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# Complex Control Systems

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# Design of a Butler-Type Android Employing State-of-the-Art AI Techniques

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***Abstract*— This paper is about the possible and likely soon creation of a functional Butler android via available AI technology and methods. "Available" in this case refers to as publically accessible to the general public. There are 2 types of AI abbreviated types of control mentioned in this paper and one of them could even easily be set up today. The more functional and also unrestricted would require additional training and possible training of additional models. It can also benefit of distillation of combined AI projects such as ChatGPT and Computer Vision AI. For the body, both the necessary kinematics and functionality already exist. There may be some gap in design optimality but the currently existing designs can be considered "Good enough". Some are also publically available and several companies are already mass producing robot bodies even if the software is yet to be perfected. The paper goes through the basics and the architecture of achieving the control.**

***Keywords—AI, Artificial General Intelligence, Neural Network, AI Distillation, VR, Housekeeping, rudimentary tasks. Butler, Android;***

## I. INTRODUCTION TO THE PROJECT

This project is written within the currently available technologies of at the date it is written. It is not Sci Fi and thus the end results should be within realistic expectations. Then again, a walking talking butler android who can carry things around is still ahead of current normality, yet it is fully achievable. The real magic is the core around which the technology runs through and that actually happens to be ChatGPT. For some it may be a simple chat bot, for others a substitute to Google. The opportunities it provides however, and its actual capabilities actually go far, far beyond that. The rest of the parts are also AI projects we have seen implemented and publically tested in popular video format. Unfortunately, other than the animation of some plastic toys, they have yet to see proper use. At least according to what the public is allowed to see.

## II. THE AIS OF THIS PROJECT

### *A. ChatGPT, more than a chatbot*

First we start with the heart of the project, the Narrator. The way we would imagine using a neural network for this type of project and the way we actually do are very different. Normally the Neural Network would be the brain and its end nodes would control the limbs of the robot, and the Neural Network would grow and change and have memories and maybe even feelings. Science fiction is beautiful. Reality, close but not so much.

Instead of the Neural Network controlling the robot, it controls a story. A story of a humble robot butler that would never hurt his/her clients and follow their every command to the best of his abilities.

In this use the Neural Network is immutable and it's the characters within its story that are by design and whim of the owner of the hardware. Switching the Neural Network with a better one will not change the characters of the story significantly, although better writing is always welcome. Luckily, one of the things ChatGPT was fed during creation was book novels with all sorts of interesting made up characters. If you would ask ChatGPT to role play as one or several you would be amazed how deep, and realistic it can go.

### *B. The role of ChatGPT*

ChatGPT plays the role of a narrator, controls the story and follows the input of the user. That would be great for a video game character and there are implementations of that, such as adding Darth Vader to the popular game "Fortnite" [1]. The character is incredibly responsive and acts strongly within parameters. In fact, it will keep the conversation within its comfortable zone and will ignore any attempts to be brought out of character as attempts of meaningless distraction.

Writing a character for ChatGPT is as simple as writing the rules an actor has to follow to get into character. It is done by writing a free text explaining what his role is, what he should do at certain conditions and so on. If there is any formatting, it's for the user not for ChatGPT. One of the uses for ChatGPT is tech support or someone to answer phone calls. It is done by combining Voice to text, ChatGPT and Text back to voice. It's end user will have a hard time detecting whether they talk to a real person or ChatGPT. Especially since the Text to Voice is made via a

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trained Neural Network and is giving a realistic and emotionally coherent and according to the text response.

Now to bring it out of virtual world and into reality, to do so we need to first understand what ChatGPT actually is. With all its intellect and versatility, it is still just a predictive algorithm that predicts the next word in a sentence. It's basically blind, deaf and can only see and communicate via text.

And with that in mind we can arrange the system around it.

*C. Necessary system for the creation of a butler android*

The main component, as already stated, is the ChatGPT. However, it will require a few more things to get to a proper functional results for the devices on Figure 1.

Figure 1. Butler and maid designs (picture is generated)

How to bring a story to real life? If the only communication is via text, one of things the system would require is computer vision AI that will track the world through cameras and describe it in detailed text so that ChatGPT has an understanding of the location environment of its characters. There are many pre-trained Neural Networks for this task that we can chose from.

The task that it has to do is convert an image to text such as seen on Figure 2.

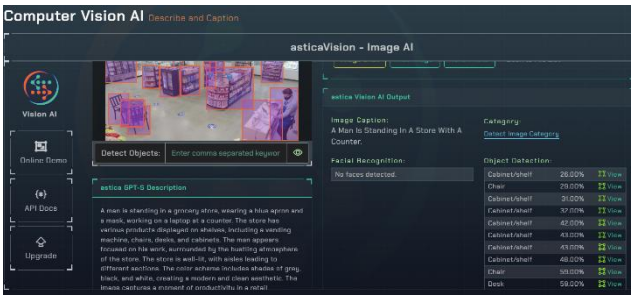


Figure 2. Image to text conversion [2]

Once the ChatGPT is no longer blind it will have an understanding of the environment around it and thus act in a responsive to the environment manner. Combined with Speech to text for the user and if it's able to recognize the source of the speech, it will have sufficient integration of the real world to its story line. Of course it will have to be extremely detailed and with explanation of how far each object and where exactly is located to the unit that is being controlled. It may be common sense that one server running ChatGPT may run several androids at a time and their storyline may even be combined.

**But how do you bring the story line to the real world?**

**How do you translate text to motion?**

On this question, the answer would be through stacking more AI projects. There are a few more projects that can be added to the system to complete the cycle. While the visual scanning may be great to describe the environment it is not enough to provide information needed for the mobility of the unit. For such task terrain recognition such as on figure 3. will be required.


Figure 3. Terrain recognition for mobility [3]

The software created for SpotMini of Boston Dynamics is perfect for our project as well. Of course with certain adjustments. What it does is map the terrain around the unit creating and underlying a path through which the robot can step on. Whether it's a bipedal or 4 legged robot is of no consequences as long as it can keep its balance. It should also understand what material is it stepping on and whether it can step on it or not, but that's up to the computer vision that was previously described. Here it's all about geometry.

Additionally, a proper training algorithm can be created and trained via a neural network such as Gymnasium [4] as seen on Figure 4.

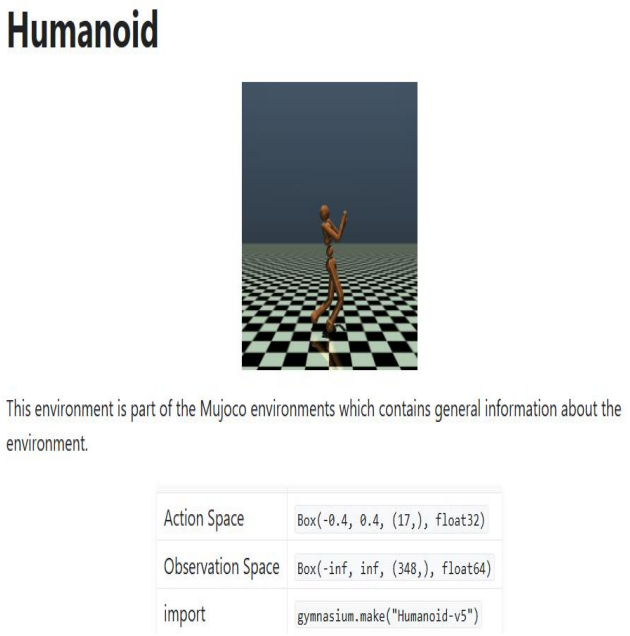


Figure 4. Training environment for walking

The environment can train a neural network, not only to walk on an even surface, but also one with bumps and other obstacles and even self-correct when pushed by wind or other unit or person. A functional body with this type of neural network for versatile mobility can be called a Drone. Of course the word is already used to describe the flying drones but that's only because their functionality already allows for free mobility, thus making flying unironically easier to achieve than walking.

### *D. Summary and completion*

So far the butler robot can walk, talk, understand a conversation and recognize people and objects. However, can it pick them up, can it manipulate the environment and can it do complicated tasks? Not yet.

The computer vision for walking can be further worked on to separate objects from one another and with computer vision for analysis to label them. That way it will not be just a 3D environment in which it can only walk around but it may be possible to manipulate it.
Using a pre-trained Neural Network to train another is called Distillation and that is exactly what is required to to create the final piece of the puzzle. It will also require a large amount of videos that will be analyzed, both as tasks that the people in the video are doing. Skeleton meshes will be recognized of the people in the video thus giving suggestion of how the butler robot could move implementing the same movements and thus doing the same task. With enough material a fully functional butler android may be achievable soon. However, for simple tasks such as grabbing things and carrying them such additional training may not be required. And carrying drinks and being there for show can be a sufficient use of the technology for today.

There is also an alternative that can provide in depth video data of the most common tasks, a butler android may be required to do and thus accelerating significantly the project. And on top of that it can provide the same functionality with no additional research required.

## III. The Alternative

### *A. AI: Actual Indians [5]*

With the already implemented software and pre-trained neural networks all that's left is the manual tasks which can be done by people with VR controllers who don't speak English and live in economy realms where their salaries are not difficult to provide. Walking, talking can be handled by the Artificial Intelligence. The manual tasks that are still difficult for the AI can be done by these people who are monitored by the AI and have signed NDAs and work for reputable local companies. Most people who would require the type of service of a butler could have already given that job to a human before and thus concern about privacy may not be in the highest regard. Never the less there are ways to ensure that privacy is respected and no harm is done. Just because it is humans, it alone should not be an issue. They will only follow written commands and be constantly monitored by AI at all time.
An example is on Figure 5.

Figure 5. XR + humans, a sufficient alternative to AI (for now)
The hand controller or hand detection is a great and accurate control mechanism for the upper body of the androids. The lower body can be moved via buttons or by stepping onto a designated circle around the user. Step forward will have the android walk forward until the user steps back in the middle and so on.

This way the humans can both provide the necessary data for the training of the AI in doing the manual tasks and can provide the completion of said tasks in the meantime. The XR users will not talk to the owners of the androids and

only do tasks written to them by ChatGPT as subtitles, usually as simple easy to understand commands. Communication is handled by the AI. Where to go can be handled by giving the XR personnel arrows to follow and thus completing the cycle. Recording devices will obviously be forbidden in the XR studio and with a signed NDA. With that alone the level of privacy is already higher than hiring a cleanup crews or butler / maid on salary.

## IV Conclusion

Understanding the technology on the inside can help us understand its limitations on the outside. And they are currently many. Thus a work around is required. Using XR technology for tasks such as Dark Factories or in this case Butler / Maid androids may soon become a very common thing. XR is a great way to turn manual labor that previously was solely done in person into a remote work, that can even eventually be even replaced by AI. It may feel a bit negative for the worker to be replaced by AI and have to change job, but the benefit to the economy can make their life and of everyone around them better and thus it's not a worthless sacrifice. Especially if it's a dirty job that nobody really likes such as cleaning stuff. A better economy allows for pursuit of a job of passion instead of necessity. Yet, there are jobs that "Someone has to do" and if those go to the AI, the world will become a slightly better place.

