + x_1(t)x_2(t).
\end{aligned}$$

Notice that chaotic attractors of the hyper-chaotic Lorenz system, Rossler system and Chen system appear with bounded regions hence numerical simulations by computer are feasible. Thus, by means of numerical simulations, one can find that there exist some constants for the first network as follows

$$M_{11} = 25, M_{12} = 25, M_{13} = 45,\ M_{14} = 180,$$

such that $|s_{11}| \le M_{11}$, $|s_{12}| \le M_{12}$, $|s_{13}| \le M_{13}$, $|s_{14}| \le M_{14}$.

For the parameters of Assumption 1, they can be calculated using the following method as illustrated with its application to o the first network as a guidance example. Indeed, one has:

$$\begin{aligned}
&(x_i - s^1)^{\mathrm{T}}(f^1(x_i) - f^1((s^1)) \\
&= e_i^{\mathrm{T}}(10e_{i2} - 10e_{i1} + e_{i4}, 28e_{i1} - e_{i2} - x_{i1}x_{i3} + s_{11}s_{13}, \\
&x_{i1}x_{i2} - s_{11}s_{12} - 8/3e_{i3}, 1.3e_{i4} - x_{i1}x_{i3} + s_{11}s_{13})^{\mathrm{T}} \\
&\le -10e_{i1}^2 - e_{i2}^2 - 8/3e_{i3}^2 + 1.3e_{i4}^2 + (38 + M_{13})|e_{i1}e_{i2}| + M_{12}|e_{i1}e_{i3}| \\
&\quad + (1 + M_{13})|e_i e_{i4}| + M_{11}|e_{i3}e_{i4}| \\
&\le (-10 + \frac{\varepsilon_1(38 + M_{13})}{2} + \frac{\varepsilon_2 M_{12}}{2} + \frac{\varepsilon_3(1 + M_{13})}{2})e_{i1}^2 + (-1 + \frac{38 + M_{13}}{2\varepsilon_1})e_{i2}^2 \\
&\quad + (-\frac{8}{3} + \frac{M_{12}}{2\varepsilon_2} + \frac{\varepsilon_4 M_{11}}{2})e_{i3}^2 + (1.3 + \frac{1 + M_{13}}{2\varepsilon_3} + \frac{M_{11}}{2\varepsilon_4})e_{i4}^2
\end{aligned}$$

where $\varepsilon_i (i = 1,2,3,4)$ are arbitrary positive constants. Then computing using $(\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4) = (1.0, 0.4, 0.6, 1.2)$ yields $\theta_1 = 50.3$ hence Assumption 1 holds true. For the second and third networks it can be found $\theta_2 = 38.1$, $\theta_2 = 44.5$.

The coupling matrix of the multi-network is given as:

$$A=\left[\begin{array}{cccc:ccc:ccc}
-100 & 50 & 0 & 40 & 10 & 0 & 0 & 0 & 0 & 0\\
30 & -110 & 40 & 40 & 0 & 0 & 0 & 0 & 0 & 0\\
20 & 0 & -140 & 80 & 0 & 10 & 0 & 0 & 30 & 0\\
0 & 40 & 30 & -70 & 0 & 0 & 0 & 0 & 0 & 0\\
\hdashline
10 & 0 & 0 & 30 & -70 & 0 & 30 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 70 & -70 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 50 & -50 & 0 & 0 & 0\\
\hdashline
0 & 0 & 0 & 0 & 0 & 0 & 0 & -40 & 30 & 10\\
0 & 0 & 20 & 0 & 0 & 10 & 0 & 0 & -60 & 30\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 70 & 20 & -90
\end{array}\right]$$

Initial values for the hyper-chaotic Lorenz system, for the Rossler system, and for the Chen system, respectively, are $x_0=(7,6,5,4)^{\mathrm{T}}$, $x_0=(-10,0,10)^{\mathrm{T}}$ and $x_0=(-4,2,8)^{\mathrm{T}}$. In turn, computer simulations yielded the time-evolution curves of state response that are depicted in Figures 2-4.

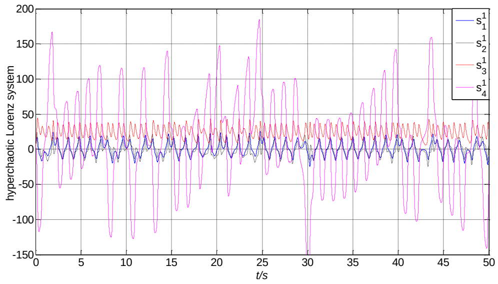

Fig.2 State responses of the hyper-chaotic Lorenz system in the time domain when $s_{10}=(7,6,5,4)^{\mathrm{T}}$

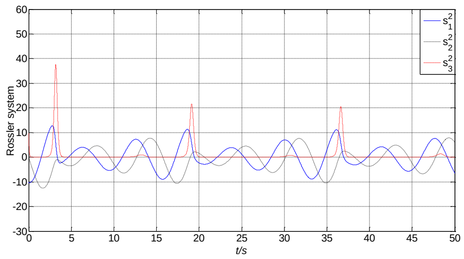

Fig.3 State responses of the Rossler system in the time domain when $s_{20}=(-10,0,10)^{\mathrm{T}}$

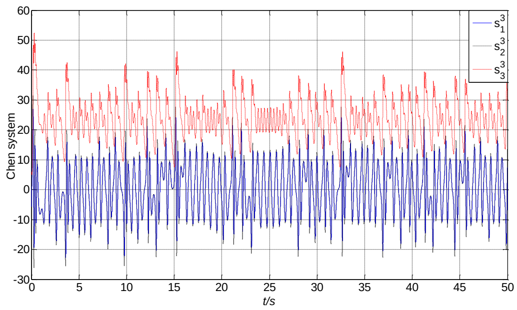

Fig.4 State responses of the Chen system in the time domain when $s_{30}=(-4,2,8)^{\mathrm{T}}$

The hyper-chaotic Lorenz system has the state response shown in Fig. 2, the Rossler system has the state response shown in Fig. 3, and the Chen system has the state response shown in Fig. 4. They all are the final synchronization states of three directional networks respectively.

Simulation is carried out without applying control in order to compare the effect of multi-network synchronization before and after implanting the control infrastructure. The error evolution curves in the time domain for the nodes in multi-network system and for isolated nodes are shown in Figures 5-7. As it can be seen from these figures, each node in the multi-network cannot achieve synchronization only on the grounds of the coupling effects among the networks.

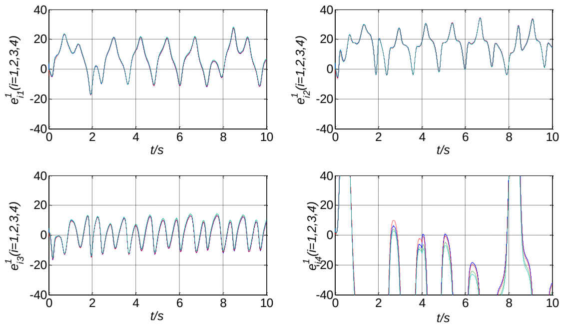

Fig.5 Error response curve $e_i^1\in\mathbb{R}^4, i=1,2,3,4$ in the time domain of the first uncontrolled network

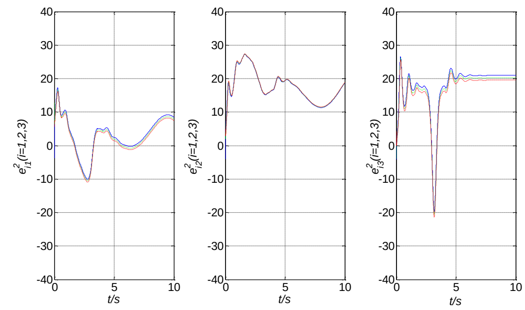

Fig.6 Error response curve $e_i^2\in\mathbb{R}^3, i=1,2,3$ in the time domain of the second uncontrolled network

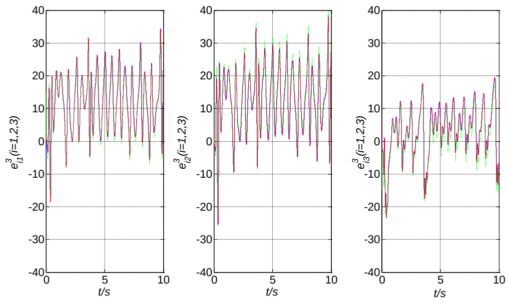

Fig.7 Error response curve $e_i^3\in\mathbb{R}^3, i=1,2,3$ in the time domain of the third uncontrolled network

A. Results under Specifically-designed Pinning scheme

Let consider the case where a permanent fault and a recoverable fault occur among different networks; step signal is the permanent one. By choosing $m_{11}^{12}(t)=40*\varepsilon(\mathrm{t}-3)$,

$m_{11}^{21}(t) = 35 * \varepsilon(t-3)$, $m_{22}^{32}(t) = 30 * \varepsilon(t-3)$, $m_{32}^{12}(t) = 35 * \varepsilon(t-3)$. The fault curve is shown in Fig. 8. The probabilities of the normal connection of recoverable nodes are $\bar{\delta}_3^{13} = 0.4$, $\bar{\delta}_1^{21} = 0.75$. Recoverable fault curves are shown in Fig. 9 and Fig. 10.