## ACKNOWLEDGMENT

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# Using disruptive technologies as blockchain and AI in IoT cybersecurity

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***Abstract* - In this article, we examine innovative methods for ensuring cybersecurity of the Internet of Things (IoT) infrastructure. These methods are based on new revolutionary technologies such as artificial intelligence and blockchain. We examine aspects such as the architecture of IoT, typical vulnerabilities and attacks against IoT, classic methods for protecting data, communications and devices in the Internet of Things (IoT). We also examine the essence of new revolutionary technologies such as blockchain and AI and their application for ensuring IoT cybersecurity.**

***Keywords: IoT, AI, artificial, intelligence, blockchain, disruptive, cybersecurity, attack, protection***

## I. INTRODUCTION

The term "Internet of Things" (IoT) refers to networked electronic and physical devices, sensors and actuators. IoT communicate and exchange data with each other and, through networks such as the Internet, transmit data to the corresponding control and computing devices.
Their exponentially growing number, as well as the critical importance of IoT in various aspects of modern life, require ensuring the security of the IoT ecosystem. As IoT is inextricably linked to communication in the Internet environment, we are talking about cybersecurity of the IoT infrastructure.

In this article, we examine some innovative and disruptive methods for ensuring cybersecurity of the Internet of Things (IoT). These methods are based on new revolutionary technologies such as artificial intelligence and blockchain. We examine aspects such as vulnerabilities and attacks against IoT, methods for protecting data, communications and devices in the Internet of Things (IoT).

## II. IOT ECOSYSTEM

By definition, Internet of Things (IoT) devices are defined as physical objects connected to the Internet and capable of collecting and exchanging data. These objects can be physical devices such as vehicles, sensors, relays, actuators (on/off keys, valves, switches, actuators, interrupters), electronic devices (controllers, fans, thermostats, trackers, heaters, coolers), computing machines (cloud and edge computers, mobile computers, Raspberry PI). The communication itself can be carried out over various protocols and transmission networks, between people, people-devices or devices-devices.

The versatile use of IoT devices in everyday life and business for the purposes of industrial production, communication, healthcare, education, sports and many other activities is the reason for the sharp in their number. In 2025, the number of IoT devices will reach 20.1 billion worldwide,

which is an increase of 13.21% compared to 2024 [1].

This growth of IoT is driven by enterprise adoption, digital transformation, and the increasing integration of IoT with artificial intelligence, 5G, and edge computing, such as the Industrial IoT (IIoT) sector.

The vast number of connected IoT devices is building a communication infrastructure that has the potential to grow into a self-contained next-generation communication network [2]. These interconnected IoT devices are used in a number of areas such as:

1. Smart Home,
2. Healthcare,
3. IoT Automotive,
4. Logistics,
5. Smart Agriculture,
6. Smart Energy Distribution,
7. Retail sector,
8. Wearables,
9. Entertainment,
10. Education,
11. Smart Cities,
12. Industrial IoT.

**Smart Home**
The purpose of IoT devices in this category is to manage security systems, video surveillance, air conditioning, ventilation, lighting, utilities and home appliances. The main role of IoT devices is monitoring and management without human intervention, including remotely. There are no high requirements for communication speed, only for a reliable connection. A large part of IoT activity is automated. There are low requirements for computing resources, but high requirements for security, privacy and reliability.

**Healthcare**
In the field of healthcare, the role of IoT is monitoring various health parameters, supporting diagnostic, therapeutic and rehabilitation activities, alerting and supporting medical or emergency assistance when necessary. This area also includes medical robots such as Da Vinci Robotic Surgical Systems. The requirements for IoT infrastructure are very high, due to the fact that critical activities for human health and life are performed. There are high requirements for fast, stable and reliable communication, providing backup power to critical

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components and duplication of main nodes. Other important requirements are for cyber-security and privacy. It can be considered as part of Smart Home and Smart Cities. AI is widely used in this area of IoT [4].

**IoT Automotive and Logistics**
The goal of IoT systems in the field of Automotive and Logistics is to achieve increasingly higher autonomy of transport, including self-driving cars and robotic vehicles. The future goals of this area also include the development of autonomous diagnostics, as well as autonomous and remote repair activities. Here, the requirements for the infrastructure parameters are high - high communication speeds, reliability and wide coverage. The requirements for reliability and security are extremely high, mainly for safety purposes. This part of IoT is also characterized by high requirements for the quality of IoT devices. An example is the fact that modern cars contain over 100 sensors, with a tendency to increase.

**Smart Agriculture**
In the field of smart agriculture, the main requirements for IoT are the collection, processing and communication of large amounts of data needed for GIS, crop monitoring, soil moisture, fertilization management, management of various facilities and vehicles, objective control, weather and natural disaster prediction. The requirements for the infrastructure are for a wide range of communication coverage and increased requirements for computing power due to the need to process huge amounts of data. This area also includes functions such as animal tracking, health monitoring, food, fodder and waste management.

**Smart Energy Distribution**
The role of IoT systems is to monitor, measure and control the production, transmission and distribution of energy to end users, billing and maintenance of the electricity grid. The requirements for the system are very high, due to the central role of energy for the normal life of people and industry as well as for all other types of IoT systems.

**Retail**
This area includes supply management, logistics, sales, warranty service and intelligent inventory management. There are no high requirements for the infrastructure, except for reliability and safety.

**Wearables**
This includes various smart gadgets as watches, fitness trackers and sensors for measuring health indicators. There are also no high requirements for infrastructure. The requirements for safety and privacy are increased.

**Entertainment and Gaming**
IoT devices in this category are related to Games, Virtual Reality (VR) and Augmented Reality (AR). An area with high potential for expansion. There are no high requirements for IoT infrastructure, except for sensor precision and ensuring safety and privacy.

**Education**
A very promising area related to Smart Education, Smart classroom and STEM centers. High requirements related to ensuring safety and privacy.

**Smart Cities**
Here the role of IoT devices is more complex. The goal is to manage entire areas of modern city life such as street traffic, utilities (water, gas, sewage) on a city and surrounding scale, retail sector, healthcare, air quality control, waste management, street lighting and video surveillance, etc. Here there are increased requirements for security, low latency of communications, high availability and reliability and very high requirements for scalability and flexibility of IoT systems.

**Industrial IoT**
Industrial IoT (IIoT) encompasses the management of intelligent industrial assets - resource and material management, production, supply chains, logistics, customer relationships, service. Technologies such as Cloud, Edge and Fog computing, AI and Big data analytics are strongly present in this area. It is characterized by high requirements for the quality of IoT devices and IoT infrastructure - reliability, speed and coverage. There are also high requirements for computing power, due to the processing and analysis of large amounts of data. There are particularly high requirements for ensuring high levels of cybersecurity, privacy and reliability. This area largely includes elements from other IoT segments.

From a security perspective, among the many IoT use cases, we can distinguish 2 special cases - massive IoT and mission critical IoT.

**Massive IoT.** In the first case, we have a large number of IoT devices that transmit small amounts of sensitive data. Such are, for example, devices that are part of Smart Home or Smart Agriculture. The data that is transmitted from IoT devices to the cloud or to the receiving station is not large in volume and does not require high speed, but on the other hand, it requires wide signal coverage and a stable connection.

In **mission critical IoT**, due to the specifics of the activity, we have increased requirements for connection reliability and low network latency [3].

Since IoT is a network of interconnected heterogeneous objects, a flexible architecture is needed, allowing both seamless communication and easy expansion by adding or removing new devices. So far, there is no consensus established common reference model, but it can be assumed that the basic architecture of IoT is based on the three-layer model shown in Fig.1 [3].

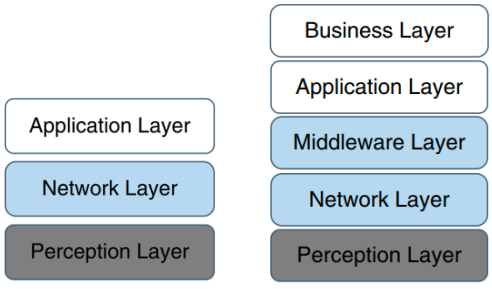


Fig. 1. Three-layer and Five-layer architectures

The first layer, called the "Perception layer", performs the interaction with external physical objects. It consists of various devices such as sensors, actuators and control devices for collecting data and manipulating various parameters through the executive devices. The collected information is transmitted to the next layers.

The next layer - "Network layer" provides the network infrastructure and protocols for data transmission between the different layers, respectively IoT devices and computing and storage resources, be they cloud, local or remotely located. It

consists of various communication devices (mobile networks, Bluetooth, Wi-Fi), network devices (routers and gateways) and provides communication through specific protocols such as Bluetooth, Zigbee (IEEE 802.15.4), DSRC (IEEE 802.11p), Ethernet, Wi-Fi, Z-Wave, LPWAN, VSAT, NFC, Li-Fi, RFID, LTE, 5G, etc.

The "Application layer" provides interaction with users and controlled assets through various applications in which the received data is processed and decisions are made based on the respective goals. This layer provides the main functionality of the various areas of the IoT ecosystem - Industrial IoT, Smart Cities, Smart Agriculture, Healthcare and etc.

Recently, a five-layer model has also gained popularity, with 2 new layers added to the three-layer model shown - Business and MiddleWare layer. The Business layer adds a higher level of services in the various areas of the IoT ecosystem, using business models and behavior patterns and ensuring the completeness of services, including billing and service services. The MiddleWare layer takes care of the processing and storage of information from the Network layer to the Application layer, using various computational libraries, connection to databases, etc.

## III. THREATS TO IOT

The ever-widening application of IoT devices, as well as the sharp increase in their number and areas of use, also expands the surface of vulnerabilities from cyber-attacks, insider threats and privacy threats.

Since security is not a priority at the core of IoT device design, it is necessary to compensate for this by designing cyber-resilient IoT systems, including the devices themselves, communication devices, channels and protocols, computing resources, and the use and distribution of raw, intermediate, and final data. Other factors affecting IoT security are the lack of uniform standards in the production of IoT devices, the lack of regular device firmware updates, the lack or non-compliance with password change policies, etc.

IoT is essentially a large-scale heterogeneous network connecting different heterogeneous objects, and integrating different communication protocols, cloud services, heterogeneous data with different characteristics. They can be considered as a complex IT system. To study the threats to it, we use the model shown in Fig. 2, showing the basic concepts of the "Cybersecurity" perspective to the system.

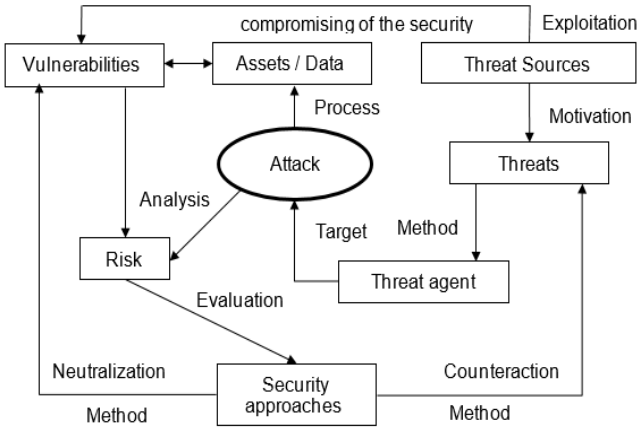


Fig. 2. Basic concepts of CyberSecurity perpective

Attacks on IoT infrastructure are no different from attacks on standard IT infrastructure, communications, and services. The difference is in scale - with IoT we have vast number of devices and communication channels. The essential difference between the two types of infrastructure is the low level of protection of IoT by default.