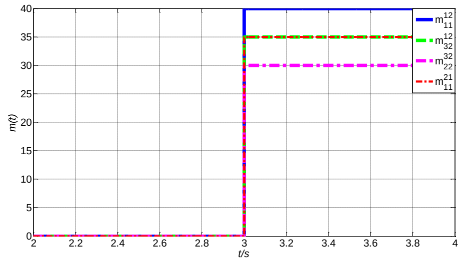

Fig.8 Evolution curve of the permanent fault in time-domain

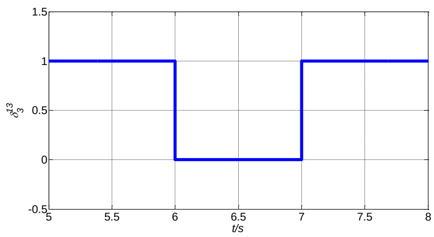

Fig.9 Evolution curve of the recoverable fault in time-domain: Recoverable failure happens about the third node in the first controlled network

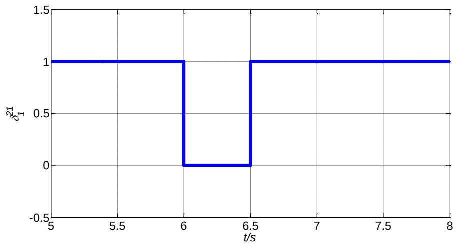

Fig.10 Evolution curve of the recoverable fault in time-domain: Recoverable failure happens about the first node in the second controlled network

Substituting the simulation values into (2.24) and (2.25), and the nodes are selected according to the node selection scheme:

(1) The inter-acting nodes 1 and 3 in the first network, the inter-acting node 1 in the second network and the inter-acting node 2 in the third network are controlled. The total number of inter-act nodes is denoted as $q_0 = 4$.

(2) In the remaining nodes, the node that diagonal element of the matrix G is more than zero is controlled, which is the node 1 in the third network. The number of nodes is $q_1 = 1$.

(3) All remaining nodes are sorted by the row sum of matrix descending order, let $q = q_0 + q_1$.

(4) G_q is negative definite through calculating when the nodes 1, 3 in the first network, the node 1 in the second network and the nodes 1,2 in the third network are controlled. Theorem 1 is satisfied by (30) to calculate feedback control gains, that are designed as follows:

(5) $\begin{cases} d_i^1 = 50, i = 1,3, \\ d_i^1 = 0, i = 2,4; \end{cases}, \begin{cases} d_i^2 = 200, i = 1, \\ d_i^2 = 0, i = 2,3; \end{cases}, \text{and} \begin{cases} d_i^3 = 80, i = 1,2, \\ d_i^2 = 0, i = 3. \end{cases}$

Under the control of the above-mentioned pinning scheme, the permanent fault occurs in the coupling connection among the networks at the third second of time, and the recoverability fault occurs in the coupling connection among the networks at the sixth time. As a result of external interference caused some nodes among networks to disconnect at the same time, after a period of self-adjustment, the node to restore network connectivity, this process alternately occurs randomly. The error response curves are shown in Figures 11-13.

The role of the pinning controller and its impact on the multi-network structure can be clearly from the error response curves in the time domain that are depicted in Figures 11-13.

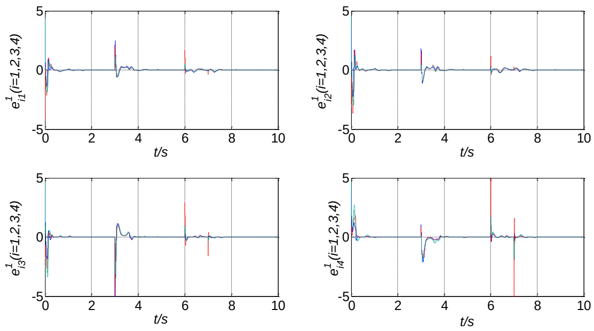

Fig.11 Evolution of the error response curve $e_i^1 \in \mathbb{R}^4, i = 1,2,3,4$ in the time domain for the first controlled network under the special pinning control

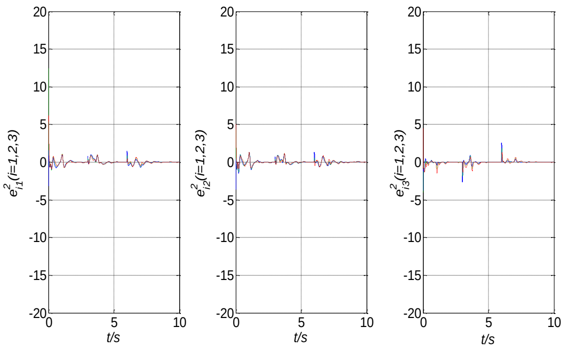

Fig.12 Evolution of the error response curve $e_i^2 \in \mathbb{R}^3, i = 1,2,3$ in the time domain for the second controlled network under the special pinning control

In the first network, in the absence of failure before/at the nodes, there is needed about 1 second to achieve the synchronization. When the permanent failure occurred in about the first 3 seconds, then about the first 5 seconds are needed to achieve synchronization again. When the recoverable fault occurred in about the first 6 seconds, then about 8 seconds are needed to reach synchronization again. In the second network, in the absence of failure before/at the nodes, about 2 seconds are needed to achieve synchronization.

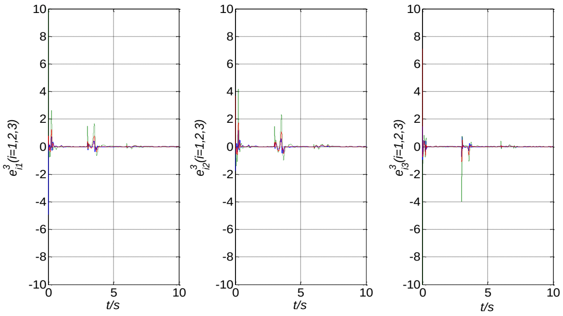

Fig.13 Evolution of the error response curve $e_i^3 \in \mathbb{R}^3, i=1,2,3$ in the time domain for the third controlled network under the special pinning control

If and when the permanent failure occurred at the first 3 seconds, then about the first 5 seconds are needed to achieve synchronization again. If the recoverable fault occurred in about the first 6 seconds, then about 8 seconds ere needed to reach the synchronization again. In the third network, when there is no failure before/at the nodes, then about 2.5 seconds are needed in order to achieve the synchronization. When the permanent failure occurred in about the first 3 seconds, then about the 5 first seconds are needed in order to achieve synchronization again. If the recoverable fault occurred in the first 6 seconds, then about 7.5 seconds are needed to reach the synchronization again.

B. Simulation Results under Randomly Pinning Control Scheme

When the network topology and the coupling strength are unchanged, the nodes 3,4 in the first network ,the node 2 in the second network and the nodes 2,3 in the third network are not selected as the pinned nodes not in accordance with pinning scheme. There is no feasible solution. The state error curves of nodes in the networks are shown in Figures 14-16. As can be seen from the figures, randomly pinning scheme cannot guarantee synchronization.

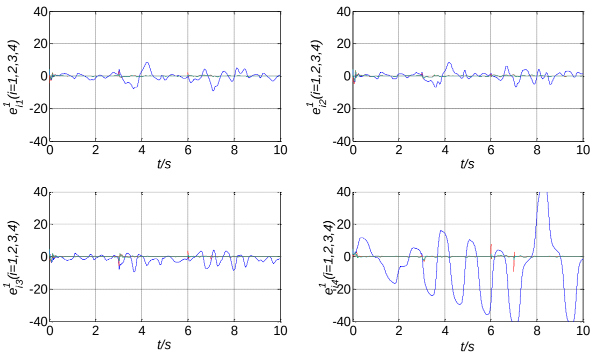

Fig.14Evolution of the error response curve $e_i^1 \in \mathbb{R}^4, i=1,2,3,4$ in the time domain for the first controlled network under random pinning control

When randomly selecting nodes 1, 3 and 4 in the first network, node 1in the second network and node 2 in the third network as the pinned nodes, the controller feedback gains are $d_i^1=60, i=1,3,4$, $d_i^2=220, i=1$, $d_i^3=100, i=2$ by the LMI.

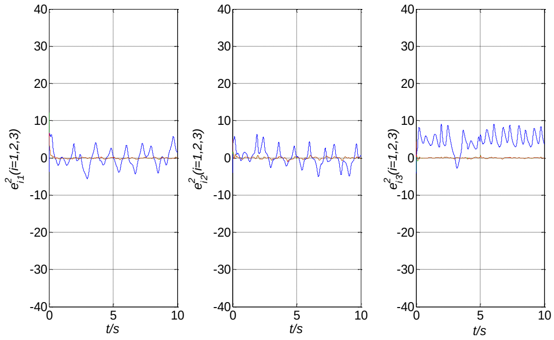

Fig.15 Evolution of the error response curve $e_i^2 \in \mathbb{R}^3, i=1,2,3$ in the time domain for the second controlled network under random pinning control

The error evolution curves in the time domain are shown in Figures 17-19. It can be seen from the figures that the first network reaches the synchronization in 8.5 seconds, the second network reaches the synchronization in 9 seconds and the third network reaches the synchronization in 9 seconds under randomly pinning control. Therefore, it takes longer to reach the network synchronization again than in the case of specifically designed pinning control. In addition, the controller feedback gains have greater values, and the impact of the faults on the network is more obvious.