We examine some unique characteristics of the IoT environment compared to standard IT infrastructure:

- IoT devices are diverse in type, functionality, hardware architecture and operating systems,
- There are no generally accepted industry standards, manufacturers use their own hardware solutions,
- They are seriously limited in terms of their own resources in terms of computing power and storage capacity,
- Due to their vast number, IoT devices generate a huge amount of data, which has a different structure and storage formats,
- The data itself is stored locally, on servers or in the cloud

These features also determine the measures for detecting, suppressing and combating threats to the IoT environment.

To analyze the various vulnerabilities, attacks and countermeasures against them, we will use the three-layer model of IoT architecture - Fig3[3].

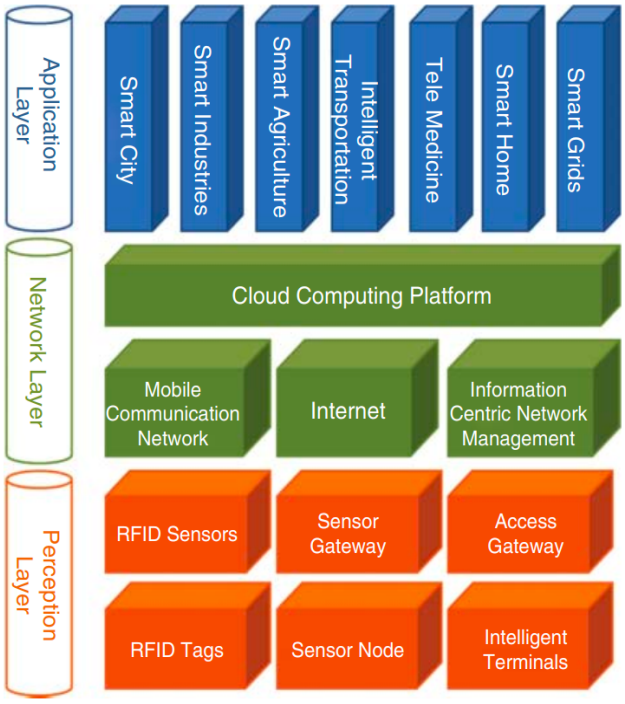


Fig. 3. Entities of the three-layer architecture

The objects and services associated with the corresponding layers - Perception, Network and Application layers use different technologies, communication protocols, different data types and functionalities. This fact enormously expands the vulnerable surface of the IoT infrastructure, respectively the damage from successful attacks and complicates the effective action of the corresponding countermeasures.

In Table 1 we consider some of the typical attacks and countermeasures to the corresponding layers and their elements.

TABLE I. ATTACKS AND MEASURES TO IOT

| Layer | Entity | Attacks | Measures |
|---|---|---|---|
| Perception | RFID Tags | Spoofing, Eavesdropping, Tracking, DoS, DDos, Repudiation | Access control, Hash-based AC, Data and Channel Encryption, IPSec protocol, Ciphertext Cryptography for side channel attack, Hidden Communication |
| | Sensor Nodes | Physical attacks, Node Outage, Impersonation,, Tampering, Jamming, Information gathering, Message interception, Subversion, | Sensor Privacy, Authentication |
| | Sensor Gateway | DoS, Interception, Man-in-the-middle MiM Interruption, Modification, Misconfiguration, Fabrication | Device Security, Message Security, Integrations Security |
| Network | Internet | DoS, DDoS, Hacking, Identity theft, Cyberbullying, Viruses, Loss of Integrity and Confidentiality | Identity Management, Communications Encryption PKI based secure channels |
| | Mobile | DoS, DDos, Eavesdropping, Tracking, Bluesnarfing, Bluejacking, Bluebugging, Corruption, Deletion | Secure access control - Biometrics, Time changing session keys, Public-key crypto primitives |
| | Cloud | Physical security, Infrastructure security Encryption, System complexity, Data access controls, Identity management, Misconfiguration of software | Pseudo anonymisation, Connection anonymization Trapdoor permutation Secret sharing Cryptographic One-way hash chain Zero knowledge proof Aggregated transmission evidence |
| Application | Smart Home, Industy, Agri-culture, Helath, Energy | Access control, Tampering, Code injection, Disclosure of information, Data Leakage | Authentication, Information Flow Control Datagram Transport Layer Security (DTLS) End-to-end encryption Key agreement Data Leak Prevention DLP |

The layers and their entities in the IoT architecture use different specific technologies and protocols for data communication, associated with specific vulnerabilities and protection measures. Classic protection measures such as access control, authentication and identification, encryption of channels and data, regular updates of hardware IoT components and communication devices are not effective due to the peculiarities of the IoT infrastructure. For this purpose, entirely new technologies must be used, which, combined with traditional protection methods, can achieve a drastic jump in the effectiveness of protection against the new sophisticated threats.

## IV. NEW DISRUPTIVE TECHNOLOGIES FOR IOT PROTECTION

We look at new technologies like Blockchain (BC) and AI. These technologies have the potential to take the security of the Internet of Things to a new level, so that it can respond to new threats and challenges to data security and privacy.

### *A. Blockchain*

The blockchain is a peer-to-peer distributed ledger with online records to ensure trusted transactions without the intervention of a third party. Blockchain technology records all transactions made online without allowing any exceptions. The set of records forms a decentralized distributed ledger system that stores the records in its copies. The blockchain itself checks the authenticity of the records using a cryptographic hash function, which changes with each change in the recorded transactions. In this way, it ensures the authenticity of the stored information and eliminates the possibility of falsification or deletion of information. In practice, a transparent public database is created that is not concentrated in one place, but in many places, avoiding the possibility of a single point of failure. The most prominent representative of blockchain technology is the Bitcoin cryptocurrency [3][5][6].

Blockchain enables the creation of secure networks with high levels of cyber-protection, ideal for IoT infrastructure. IoT devices can communicate, i.e. carry out transactions and store information without the risk of it being eavesdropped, manipulated, leaked or deleted. This without the need for central certification and communication facilities. Identification and authentication can be performed by the IoT devices themselves, ensuring complete autonomy. The other serious advantage of blockchain technology is the unlimited possibility of expansion, since scalability is at the heart of the technology.

**Blockchain Structure.**

The blockchain structure is It consists of 2 parts - Blocks and Transactions - Fig.4 [9].

Blocks are records that are chained to each other through cryptographic hashes. Each block stores information about the corresponding transaction through a timestamp, forming a chain of records. Each block consists of a Block Header and a Block Body. Each Block Header contains the size of the block, the hash of the previous Header and its version. Information about the transaction itself is stored in the Block Body.

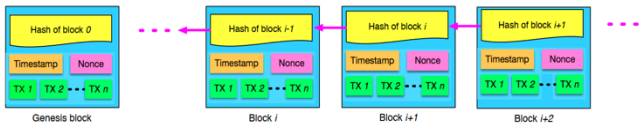


Fig. 4. Structure of blockchain

**Principle of operation.**

The sending party generates a transaction and sends it to all participants in the network, which are called “peers”. The legitimate recipient of the transaction certifies its identity through its digital signature, which essentially represents a public cryptographic key. The same key is unique and is used to encrypt its own transactions. Thus, the signature is a means of guaranteeing the identity of its owner. The transaction is encrypted using a cryptographic key and transmitted in the chain, with the authenticity of the transaction being guaranteed by a hash function. The hash function is the result of a mathematical calculation of the input data, and encrypted

with the SHA-256 algorithm. It validates the integrity of the data in the blockchain. At the slightest change in data, the hash function changes and does not correspond to the records in the other copies of the blockchain. This ensures the impossibility of changing or deleting data. The third element is the so-called "Smart Contract". It is an algorithm that defines the conditions to which the other participants agree. The smart contracts themselves are formed by the goals of the respective blockchain (Fig.5).

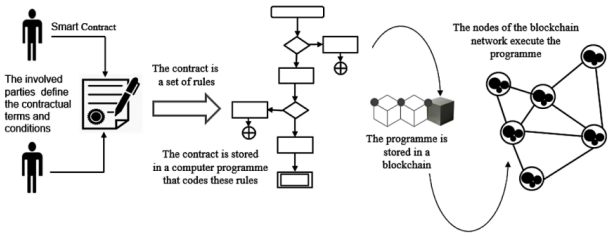


Fig. 5. Concept of blockchain contract

Blockchain provides great opportunities for providing security controls related to ensuring the authenticity of a person (Access control), Data Integrity and Identity Management - Table II [11].

TABLE II. USE OF BLOCKCHAIN FOR IOT SECURITY

| Security controls | Blockchain |
|---|---|
| Access Control | Use blockchain for Access Control;<br>Decentralized access based on BC;<br>Two factor identification based on BC. |
| Data Integrity | Smart contracts used for verification identity of legitimate users;<br>Smart contracts used to manage data integrity. |
| Identity Management | Middleware, based on BC is used for validation of transactions;<br>Middleware, based on BC is used for management of IoT infrastructure. |

Individual security controls can be imposed on the corresponding controls in the Entities of the three-layer architecture (Fig. 3), which clearly shows the place of blockchain-related security controls that can be used to ensure a sufficient level of IoT cybersecurity (Fig.6).

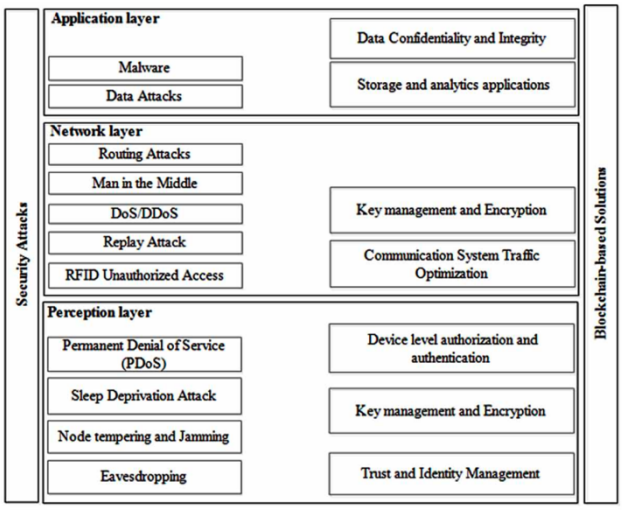


Fig. 6. Blockchain-based security controls for IoT Security

Using appropriate templates, where the functionality of blockchain-related security controls is combined with classical security controls, cybersecurity systems can be designed for various IoT applications - Smart Home, Industrial IoT, IoT Automotive, Healthcare [4][12] or Education [2].

### *B. Artificial Inteligence (AI)*

The recent development of machine learning (ML) and artificial intelligence (AI) provides new opportunities for the development of new and for enhancing the classic cybersecurity methods. AI significantly increases the effectiveness of cybersecurity approaches related to data analysis, such as detecting current malware, in Intrusion Detection and Prevention Systems (IDS) and (IPS) and many other security measures.

The application of AI and ML in critical applications, where a quick and adequate response is required, is especially important.

Blockchain-based artificial intelligence techniques can use decentralized learning to help ensure trust and information sharing and decision-making by many agents who can participate and collaborate in decision-making.

The convergence of blockchain and AI (Fig.7) allows training of AI models on data stored in blockchain while relying on high security and authenticity of data [13]. A very important point is that the confidentiality in this symbiosis is guaranteed by blockchain technology. On the other hand, participants (peers) in the blockchain network can rely on the capabilities of AI for the analysis of large volumes of data and, accordingly, increase the efficiency of IoT applications.