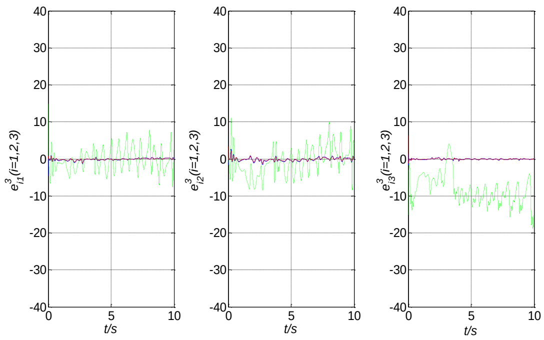

Fig.16 Evolution of the error response curve $e_i^3 \in \mathbb{R}^3, i=1,2,3$ in the time domain for the third controlled network under random pinning control

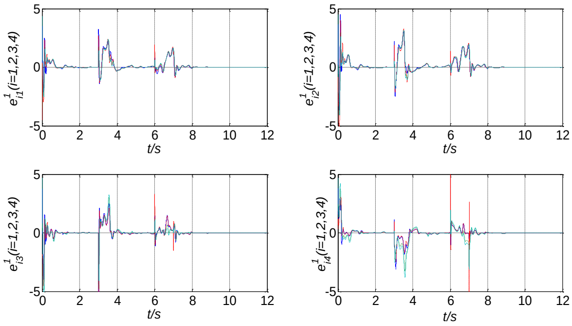

Fig.17 Error response curve $e_i^1 \in \mathbb{R}^4, i=1,2,3,4$ of the first controlled network with random pinning

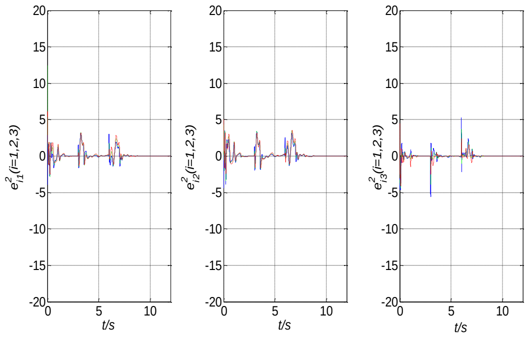

Fig.18 Error response curve $e_i^2 \in \mathbb{R}^3, i = 1,2,3$ of the second controlled network with random pinning

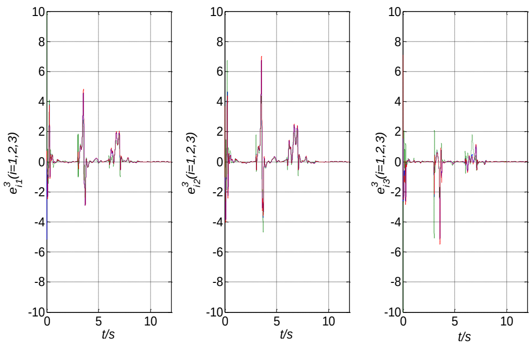

Fig.19 Error response curve $e_i^3 \in \mathbb{R}^3, i = 1,2,3$ of the third controlled network with random pinning

A simple comparison analysis of Fig.11 thru Fig.13 with Fig.14 thru Fig.19 demonstrates clearly: The specifically designed pinning scheme outperforms considerably the randomly pinning scheme when pinning control reinforces synchronization in a rather complex multi-network structure, involving hyper-chaotic Lorenz, Rossler and Chen node dynamic systems, for the case with the same topologies and coupling strengths as well as the same number of nodes.

V. Conclusion

In this exploratory research, we have considered the case when both permanent and recoverable failures in inter-network coupling connection edge may occur. A Bernoulli distribution variable is employed to describe changes between the failure and recovery events. On the grounds of proposed pinning control scheme, a feedback controller was designed and applied to some pinned nodes, and also a sufficient condition for multi-network synchronization was derived. Finally, vast computer simulation experiments is carried out on a rather complex multi-network consisted of three directed networks. The first selected network was the 4-dimensional hyper-chaotic Lorenz node-systems, the second network was selected as the 3-dimensional Rossler node-systems, and the third network was the 3-dimensional Chen node-systems. The simulation results have demonstrated that the proposed controller can reinforce the synchronization in the multiple network structures in the presence of both permanent and recoverable faults as predicted with the theoretical analysis.

One of the future research topics is envisaged towards an alternative scheme [3], [8] of controlled synchronization of multi-networks in presence of both permanent and recoverable faults. The other one worth exploring in such a setting as the above presented solution ideas is the controlled consensus in multi-agent systems with misunderstandings [43], since the consensus problem is not entirely the same as a the controlled synchronization of networks of networks when faults are taken into consideration. The third research topic, and the most difficult one, is to extend recent Chen's results [7] on pinning controllability of complex dynamical networks to the category of complex dynamical multi-networks.

Acknowledgment

The authors express gratitude to former doctoral students in Shenyang, Skopje and Nanjing, who have carried out most of computer simulations and examples. Special thanks are due to Prof. Guangrong Chen for his advice notes on observability/ reachability/ controllability in complex network topologies.

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ЗДРУЖЕНИЕ ЗА ЕЛЕКТРОНИКА ТЕЛЕКОМУНИКАЦИИ АВТОМАТИКА И ИНФОРМАТИКА НА РЕПУБЛИКА МАКЕДОНИЈА

SOCIETY FOR ELECTRONIC TELECOMUNICATIONS AUTOMATICS AND INFORMATICS OF THE REPUBLIC OF MACEDONIA

Програма на конференцијата
Conference Program

Date	Time	Main Hall	Hall 1	Hall 2
Saturday, September 21st	08:30 - 10:30	REGISTRATION *		
	10:30 - 12:00	ME	ImProc	SmartBioMed
	12:00 - 13:00	Lunch** break		
	13:00 - 13:30	CONFERENCE OPENING		
	13:30 - 14:15	PLENARY LECTURE 1 prof. Markos Papageorgiou		
	14:15 - 15:00	PLENARY LECTURE 2 prof. Fisnik Dalipi		
	15:00 - 16:00	Coffee break		
	16:00 - 17:00	SPECIAL SESSION DEDICATED TO prof. Mile Stankovski		
	17:00 - 18:30	ProcCont	ICT	ML1
	19:30 - 21:00	Welcome cocktail		

Date	Time	Main Hall	Hall 1
Sunday, September 22nd	10:00 - 10:45	PLENARY LECTURE 3 prof. Oscar Mayora	
	10:45 - 11:30	PLENARY LECTURE 4 prof. Tomislav Stankovski	
	11:30 - 12:00	SPONSOR PRESENTATION IEEE	
	12:00 - 13:00	Lunch** break	
	13:30 - 15:00	CybSec	IoT
	15:00 - 16:00	Coffee break	
	16:00 - 16:30	SPONSOR PRESENTATION Makedonski Telekom	
	16:30 - 18:00	ROUND TABLE: Emerging Trends and Challenges in Cyber Security	
	19:30 -	Gala dinner	

Date	Time	Main Hall	Hall 1
Monday, September 23rd	09:00 - 10:30	Cont	ML2
	10:30 - 11:00	CLOSING CEREMONY	
	11:30 - 15:00	Social event / Sightseeing	

* The registration desk will be open all days from 08:30 - 16:00.