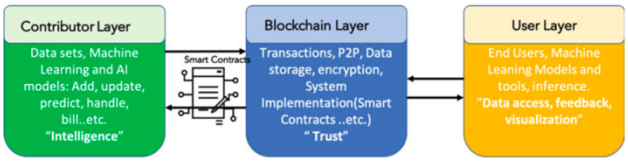


Fig. 7. Blockchain and AI convergence model

## V. DISCUSSION

It is characteristic of any new technology that when it turns from a concept into a finished product and begins to be applied on a mass scale, hidden shortcomings that were not foreseen in the theoretical part come to light.

This applies to both IoT technology and blockchain. Functionality that is theoretically an advantage quickly turns into a weak point. In both technologies, such a weak point is scalability. In practice, both technologies are infinitely expandable, but practice paints a completely different picture.

In blockchain technology, expanding the network with new nodes leads to an increase in the size of the blockchain chain itself and, accordingly, an increase in the memory requirement in which to store a copy of the blockchain. The requirements for communication bandwidth also increase due to the amount of data that is exchanged.

In IoT, we have a huge variety of hardware devices, with different parameters, communication and computing capabilities. IoT devices have different capabilities for calculating hash functions or storing the same amount of

information. Accordingly, time lags appear or directly to blocking certain devices due to overload.

The use of AI in cybersecurity, in addition to its advantages, also has serious disadvantages. This is especially evident when the power of this technology is harnessed by adversaries. AI provides incredible opportunities for detecting vulnerabilities and overcoming cybersecurity measures implemented in an organization.

One of the possible solutions to the problem is the preliminary simulation of the operation of the specific IoT system and the corresponding optimization of the structure, the technologies used, communication protocols and algorithms. Other potential problems are the lack of standardization and regulatory framework to be followed by all manufacturers, leading to certain incompatibilities and difficulties. The lack of specialists in this field should not be ignored, due to the requirement for interdisciplinary knowledge and skills.

## VI. Conclusion and Future Work

While traditional security measures can individually address device-specific, channel-specific, protocol-specific, or multi-data threats, and modern technologies such as blockchain and AI can help with this process, a systems approach is needed to fully protect the IoT infrastructure. In this approach, the IoT infrastructure and the tasks it must protect are considered holistically, specific tasks are defined, a risk analysis is performed, and appropriate technologies and security measures are selected to provide the necessary protection. In addition, solutions are selected so that the organization's resources - people, knowledge, and funds - are sufficient for its operation, maintenance, and future expansion. It is particularly important to conduct a preliminary simulation of the operation of the designed cybersecurity system for a specific IoT application, taking into account as many options as possible for the load on the devices, communication channels, and future expansion of the system. The system must be designed to be flexible not only in terms of the number of components, but also with the ability to replace key components and technologies with similar or newer ones.

## ACKNOWLEDGMENT

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# Implementation of collaborative robots in modern field medical stations

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*Abstract*— **Field medical stations are an important element in the management of crisis situations such as natural disasters (earthquakes, floods, fires, etc.), as well as military and epidemic situations. The introduction of collaborative mobile robots in field medical stations is an innovative approach to improving medical services in emergency and crisis situations. The conceptual role of collaborative robots (cobots) is to assist medical personnel by performing repetitive, risky, or precise tasks in confined and dynamic environments. Field medical stations are designed to operate in harsh conditions and typically include a combination of autonomous or remotely controlled robots that perform various medical tasks. Based on the analysis of the structure and requirements of field medical stations and collaborative mobile robots, the article proposes a model for the implementation of a modern robotic medical field station.**

**Keywords - Service Robot, mobile platform, Cobot, robotic medical field station.**

## INTRODUCTION

Modern field medical stations are high-tech solutions for providing emergency medical care at the scene of a crisis and play an important role in ensuring rapid and effective medical care for the injured in the following situations:

- Disasters and accidents, which have mass fractures, crush syndrome, blood loss, and medical personnel work in unstable conditions, limited logistics and multiple patients.
- Military context, where treatment of ballistic injuries and rapid surgical stabilization as part of damage control surgery is required.
- Epidemic situations, characterized by isolated surgical procedures for patients with high biological risk; UV/HEPA filtration for pathogen control.

Field medical stations are designed to perform various tasks [5], which can relieve the workload of medical personnel and increase patient safety. Essentially, they represent a significant advance in medical technology, offering new possibilities for treating and caring for the wounded and not only increasing the efficiency of medical services, but also increasing the safety of all participants in the treatment process.

The main advantages of robotic medical field stations [1] are:

- Increased precision: Collaborative robots (cobots) provide high precision in performing medical procedures, reducing the risk of errors.
- Personnel safety: By isolating the medical team from dangerous situations, cobots can prevent injuries and ensure safety.
- Speed of response: Task automation allows for faster response to emergencies, which is especially important in combat conditions.
- Accessibility: Collaborative robots can be located in different places in the infirmary, providing access to medical services in different situations.

## I. MOBILE, AUTONOMOUS MEDICAL BASE

In real crisis and combat situations, where access to qualified medical care is difficult, mobile autonomous medical bases (Fig. 1) for emergency care offer fast and effective solutions. They are designed to provide primary care to the wounded on site and stabilize their condition before evacuation or further treatment.

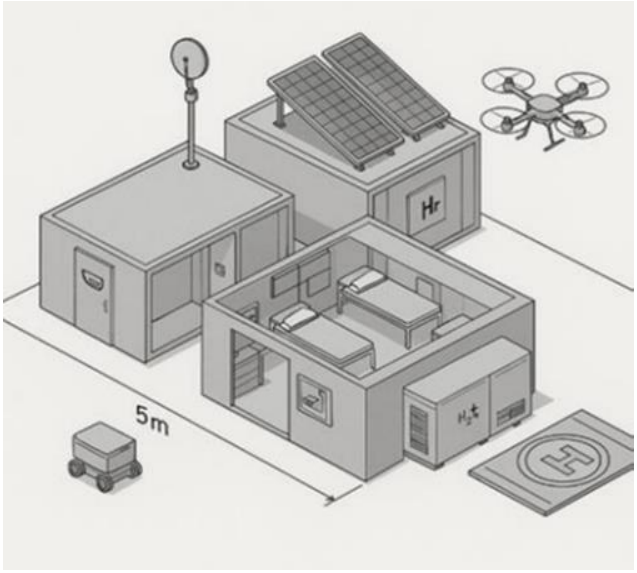


***Fig. 1 Mobile, autonomous medical base.***

The Mobile Autonomous Medical Base is a modular structure that can be deployed within minutes near a disaster site or battlefield. It is transported by military vehicles or drones and has the capacity to be automatically deployed.

ACKNOWLEDGE THE FINANCIAL SUPPORT OF THE PROJECT WITH FINANCING AGREEMENT NO. PVU-44 OF 05.12.2024 UNDER PROJECT NO. BG-RRP-2.017-0011 "ECOLOGICAL COLLABORATIVE ROBOTS POWERED BY GREEN HYDROGEN" UNDER THE RECOVERY AND RESILIENCE MECHANISM FOR THE IMPLEMENTATION OF AN INVESTMENT UNDER C2I2 "INCREASING THE INNOVATION CAPACITY OF THE BULGARIAN ACADEMY OF SCIENCES (BAS) IN THE FIELD OF GREEN AND DIGITAL TECHNOLOGIES" FROM THE RECOVERY AND RESILIENCE PLAN, BULGARIA.

The base has robotic medical stations that are prepared to perform initial diagnostics and patient stabilization. In critical situations, they can perform automatic resuscitation or intubation, using telemedicine platforms. Doctors who are far from the disaster site or battlefield can control the robotic devices through secure communication links. This allows experts to perform complex operations remotely through:

❖ Integrated monitoring systems, where each bed in the Mobile Autonomous Medical Base is equipped with systems that monitor the vital signs of patients and send data in real time to medical teams.

❖ Autonomous emergency robots: The infirmary is equipped with robots that can provide emergency medical care. They are designed to perform basic life-saving procedures, such as:

✓ Automated hemostasis: Robots can quickly apply tourniquets or other systems to stop severe bleeding.

✓ Cardiopulmonary resuscitation (CPR): CPR robots are programmed to perform compressions at the correct rate and force when resuscitation is needed in cardiac arrest.

An example of such a robot is the LUCAS system (Fig. 2), which can continuously perform CPR without interruption while the patient is being transported to a hospital. This robot is designed to perform automated cardiac resuscitation (chest compressions) on patients who have suffered cardiac arrest. With specially programmed algorithms, it applies the correct pressure and rhythm, which increases the chances of successful resuscitation.


***Фиг. 2 Системата LUCAS 3 – робот за CPR.***

✓ Intubation and defibrillation: If necessary, robots can perform intubation to secure the airway, as well as defibrillation for arrhythmias.

❖ Diagnostic robots, which are equipped with ultrasound and X-ray machines, can perform rapid diagnosis of injuries such as fractures or internal bleeding. They can quickly scan the patient using X-ray, ultrasound or MRI systems and diagnose their condition. The data is transmitted in real time to remote doctors or medical staff.

❖ Telemedicine: Doctors located in safe areas or even in other countries can remotely control the robots in the mobile autonomous medical base and perform more complex procedures. They use high-resolution cameras and haptic feedback to operate remotely controlled surgical instruments.

❖ Autonomous evacuation drones: If the patient is stabilized, special autonomous drones can transport the injured from the infirmary to larger medical facilities. The drones are equipped with life support systems for monitoring patients during transport.

## II. Structure Of Modern Field Medical Institutions

Medicine has specific requirements and structure [6] for modern field medical stations (Fig. 3), involving the construction of modular subunits.

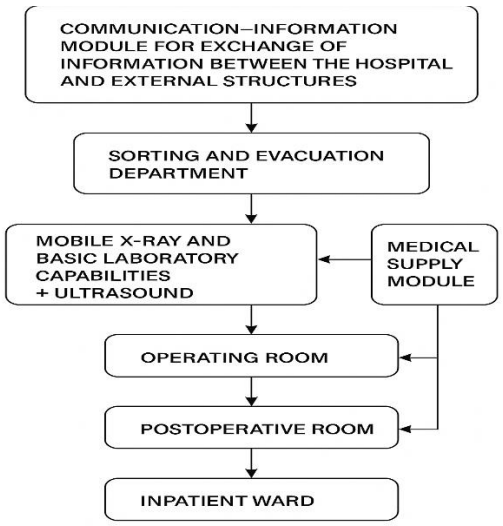


***Fig. 3 Structure of modern field medical facilities.***

By requirement, a field hospital must contain seven modules, with the main guarantee of its functioning being the communication and information module. Its structure is a key element of the healthcare and medical security management system. Its main goal is to ensure reliable, fast and secure exchange of information between hospitals, emergency centers, field medical posts, laboratories, state institutions and other units involved in the provision of medical care. This structure supports the coordinated actions of different teams and ensures effective management of resources and patient flow in real time.

The main functions of the communication and information module are:

Information exchange and integration of systems by ensuring automated data exchange between individual medical units - including patient information, test results, availability of medicines and equipment, as well as administrative data. It integrates electronic health systems (EHS), laboratory information modules, telemedicine platforms and emergency response systems, thus creating a single database for process management.