** If included with room.

SESSION NAME AND CHAIR	ID	TITLE	AUTHORS
Metrology and Electronics ME **Sat 21/9 10:30 - 12:00** **Session Chair: Mare Srbinovska**	18	Determination of the Maximum Clock Frequency of 8-bit Serial Converters for Maximum Length Sequence to Natural Binary Code	Milan Dinčić, Goran Miljković, Milica Stojanović, Dragan Denić and Ivana Ranđelović
	20	Performance Evaluation of the 24-bit Floating Point Format in Different Variance Ranges for Digital Representation of Measurement Data	Milan Dinčić, Zoran Perić, Dragan Denić, Sofija Perić, Jelena Jovanović and Aleksandar Jocić
	29	DC-DC Converters in GaN Technology – measurements and SPICE simulations	Marko Kamilovski and Katerina Raleva
	50	Dixon Outlier Detection Approach Implemented in Sensor-to-Microcontroller Interface	Zivko Kokolanski, Mare Srbinovska, Kiril Demerdziev and Vladimir Dimcev
	13	Ultra-low power wrapper of the Ethos-U55 AI accelerator in the PSOC^tm Edge E84 MCU	Aleksandar Simevski, Henrik Hostalka and Bernd Waschneck
	58	Comparison of the properties and efficiency of photovoltaic cells	Filip Bojadjievski, Katerina Raleva, Marija Kalendar, Asami Mei and Ma Depu
Image Processing and Recognition ImProc **Sat 21/9 10:30 - 12:00** **Session Chair: Tomislav Kartalov**	42	PointFEIT – Point Feature Extraction with Image PreTraining for 3D Semantic Segmentation	Dimitar Dimeski, Hristijan Gjoreski and Gorjan Nadzinski
	51	Siamese Neural Network Architectures for Efficient Person Re-identification	Elena Vasileva, Tatjana Petkovska and Zoran Ivanovski
	52	Siamese Networks for Vehicle Re-Identification	Monika Todevska, Elena Vasileva and Zoran Ivanovski
	15	Automatic private parking system using license plate recognition and car make and model recognition	Darko Pajkovski, Ilija Jolevski and Nikola Rendevski
	57	System for Visual Graphic Animation and Recognition of Macedonian Sign Language Using Machine Learning and 3D Visualisation Tools	Teodora Kochovska, Marija Kochovska, Bojana Velichkovska and Marija Kalendar
Smart Biomedicine SmartBioMed **Sat 21/9 10:30 - 12:00** **Session Chair: Branislav Gerazov**	12	Assistive Keyboard for Children With Ataxia	Martin Milanoski, Vladimir Kitanovski, Marko Zajkov, Nikola Jovanovski, Danche Todorovska and Branislav Gerazov
	14	Open ended acoustic obstacle avoidance interface for visually impaired people based on consumer grade mobile device	Ana Sofronievska, Piotr Walas, Daniela Stojceska, Hristijan Slavkoski, Kristijan Lazarev and Branislav Gerazov
	31	Exploring Pigmented Skin Mole Borders: Minkowski Dimensions in Malignancy Detection	Mia Darkovska, Ilija Mizhimakoski, Ana Ristovska Dimitrovska and Vesna Andova
	39	Health Risk Prediction for Children Built on a Combination of Heterogeneous Datasets	Sebastjan Kramar, Marko Jordan, Marcel Založnik, Nina Rescic and Mitja Lustrek
	47	Recognizing Finger Flexions From EMG Signals Using Wavelet Transform and Machine Learning	Klimentina Paunkoska, Gorjan Nadzinski, Blagoj Hristov and Vesna Ojleska Latkoska
	49	Gesture control robotic arm using flex sensors	Hristijan Ivanoski and Katerina Raleva
Process Control in Industry and Manufacturing ProcCont **Sat 21/9 17:00 - 18:30** **Session Chair: Dushko Stavrov**	10	Design and implementation of a laboratory-scale photobioreactor	Jovan Kamchev, Bojan Glushica, Martin Milanoski, Toni Atanasovski, Bojan Ginoski, Nikola Jovanovski, Mario Makraduli, Darko Dimitrovski and Branislav Gerazov
	27	Integrated Hybrid Manufacturing: Design, Control and Implementation of a Dual-Function CNC Machine	Nikola Jovanovski and Josif Kjosev
	53	Modern SCADA Solution for Mitigation of Water Losses in Water Distribution Network	Stefan Boshkovski, Gorjan Nadzinski, Goce Taseski and Mile Stankovski
	32	Model Predictive Control of a 2-DOF Robotic Arm and Comparative Analysis with Fuzzy Logic Control	Marija Bikova, Dushko Stavrov, Vesna Ojleska Latkoska and Blagoj Hristov
	33	Optimal Control Algorithm for Electrical Load Management in Touring Buses and Comparative Analysis with Fuzzy Logic Control	Boris Butevski, Vesna Ojleska Latkoska, Dushko Stavrov and Gorjan Nadzinski
Information and Communications Technology ICT **Sat 21/9 17:00 - 18:30** **Session Chair: Marko Porjazovski**	21	Segment Routing IPv6 for Future Networks	Toni Janevski and Darko Koloski
	22	Technical Aspects of using SRv6 compared to MPLS for a Telecom Operator	Toni Janevski and Olivera Koteska
	25	The impact of SD-WAN on the Quality of Services compared to Traditional WAN	Mitko Jankuloski and Stojan Kitanov
	28	Optimization and Testing of Smart Contracts for Generation and Verification of Academic Diplomas	Avni Rustemi, Fisnik Dalipi, Vladimir Atanasovski and Aleksandar Risteski
	41	AI Strategies for Reducing Carbon Footprint in the ICT Sector: An Evaluation through the Science-Based Targets Initiative	Jelena Gjorgjev, Nexhibe Sejfuli-Ramadani, Valentina Angelkoska, Valentin Rakovic and Aleksandar Risteski