Coordination and communication between structures by ensuring constant communication between hospitals, emergency centers, field medical stations and government authorities via radio, mobile, satellite and optical connections. This allows for timely coordination of actions in crises, disasters or major incidents and optimal distribution of medical resources according to needs.

Management and decision-making support by providing management teams with analytical and visual data on the state of the health network, the occupancy of departments, the number of free beds, as well as available resources. This facilitates the decision-making process and supports strategic planning in real time in emergency circumstances.

Telemedicine and remote consulting by conducting remote medical consultations and diagnostics through video conferencing and sharing medical images and data. This function is especially important when serving remote areas or field conditions where access to specialists is limited.
Logistical and resource support by supporting the tracking and management of material and human resources - medical teams, ambulances, equipment, medications and consumables. Thanks to GPS and RFID technologies, transparency and control of the movement of resources in real time are ensured.
Information security and data protection by ensuring the security of medical information through encryption, access control and backup archiving. This protects patients' personal data and ensures the system's resilience in the event of accidents or cyberattacks.
In conclusion, it can be argued that the communication and information structure is fundamental for the effective functioning of the health system, especially in crisis and emergency situations. It ensures the continuity of medical services, improves the quality of care and supports rapid decision-making through reliable data exchange and technology integration. The construction and maintenance of a modern communication and information infrastructure is a prerequisite for sustainable, effective and coordinated healthcare.
Two other important modules are: triage and evacuation department, where victims are admitted and assistance is provided, and operating room.

***The Sorting and Evacuation Department***

(or triage and evacuation unit) is one of the most important structures in the system of field and hospital medical organization, especially in mass incidents, wartime situations or disasters. Its functions are related to the rapid reception, sorting, stabilization and referral of victims to the appropriate medical units. Here is how the functioning of the sorting and evacuation department looks like:
1. Reception and primary registration of victims
2. Medical sorting (triage). It divides patients into categories depending on the urgency:
• Group I – critically injured (requiring immediate assistance and stabilization)
• Group II – severely injured, but stable (needing medical assistance in the short term)

***Fig. 4 Collaborative hominoid robot performing CPR, Cardiopulmonary Resuscitation – A life-saving procedure in the event of cardiac or respiratory arrest while another robot with tourniquets stops bleeding from wounds.***

• Group III – slightly injured (can wait without risk)
• Group IV – no chance of survival (palliative care is provided)
This organization ensures effective use of medical resources and minimizes mortality.
3. Stabilization and primary medical care (Fig. 4).
4. Preparation and organization of evacuation.

***Fig. 5 Example of evacuation. Once the patient is stabilized, an autonomous drone evacuates him to a larger medical facility for further treatment.***

5. Keeping records and exchanging information.
7. Coordination with other medical structures.
The triage and evacuation department is a central link between primary medical care and subsequent hospital treatment.
It ensures organization, speed and accuracy in conditions of mass admissions of injured persons.
The effective functioning of this structure is of crucial importance for:
✓ Reducing mortality,
✓ Rational use of resources and
✓ Successful medical evacuation in crisis situations.
The first two groups of the triage and evacuation module, namely the critically and severely injured, enter the ***Operational Module*** (Fig. 6). It represents a critical functional area in the structure of each field medical station, as it provides conditions for carrying out emergency operational interventions in an environment often characterized by limited resources, high dynamics and unpredictability (disasters, accidents, military operations, epidemic situations).

***Fig. 6 Operational module of a field medical station.***

This module performs multiple interrelated functions that ensure continuity of medical care, stabilization of critically injured patients, and maintenance of high standards of surgical safety similar to those in inpatient hospital settings.
Evaluation of the effectiveness of the operating module is assessed by:

- time to life-saving intervention;
- autonomy (hours/days of continuous operation);
- biosecurity;
- logistical flexibility and deployment time (<60 minutes for modern systems);
- integration with other modules (triage, ICU, diagnostic modules).

The operating module is the core of the medical capability of the field station. Its effectiveness determines whether the mission can provide rapid and quality surgical care under extreme conditions. The combination of modern energy systems, intelligent surgical technologies, robotic assistance and well-optimized logistics turns this module into a fully functional mobile operating room, capable of operating autonomously and reliably even in the most severe scenarios..

## III. Requirements For The Design Of A Field Medical Station

The field medical station (Fig. 7) requires specific equipment to provide effective medical care to the wounded.

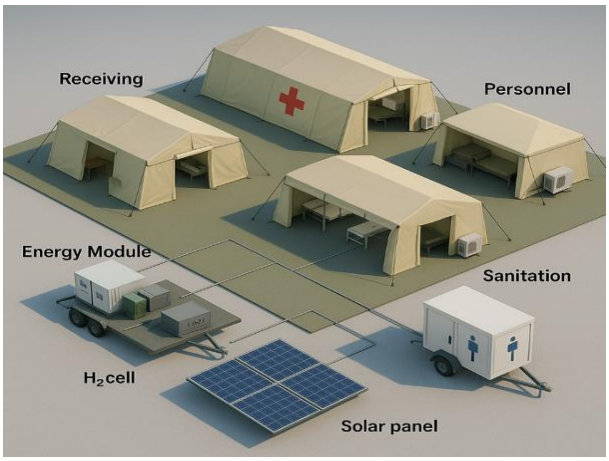


***Fig. 7 Field medical station.***

Here are the main categories of equipment needed:
1. Medical instruments: Surgical instruments (scalpels, tweezers, scissors, etc.); Diagnostic instruments (stethoscopes, thermometers, blood pressure monitors).
2. Beds and trolleys: Operating tables; Patient beds; Patient transport trolleys.
3. Medications: Painkillers; Antibiotics; Dressings and antiseptics.
4. Resuscitation equipment: Artificial respiration apparatus; Defibrillators.
5. Communication equipment: Radios; Telephones for communication with the main command post.
6. Disinfection and sanitation: Disinfection systems; Hazardous waste containers.
7. Supporting infrastructure: Electricity generators; Water supply and sanitation.
8. Personal protective equipment: Masks, gloves, protective clothing.

This equipment allows medical personnel to respond quickly and effectively to the needs of the wounded and provide the necessary care in conflict situations.

## IV. COLLABORATIVE ROBOTS FOR FIELD MEDICAL STATION

Collaborative robots for field medical stations are collaborative robots that have the potential to improve efficiency, improve service quality, and reduce costs in various ways. The parameters of a service robot can vary depending on its intended function and design. However, here are some common parameters [2] that are often considered when developing a cobot.

❖ They come in a variety of sizes, ranging from small, desktop (stationary) robots to larger, human-sized robots.

❖ Work environment: the robot's work area and workspace.

❖ In summary, the work area defines the physical boundaries of the robot's operations, while the workspace refers to the volume of space within which the robot can reach and manipulate objects. Both concepts are important considerations in robot design, implementation, and safety planning.

❖ Mobility: These robots are designed to move autonomously or semi-autonomously both indoors and outdoors.

❖ Sensors: Service robots are equipped with a variety of sensors to perceive and interact with their surroundings. These sensors can include cameras, depth sensors, infrared sensors, touch sensors, and microphones. The specific sensors used depend on the robot's tasks and the information it needs to collect.

❖ Manipulation & Gripping. This function enables precise operations to be supported by a multi-link manipulator or tool module for gripping, positioning and manipulating objects of various shapes and sizes. This is achieved by using force and tactile sensors to control pressure and prevent damage, making it suitable for surgical, logistical or service tasks in mobile medical stations.

❖ Power Supply: Powered by autonomous energy systems — Li-ion batteries, supercapacitors or hydrogen fuel cell, with critical operations requiring an uninterruptible power supply (UPS) and the ability to operate in conditions of limited electrical infrastructure. Optimized energy management is required for extended autonomous mode.

❖ Communication Interface to ensure support for wireless communication: Wi-Fi, LTE/5G, LoRa or tactical networks, as well as the ability to integrate with central medical systems and telemedicine platforms, low latency for real-time management, support for encrypted channels for secure communication.

❖ Processing & Control System is implemented through an embedded microcontroller or industrial computer to manage all functions and algorithms for local decision-making, navigation, stabilization or surgical precision through real-time processing of data from sensors (IMU, camera, force sensors). It is necessary to have the ability for remote monitoring and telesupport.

❖ Adaptability is implemented by automatically adapting to different loads, environments and operational situations, as well as adjusting operating parameters

according to the patient, task or conditions (temperature, vibration, lighting). This is achievable through a modular design for rapid reconfiguration in field conditions. Support for various tools or accessories is required.

❖ Safety features are guaranteed by mechanical and electronic protection mechanisms against overload, short circuit or movement errors, as well as emergency stop systems (E-STOP) and automatic diagnostics. It is important to be able to limit force and speed when interacting with personnel or patients. Certified medical safety protocols and electrical insulation must be used.

These are the main aspects and functions of collaborative robots [4], when implemented in a field hospital they are implemented through their functional subsystems, systematized in Table 1.

***Table 1 Main functional subsystems of cobots***

| *Subsystem / Component* | *Description* |
|---|---|
| **Collaborative Manipulator (Cobot)** | Executes medical tasks, assists personnel, interacts safely with humans |
| **Operator / Medical Staff** | Controls and supervises robotic and medical processes |
| **Power Supply System** | Provides electrical power to all modules (battery, fuel cell, etc.) |
| **Sensors** | Collect environmental and operational data (vision, proximity, vital signs) |
| **Communication Interface** | Ensures data exchange between modules and remote medical teams |
| **Processing and Control Unit** | Performs computation, decision-making, control algorithms |
| **Actuators** | Enable movement, manipulation, positioning of the robot |
| **Safety System** | Ensures operational safety, emergency stops, collision avoidance |

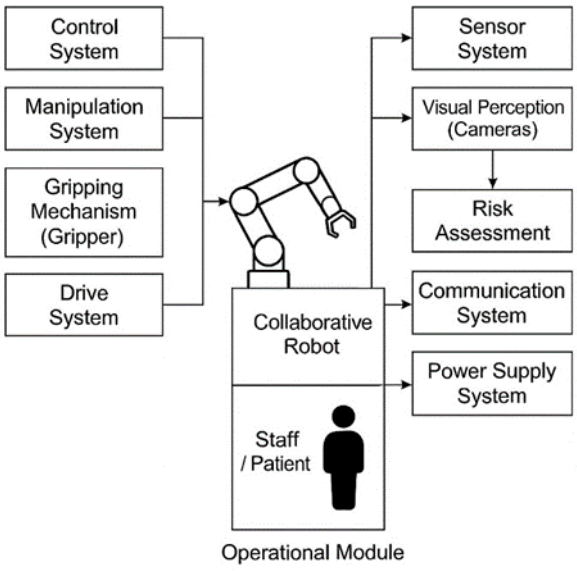


***Fig 8 Functional subsystems of cobots***

Robotization in the field medical station (Fig. 9) offers numerous advantages, including increased efficiency and reduced risks for medical personnel.

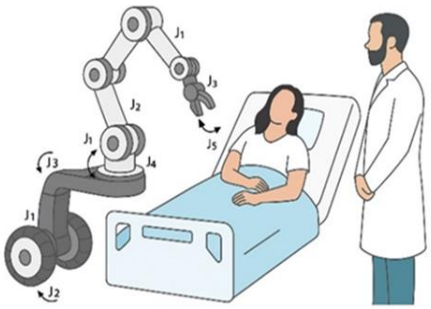

***Fig. 9 Robotization of a field medical station.***

Here, the conceptual role of collaborative robots (cobots) is that they are designed to assist medical staff by performing repetitive, risky or precise tasks in confined and dynamic environments. Unlike industrial robots, they are safe to work in close proximity to humans, with adaptive sensors, limited force and intelligent control. They are considered part of an intelligent mobile medical infrastructure operating in extreme conditions.

## V. IMPLEMENTATION OF COLLABORATIVE ROBOTS IN MODERN FIELD MEDICAL STATIONS

Through the use of robots and automated systems, various tasks can be performed, such as:

❖ Triage and monitoring: The robot can measure vital signs (temperature, pulse, $SpO_2$) and classify patients according to urgency.

❖ Operating room assistance: Supports surgical teams by positioning instruments, cameras or through precise manipulations (in sync with systems such as da Vinci).

❖ Disinfection and sterilization: Autonomously disinfects rooms and equipment using UV or aerosol systems.

❖ Logistics and delivery: Transports medications, supplies and samples between tents.

❖ Teleassistance: Connects remote specialists with field surgeons through audio-video connection and AR visualization.

❖ Psychological and communication support: In humanitarian missions – communication with patients, maintaining calm, language assistance.

However, it is important to pay attention to the ethical aspects and the interaction between the human and the collaborative robot [3], standards ISO 10218-1/2 and ISO/TS 15066 guarantee safe joint work.

Built-in force and proximity sensors prevent contact with people, which ensures safety. Built-in cybersecurity for the protection of medical data and communications is particularly important.

Fig. 10 presents a concept for a robotic field medical station, which has a built-in mobile collaborative robot, representing an anthropomorphic structure with degrees of redundancy, which performs mobile movement on a rail track. This allows the service area of the robot to increase significantly, so that it can reach the shelves with drugs and medications and deliver them to the doctor.

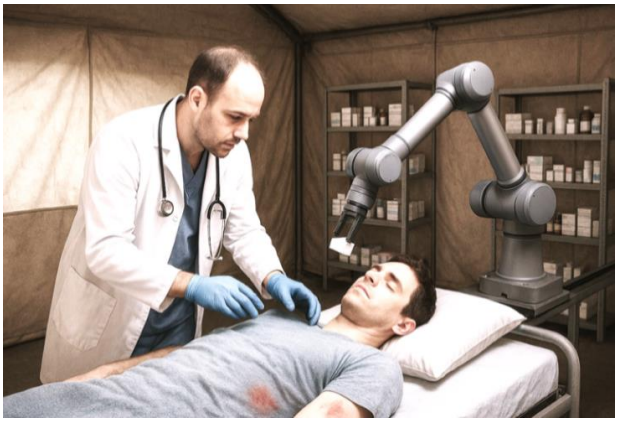

*Fig. 10 Robotic field medical station TYPE 1.*

The robotic field medical station type 2 (Fig. 11) has an auxiliary table to which the cobot delivers the medications and instruments requested by the doctor via voice command and removes them to the specified location. The use of an auxiliary table significantly increases the reliability of the system's operation.

*Fig. 11 Robotic field medical station TYPE 2.*

Future developments will be aimed at optimizing the mobility of the cobot.

## Conclusion

The use of robotic technologies can increase the safety and efficiency of medical services, especially in conditions of natural disasters and combat operations.
Benefits of a field hospital are:

- ❖ Increased efficiency and accuracy with limited personnel.
- ❖ Reduced risk to medical teams in infectious or hazardous environments.
- ❖ Rapid deployment thanks to modular architecture.
- ❖ Energy independence through integration with H2 cells and photovoltaics.
- ❖ Interoperability with other mobile systems (drones, autonomous transport platforms).

## Acknowledgment

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# Adaptive Hosking Generator with Time-Varying Hurst for HRV Simulation in Support of Digital Twin Modeling

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***Abstract*—This paper proposes an adaptive Hosking-type generator for simulating heart rate variability (HRV) with a time-varying Hurst exponent ($t$). Building on the classical Durbin-Levinson (Hosking) framework for fractional Gaussian noise (fGn), the new method allows for both segmental and online control of $H(t)$ ) to reproduce realistic transitions between rest, exercise, and recovery; introduces local anchoring of physiological metrics by matching SDNN and RMSSD moments in sliding windows; and provides seamless transitions between moment-matched modes (mean and variance) to avoid artifacts. The approach is validated using local estimates of the Hurst parameter and SDNN/RMSSD target coherence. Demonstrations show robust tracking of set targets across segments and smooth, jump-free transitions in the first two moments. The method is computationally efficient and suitable for real-time use, algorithm testing, and scenario-driven modeling in sports and clinical cardio-monitoring settings.**

***Keywords— heart rate variability; Hosking algorithm; time-varying Hurst exponent; fractional Gaussian noise; moment matching; SDNN; RMSSD; adaptive simulation; DFA; sports physiology.***

## I. Introduction

Heart rate variability (HRV) is a well-established noninvasive marker of autonomic regulation, recovery, and stress. Normal RR intervals have been shown to exhibit self-similarity and long-term correlation memory, characteristic of fractal processes. Quantification is often performed using the Hurst exponent (H), as well as classical metrics such as SDNN and RMSSD, which reflect long-term and short-term variability, respectively.

Existing approaches to HRV simulation are typically either spectrally-based or based on fractional Gaussian noise/Brownian motion (fGn/fBm) with constant H. This limits the ability to realistically simulate dynamic transitions between physiological states (e.g., from rest to exercise to recovery), where statistical parameters and measures of self-similarity change over time. At the same time, there is no generally accepted single methodology for reliable estimation of H, and the generation of synthetic data with controlled transitions and target metrics remains an open research question.

The Hosking algorithm (Durbin–Levinson recursion) allows for the accurate generation of Gaussian processes with arbitrarily set autocovariance. For fGn, this autocovariance is an analytic function of H, making Hurst a natural control parameter of the simulator. However, the classical use with a constant H does not capture the transitions between physiological states and often introduces artifacts when trying to create segments with different variability parameters.

In this work, an adaptive Hosking generator for HRV with segmental time-varying H(t) is presented, attempting to solve the issue of smooth transition between individual modes, with the aim of working on online control towards target SDNN/RMSSD in the future. The main idea is to set modes (rest, load, recovery) with different values of H, with the transitions being implemented through cross-fade and moment matching (mean and variance) to avoid abrupt transitions from one state to another. Additionally, local sliding window control is applied to bring SDNN/RMSSD closer to realistic targets without disturbing the global fractal structure.

The presented approach provides realistic, labeled synthetic data for training and validation of algorithms (detection of stress, fatigue, dysfunction, etc.). The module can serve as a simulation layer in a digital twin of HRV, allowing personalized "what-if" scenarios and assessment of the response to training/recovery while maintaining confidentiality (without sharing raw patient data).

Contributions of the study:

1. An adaptive Hosking algorithm with time-varying H(t) (segmentally or in the form of a profile) is proposed.
2. We introduce seamless stitching via cross-fade with moment match, which eliminates artifacts in transitions.
3. A diagnostic toolkit is used: sliding metrics, Poincaré diagrams (SD1/SD2) and recurrence plots for comparable assessment between modes.
4. Applicability for customized simulations and tests in the context of a digital twin of HRV is demonstrated.

## II. Background

Heart rate variability is a standard indicator of autonomic regulation and risk, with definitions and measurement methods established by the ESC/NASPE Task Force (Task Force, 1996) [1]. The document provides recommendations for the determination of temporal, frequency, and geometric indices and is a starting point for assessing HRV.

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HRV signals exhibit self-similarity and long-term correlations, described by fractal parameters and the Hurst exponent $H$ [2]. To accurately generate Gaussian processes with a predetermined autocovariance, the Hosking algorithm (Durbin–Levinson recursion) is used [3]. In fractional Gaussian noise (fGn), the autocovariance is an analytic function of $H$, so $H$ becomes a natural input parameter of the generator. Hosking's original work and related materials on Durbin–Levinson and Toeplitz structures are the main technical sources on this subject [4,5,6].

Poincaré plots (SD1/SD2) [7,8] are used to study the nonlinearity of HRV, which capture short-term versus long-term variability and relate it to physiological state.

Another research method is Recurrence Plots (RP) and Recurrence Quantification Analysis (RQA), which assess determinism, laminarity, and transitions between regimes [9,10].

Recent research articles and methodological reviews on nonlinear HRV analyses (including Poincaré/RP) in a clinical context—show the utility of HRV simulation methods [11,12,13].

## III. Adaptive Hosking Generator for HRH with Time-Variating Hurst and Momentary Matching of Metrics

Let $X_t$ be a stationary Gaussian process (fGn) with variance $\sigma^2$and Hurst H$\in$(0,1). The autocovariance is given by the formula:

$$\gamma_H(k) = \frac{\sigma^2}{2}(|k-1|^{2H} - 2|k|^{2H} + |k+1|^{2H}), k \geq 0 \quad (1)$$

Using Durbin–Levinson recursion, AR coefficients $\{\varphi_{n,j}\}$ and variance are determined $v_n$, after which one step of the process is generated:

$$X_{n+1} = \sum_{j=1}^{p} \varphi_{n,j} X_{n+1-j} + \varepsilon_{n+1} \quad (2)$$

$$\varepsilon_{n+1} \sim N(0, v_n), \quad (3)$$

$p \epsilon [10,30]$ – order of the process.

**Creating a time-varying H(t)**

The signal is divided into S segments $[t_{s-1}+1, t_s]$, each with a constant $H_s$. In each segment $\gamma_H(k)$ is used and $X_t$ is generated using Hosking's algorithm.

The smooth transition from one segment to another in a zone of length C around the boundary $t_s$ is realized by blending the end of segment s and the beginning of s+1:

$$\tilde{X}_t = \alpha_t X_t^{(s)} + (1-\alpha_t) X_t^{(s+1)} \quad (4)$$

$$\alpha_t = \frac{t_s - t + 1}{C}, \quad (5)$$

$$t \in [t_s - C + 1, t_s]. \quad (6)$$

Before mixing, it is performed:

$$X^{(\cdot)} \leftarrow \mu^* + \frac{\sigma^*}{\hat{\sigma}^{(\cdot)}}(X^{(\cdot)} - \hat{\mu}^{(\cdot)}) \quad (7)$$

$(\widehat{\mu}, \widehat{\sigma})$ are empirical moments in the window, and $(\mu^*, \sigma^*)$ – are target moments.

Matching SDNN and RMSSD. Working on a sliding window of RR intervals. Let $R_t$ be an RR series with a desired mean $\mu_{RR}$:

$$R_t = \bar{R} + s(R_i - \bar{R}), \quad (8)$$

$$i \in [t - W + 1, t], \quad (9)$$

$\bar{R}$ – average value in the window;

s – combination of two multipliers that change SDNN and RMSSD:

$$s_{SD} = \frac{SDNN^{target}}{\widehat{SDNN}}, s_{RM} = \frac{RMSSD^{target}}{\widehat{RMSSD}}, \quad (10)$$

$$s = \alpha . s_{SD} + (1-\alpha) s_{RM}, \alpha \in [0,1]. \quad (11)$$

where:

$$\widehat{SDNN} = \sqrt{\frac{1}{W-1}\sum_{i=2}^{W}(R_i - \bar{R})^2}, \quad (12)$$

$$\widehat{RMSSD} = \sqrt{\frac{1}{W-1}\sum_{i=2}^{W}(R_i - R_{i-1})^2}. \quad (13)$$

The proposed method locally corrects the amplitude while preserving the long-term correlation structure, using short windows and preserving the average $\bar{R}$.