Machine Learning 1 **ML1** **Sat 21/9** **17:00 - 18:30** **Session Chair: Tomislav Kartalov**	8	Static, Dynamic, and High-Order Functional Connectivity Analysis in Schizophrenia and Bipolar Disorder Differentiation	Daniela Janeva, Martin Breyton, Spase Petkoski and Branislav Gerazov
	17	Comparative Sentiment Analysis and Semantic Meaning in Text using sentiment models from Hugging Face and Power Automate	Aneta Trajkovska and Ilija Jolevski
	26	Optimizing Sensor Configuration on OCOSense for Accurate Detection of Facial Gestures	Ana Sofronievska, Daniela Stojceska, Jovana Angelovska, Sandra Shukleva, Borjan Sazdov and Hristijan Gjoreski
	30	A system for real-time voice control of robots in Macedonian	Marija Neceva, Branislav Gerazov, Zoran Ivanovski, Tomislav Kartalov, Nikola Jovanovski and Dimitar Taskovski
	38	Optimizing Chewing Rate Estimation: Insights from Sensor Data using OCOsense glasses and Machine Learning	Mia Darkovska, Kristina Kalamukoska, Damjan Mihajloski, Ognen Sekuloski, Hristijan Gjoreski and Simon Stankoski
	11	Performance comparison between PPG and ECG based heart rate detection	Marko Petrov, Branislav Gerazov, Nikola Jovanovski and Tomislav Kartalov
Cyber Security Applications **CybSec** **Sun 22/9** **13:30 - 15:00** **Session Chair: Marko Porjazovski**	6	GPU-Accelerated Password Hacking: Analyzing Performance Across Varied Password Lengths	Bisera Naumovska, Aleksandar Cvetanov, Bojana Velichkovska, Goran Jakimovski and Danijela Efnusheva
	7	Web Application for Web Attack Detection Through Network Traffic Analysis	Ivana Dineva, Danijela Efnusheva and Goran Jakimovski
	40	Analysis of models for detection of cyberattacks in computer systems and networks	Georgi Kamchevski, Dimitar Gugucheski and Hristijan Gjoreski
	55	Binary Classification of VPN Proxy IP Address	Teodora Kochovska, Marija Kochovska, Ana Cholakoska Cilakova and Danijela Efnuseva
	56	A Review on Machine Learning Based Intrusion Detection System: Techniques, Public Datasets and Challenges	Goce Stevanoski, Marko Porjazoski, Ivo Paunovski, Monika Kachurova and Aleksandar Risteski
Internet of Things **IoT** **Sun 22/9** **13:30 - 15:00** **Session Chair: Bojana Velichkovska**	36	An IoT System for Detection and Displaying of PM Particles Concentrations in the Air	Josif Kjosev, Nikola Jovanovski, Marko Petrov, Filip Petkovski, Tijana Petkovska and Andrej Ilievski
	2	Ethical Aspects in Building a Short-Range Object Detection Radar System with Arduino Mega 2560	Rexhep Mustafovski, Aleksandar Risteski and Tomislav Shuminoski
	46	Digital development board for short distance detection in a 360-degree	Rexhep Mustafovski, Aleksandar Risteski and Tomislav Shuminoski
	45	Ambient CO2 and Temperature IoT Monitoring Solution	Aleksandar Kormushoski, Marija Kalendar, Ana M. Lazarevska and Valentina Gecevska
	48	Design and Implementation of a Cloud-based System for IoT Sensor and Security Metrics Analysis	Marija Andonovska, Marija Kalendar and Daniel Denkovski
	9	Enhancing Music Genre Classification: A Divide and Conquer Approach	Alek Pachemski, Ivan Jovanovski and Hristijan Gjoreski
Control and Control Applications **Cont** **Mon 23/9** **09:00 - 10:30** **Session Chair: Vesna Ojleska Latkoska**	24	Complex Networked Time-delay Systems: Synchronization by Variable-Structure Control Coordinator	Georgi Dimirovski, Mile Stankovski and Boban Temelkovski
	43	Modelling, Simulation and Development of a Test Rig for Comparative Analysis of Temperature Controllers	Ana Sofronievska and Filip Donchevski
	35	Quality control with real-time data analysis using intelligent algorithms	Aleksandar Arsovski, Vesna Ojleska Latkoska, Dushko Stavrov and Mile Stankovski
	34	Designing Haptic Interfaces for the Internet of Things: An Open-Source Experimentation Platform	Alper Başaran and Dilek Tukel
	44	A Fuzzy Systems Approach to Discrete-time Sliding-mode Control for Uncertain Nonlinear Plant Systems	Yuanwei Jing, Yan Zheng, Gorjan Nadzinski and Georgi Dimirovski
Machine Learning 2 **ML2** **Mon 23/9** **09:00 - 10:30** **Session Chair: Goran Jakimovski**	23	Artificial Intelligence architectural, regulatory and business framework for telecom networks	Dimitar Tanevski, Toni Janevski and Venceslav Kafedziski
	54	Bitcoin Price Prediction Using Machine Learning Algorithms	Teodora Kochovska, Marija Kochovska, Valentina Angelkoska, Pero Latkoski and Aleksandar Risteski
	37	A Comparison of Gradient Boosting Algorithms: XGBoost, CatBoost, and LightGBM	Ognen Pendarovski, Kristijan Milosheski and Hristijan Gjoreski
	16	Analyzing Telecom Customer Churn using Machine Learning	Stefan Shipinkoski and Hristijan Gjoreski
Special Session Dedicated to prof. Mile Stankovski **Sat 21/9** **16:00 - 17:00** **Session Chair: Georgi Dimirovski**	19	Dynamic Graphs, Networks-of-Networks with Faulty Inter-network Connections, Pinning-control Synchronization Coordinator: Coincidences and Confluences	Georgi Dimirovski, Jinde Cao, Tao Ren, Lin Lin and Mile Stankovski