## IV. Rezults

The following 3 figures show the variable nature of the HRV and its two parameters in three simulated segments with different Hurst exponents. Figure 1 shows the simulated RR intervals in the individual sections, separated by a green vertical line. In the first section, the blue series passes through two green markers, with the average RR being longer at rest, shortening under load (increased heart rate) and gradually returning to higher values in recovery; the transitions are smooth thanks to cross-fade.

The resulting RR series is smooth and without jumps when changing modes, which confirms that cross-fade + match sometimes eliminate artifacts at the boundaries. The sliding SDNN and RMSSD reflect the change in self-similarity: in the middle segment (different H) a rearrangement of the short-term variability is clearly visible, followed by stabilization in recovery. The absolute values of the metrics here are small (demo without aggressive scaling), but the relative profile and smooth transitions show that the proposed scheme can controllably model rest–load–recovery scenarios and preserve the continuity of the first two moments – key for correct subsequent DFA/PSD-analyzis. If necessary, by momentary matching (target SDNN/RMSSD) we can set the levels to realistic clinical ranges without disturbing the evolution of H(t).

The Figure 2 (sliding SDNN, win=120) shows the expected profile: higher long-term variability at rest, reduction under load and partial recovery after the second marker. The Figure 3 (sliding RMSSD) reflects the short-term dynamics: lower values at rest, a clear drop at the beginning of the load and a gradual decrease after the peak, which is consistent with the recovery and damping of high-frequency oscillations. The overall result confirms that the adaptive Hosking generator with segmented H and seamless stitching reproduces realistic regime changes, preserving continuity and stable instantaneous characteristics.

The proposed model can simulate transient processes when studying the three physiological states of rest, exercise and recovery.

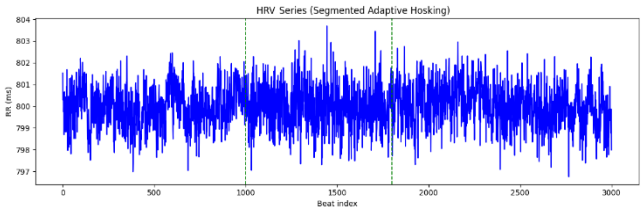


Fig. 1. Fig. 1. Synthetic RR sequence generated with a segmented Hosking model (3 segments).

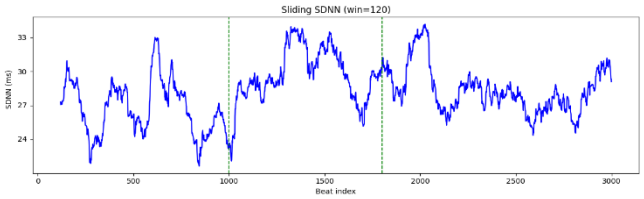


Fig. 2. Sliding SDNN window (3 segments).

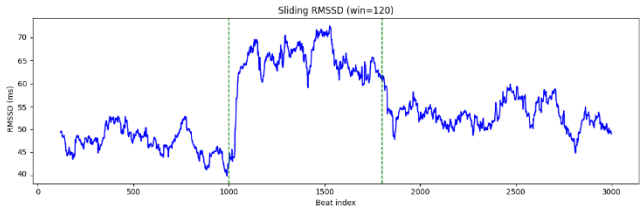


Fig. 3. Sliding RMSSD window (3 segments).

The following figures show the simulated graphs in 9 different segments (to demonstrate the possibility of simulating multiple segments with different Hurst exponents): the generated HSC is given in Figure 4; Figure 5 presents the SDNN of the series and Figure 6 shows the RMSSD values. The individual segments are separated by green vertical lines and have the following Hurst exponent values: 0.8; 0.6; 0.75; 0.8; 0.65; 0.7; 0.83; 0.62; 0.77. Figures 5 and 6 show that changes in the Hurst exponent lead to changes in the studied HSC parameters.

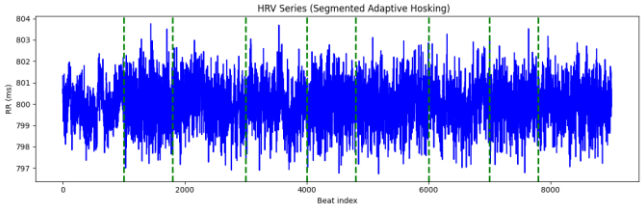


Fig. 4. Synthetic RR sequence generated with a segmented Hosking model (9 segments).

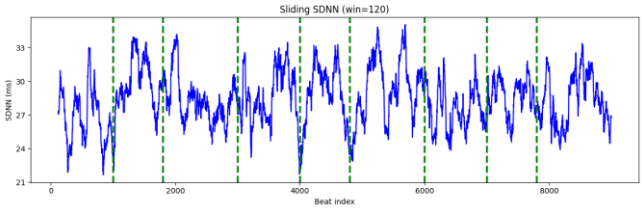


Fig. 5. Sliding SDNN window (9 segments).

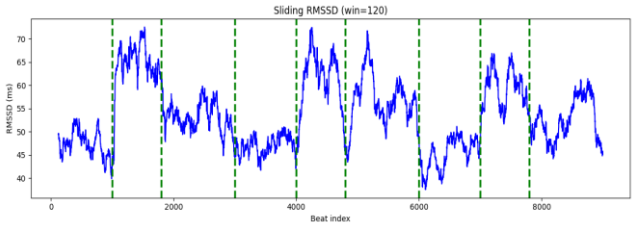


Fig. 6. Sliding RMSSD window (9 segments).

The three Recurrence Plots show a change in the dynamics of the VCH by mode. At rest (Figure 7: Segment 1) the matrix is denser with clearly outlined short diagonal chains, which indicates increased determinism and a more stable short-term structure (at higher H and slower rhythm). At load (Figure 8: Segment 2) the total recurrence decreases, the diagonal threads are rarer/shorter and more “noisy” points appear; the diagram shows more unstable transitions and a lower order in the oscillations (accelerated pulse, lower autocorrelation). At recovery (Figure 9: Segment 3) the density and lengths of the diagonals increase relative to the load, but remain below the rest level, with a gradual structuring in the middle part — a partial return of the order and memory of the process. These differences in RP (at fixed ε) coherently reflect segmental changes in μRR and H: greater determinism and recurrence at rest, reduction under load, and smooth recovery of correlation structures.

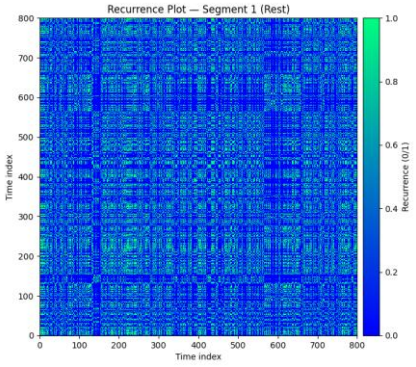


Fig. 7. Recurrence Plot (Segment 1).

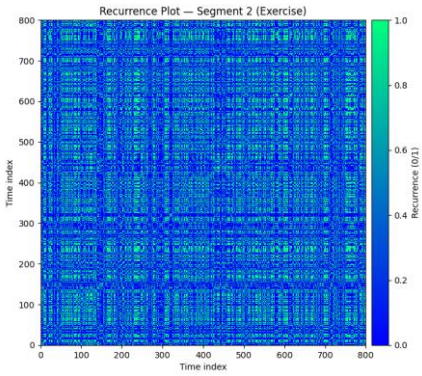


Fig. 8. Recurrence Plot (Segment 2).

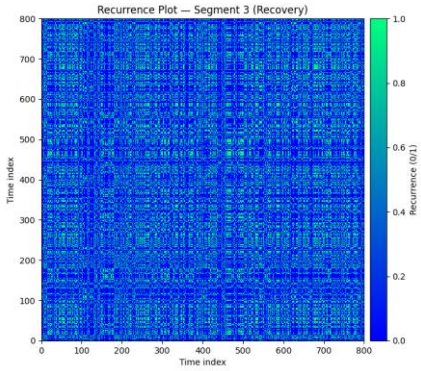


Fig. 9. Recurrence Plot (Segment 3).

**Practical applications in a HRV Digital Twin**

- Personalized "what-if" simulations. Ability to switch modes (rest, exercise, recovery) and analyze how SDNN/RMSSD, H(t), LF/HF would change under different training and stress situations.
- Calibration to a specific person. Estimating H(t), SDNN, RMSSD, etc. from real recordings and allowing the simulator to reproduce them. Creating a digital twin that matches the HRV parameters of the real athlete/patient.
- Generating synthetic data with labels. Creating large, controlled sets (rest/exercise/recovery) for training/validation of detectors for fatigue, stress, arrhythmias – with guaranteed target metrics and H(t).
- Real-time algorithm testing. Possibility to implement online control, where RR series are fed to detectors (DFA-based, LF/HF, etc.) to test stability, latency, thresholds without waiting for the actual session.
- Recovery and load assessment. Support optimal training planning: simulate high-interval training vs. volume session, compare expected RMSSD decline and H(t) recovery.
- Method robustness. Add controlled transitions and micro-artifacts; check which algorithm works or fails with a sharp shift in H(t) or low RMSSD.
- Boundary conditions and safety. Simulate extreme scenarios (dehydration, sleep deprivation) and study which combinations of H(t)/SDNN/RMSSD trigger an alarm.
- Privacy: Synthetic Twins. Create models and interfaces with non-identifying synthetic RRs that statistically match the patient without sharing raw data.
- Sensor/Telemetry Planning. Assess how down-sampling/losses affect local metrics; optimize buffers, compression, and data transmission thresholds.
- Visualize the "target" SDNN/RMSSD/H(t) curve and simulate how, for example, breathing exercises/rests would bring metrics back into the green zone.
- Compare across the same scenarios different stress/fatiue models, examining the impact of different factors.
- Integration into the digital twin as a simulation module layer.


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# Development of Recovery and Prognostic Indices for HRV-Based Digital Twin Modeling in Athletes

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***Abstract*— The analysis of Heart Rate Variability (HRV) plays a pivotal role in assessing physiological recovery and readiness in athletes. This study introduces two novel composite indices: a Recovery Index, evaluating short-term autonomic restoration after training, and a Prognostic Index, estimating pre-training adaptability and long-term regulatory potential. The indices are constructed by integrating time-domain, frequency-domain, and non-linear HRV parameters, including SDNN, RMSSD, normalized HF power, entropy, fractal scaling exponents (DFA α1/α2), Hurst exponent, and Poincaré metrics. Unlike traditional dimensionality reduction methods, the indices are calculated using complete parameter sets, followed by correlation heatmaps and tabular analysis to evaluate internal consistency and inter-individual variability. The approach was applied to six elite wrestlers monitored before, immediately after, and two hours post high-intensity training. The results highlight substantial differences in autonomic recovery and stress resilience, confirming the utility of the indices for personalized assessment. These metrics are suitable for integration into Digital Twin architectures, supporting real-time physiological simulation and adaptive load management in athletic environments.**

***Keywords*— Heart Rate Variability (HRV); Recovery Index; Prognostic Index; Fractal Analysis; Entropy; Digital Twin; Athlete Monitoring; Non-linear Dynamics; Correlation Heatmap; Sports Physiology.***

## I. INTRODUCTION

Heart rate variability (HRV) is a dynamic characteristic of the intervals between consecutive heartbeats and is widely recognized as an indicator of autonomic regulation and overall cardiovascular health. High variability is associated with good adaptability of the body to external and internal stressors, while reduced HRV is a predictor of a number of pathological conditions, including cardiovascular diseases, diabetes, depression and even mortality.

Contemporary interest in HRV goes beyond traditional linear metrics such as mean, standard deviation (SDNN), root mean square of sequential differences (RMSSD), etc. Research in nonlinear dynamics, the development of fractal and wavelet analysis, opened up opportunities for the analysis of long-term dependence, fractal structure and entropic characteristics of the heart rhythm. The methods detrended fluctuation analysis (DFA), multifractal DFA (MFDFA), information complexity indicators (Sample Entropy, Shannon Entropy) allow a deeper understanding of the hidden regulatory mechanisms of cardiac activity.

**Aim and objectives of the study**

The main aim of this study is to propose and evaluate the effectiveness of two integral indicators – Recovery Digital Twin Index (RDTI) and Prognostic Digital Twin Index (PDTI) – for quantitative assessment of post-training dynamics of heart rate variability in athletes. By combining time, frequency and nonlinear HRV parameters, the aim is to build measures that reflect the current level of recovery and prognostic adaptation potential.

To achieve the set goal, the following tasks have been formulated:

1. To calculate the classical HRV indicators (SDNN, RMSSD, HF, SD1, SD2, DFA $\alpha_2$ and Hurst exponent) in three stages of the study – before, immediately after and two hours after training load; to repeat these studies after 2 and after 5 weeks.

2. To develop formulas for RDTI and PDTI by integrating normalized HRV parameters with certain weighting factors.

3. To analyze individual differences in RDTI and PDTI values between athletes and to examine their correlations with classical HRV indicators.

## II. LITERATURE REVIEW

Heart rate variability analysis is one of the most reliable noninvasive methods for assessing autonomic regulation and adaptation mechanisms in athletes. Numerous studies have highlighted the importance of HRV dynamics as a sensitive indicator of recovery, fatigue, and functional readiness after exercise [1–3]. Plews et al [1] demonstrated that regular HRV monitoring allows for individualized adaptation of the training process, with SDNN and RMSSD indicators used to monitor the balance between sympathetic and parasympathetic activity. In the same vein, Stanley et al [2] demonstrated that rapid parasympathetic reactivation (increased RMSSD and HF component) within the first hours after exercise is a marker of effective recovery. Bellenger et al [3] summarized that HRV metrics, especially temporal and spectral indicators, can serve as a prognostic tool for detecting accumulated fatigue and an impending decline in sports form. Schmitt et all [4] propose the use of HRV for early detection of functional overstrain, emphasizing that not only instantaneous values, but also the recovery trend have a greater diagnostic value. Hautala et all [5] confirm that after high-intensity loads HRV decreases sharply, but in well-trained athletes the recovery of SDNN and RMSSD occurs within 24–48 hours, which is a sign of optimal adaptive capacity. In newer interpretation models, HRV is analyzed not only linearly, but also by

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entropy and fractality indices, which describe the complexity and self-regulating nature of autonomic dynamics [6–8]. Rogers et all [7] show that the fractal index DFA $\alpha_2$ can serve as a boundary between functional stability and autonomic rigidity - lower values reflect a more flexible and adaptive physiological system. The increase in entropy indices, such as Sample Entropy (SampEn), is associated with the restoration of the rhythmic complexity of the heart rhythm and the return of homeostasis [6].

In the study [9], a complex approach was presented, including SDNN, RMSSD, LF, HF and LF/HF, to assess HRV dynamics in wrestlers training according to different training programs.

According to the latest developments [10], predictive models based on HRV and fractal characteristics allow to assess the recovery trajectory and the risk of overtraining. Thus created new complex indices can be considered as a tool for personalized management of the training process - by quantifying the autonomous endurance and predicting the future development of sports form.

A fatigue assessment index FDTI (Fatigue Digital Twin Index) has been proposed and determined by the direct or reciprocal values of the main HRV parameters after exercise (1/SDNN, 1/RMSSD, LF/HF, 1/SD1, SD2/SD1, DFA $\alpha_1$, 1/SampEn), multiplied by weighting factors [11].

## III. MATERIALS AND METHODS

### A. Participants

Six wrestlers from a Veliko Tarnovo club team, with long-term training experience (over 8 years) and similar anthropometric characteristics, participated in the study. All participants were clinically healthy, without cardiovascular diseases. The training protocol included intensive load with strength and aerobic exercises, followed by discipline-specific training.

### B. Signal recording and pre-processing

Cardiac activity was recorded using a Holter device for approximately 10 minutes. The RR intervals were extracted from the recordings and checked for artifacts and extrasystoles. The data were anonymized and normalized. The following recordings were performed:

- Pre-training (Pre): recording at rest;
- Post-training (Post): after the end of the exercise;
- 2h recovery (2h): recording 2 hours after the exercise.

Additionally, HRV parameters were examined for the prognostic model for 2 weeks and 5 weeks after the initial recordings.

### C. Calculation of HRV parameters

For each time point, the following Heart rate variability indicators were calculated:

Time parameters:

SDNN (ms) – standard deviation of NN intervals;

RMSSD (ms) – square root of the mean of the differences between adjacent NN intervals;

Frequency parameters:

LF, HF, LF/HF – powers in the low- and high-frequency range, reflecting the sympathetic-parasympathetic balance.

Nonlinear parameters:

SD1 and SD2 – parameters from the Poincaré diagram;

Sample Entropy (SampEn) – index of rhythmic complexity (entropy analysis);

Detrended Fluctuation Analysis (DFA $\alpha_1$, DFA $\alpha_2$) – fractal indicators of short-term and long-term correlation structure;

Hurst exponent – additional marker of self-similarity and long-term dependence (fractal analysis).

### D. Recovery Index (RDTI)

RDTI assesses HRV parameters 2 hours after exercise, with higher values indicating more effective restoration of autonomic balance. The proposed formula is:

$$\text{RDTI} = w_1 \frac{SDNN_{2h}}{SDNN_{pre}} + w_2 \frac{RMSSD_{2h}}{RMSSD_{pre}} + w_3 \frac{nHF_{2h}}{nHF_{pre}} + w_4 \frac{SD1_{2h}}{SD1_{pre}} + w_5 \frac{SamplEn_{2h}}{SamplEn_{pre}} + w_6 \frac{DFA\alpha 2_{pre}}{DFA\alpha 2_{2h}} \quad (1)$$

Where: $w_i$ – weighting factors.

For parameters that increase with recovery (SDNN, RMSSD, nHF, SD1, SampEn), the ratio 2h/pre is used — if the value after 2 hours increases, this gives RDTI > 1. For DFA $\alpha_2$, which decreases with good recovery, the ratio is pre/2h, so the decrease again leads to a higher RDTI (i.e. better recovery).

### E. Prognostic index (PDTI)

The proposed Predictive Digital Twin Index (PDTI) combines the recovery component and the fatigue component, expressing the overall trend of autonomous adaptation:

$$\text{PDTI} = w_{p1} \frac{SD2_t}{SD2_{pre}} + w_{p2} \frac{H_t}{H_{pre}} + w_{p3} \frac{SamplEn_t}{SamplEn_{pre}} + w_{p4} \frac{DFA\alpha 2_{pre}}{DFA\alpha 2_t} \quad (2)$$

Justification for the use of the included parameters:

$\frac{SD2_t}{SD2_{pre}}$ - captures the long-term component of variability and the overall reserve of autonomic regulation, so its increase over time is a marker of systemic recovery and resilience.

$\frac{H_t}{H_{pre}}$ - characterizes the degree of long-term dependence/self-similarity; stabilized or rising H indicates more stable and predictable heart rate dynamics over days/weeks.

$\frac{SamplEn_t}{SamplEn_{pre}}$ - measures rhythmic complexity and adaptability; recovery/increase in entropy reflects a more flexible autonomic system and better ability to cope with training stress.

$\frac{DFA\alpha 2_{pre}}{DFA\alpha 2_t}$ - indexes long-term fractal correlations; a decrease in $\alpha_2$ (leading to a larger pre/t ratio) indicates a reduction in fractal rigidity (a reduced ability of a biological system to change its dynamics, of adaptability in the self-similarity of the signal) and a shift to more adaptive control, which is prognostically favorable.

High PDTI values (>1.2) reflect effective adaptation and improved autonomic control, while values below 0.6 signal a risk of accumulated fatigue or overtraining.

### F. Statistical analysis

Mean values and standard deviations (Mean ± SD) were calculated for all parameters. Differences between the three conditions (Pre, Post and 2h) were assessed by t-test for dependent samples or ANOVA for repeated measures, depending on the normality of the distribution of the particular parameter.

Correlations between indices (FDTI, RDTI, PDTI) and HRV indicators were calculated by Pearson's coefficient (r).

Statistical significance was assumed at $p < 0.05$. Visualizations (heatmaps, line plots) were generated in Python.

## IV. RESULTS

### A. Changes in HRV parameters after exercise

After the training load (Table I), a clear transition from parasympathetic to sympathetic dominance was observed, expressed by an increase in heart rate (HR) and a decrease in SDNN and RMSSD. The mean HR value increased significantly from 86.6 ± 5.2 bpm (Pre) to 105.7 ± 10.3 bpm (Post), which confirms an increased sympathetic tone in the post-training phase.

The SDNN parameter decreased from 56.35 ± 12.04 ms (Pre) to 50.83 ± 15.71 ms (Post) ($p = 0.048$), with a partial recovery after 2 hours (53.93 ± 12.05 ms). RMSSD also showed a transient decrease, with a tendency to recover after 2 hours (46.65 ± 21.39 ms, $p \approx 0.067$).

Frequency analysis shows a slight decrease in nHF and an increase in LF/HF immediately after exercise (from 1.95 ± 0.9 to 2.95 ± 1.7), reflecting the dominance of sympathetic activity. After 2 hours, parasympathetic reactivation is observed, expressed by an increase in nHF (38.17 ± 8.21%) and SD1 (32.1 ± 14.3 ms).

The SampEn and DFA $\alpha_2$ indicators also follow an adaptive profile – entropy decreases after exercise (1.02 ± 0.38) and partially recovers after 2 hours (1.16 ± 0.35), while $\alpha_2$ decreases from 0.74 ± 0.07 to 0.67 ± 0.09, reflecting increased short-term flexibility of cardiac dynamics.

TABLE I. CHANGES IN KEY HRV PARAMETERS ACROSS THREE MEASUREMENT POINTS (PRE – POST – 2H)

| Parameter | Pre-training | Post-training | 2 h after training | Trend / Interpretation |
|---|---|---|---|---|
| **HR (bpm)** | 86.6 ± 5.2 | 105.7 ± 10.3 | 96.3 ± 7.0 | ↑ Significant rise post-exercise; partial normalization after 2 h |
| **SDNN (ms)** | 56.35 ± 12.04 | 50.83 ± 15.71 | 53.93 ± 12.05 | ↓ Reduced immediately after; moderate recovery at 2 h |
| **RMSSD (ms)** | 43.35 ± 13.13 | 49.77 ± 1.50 | 46.65 ± 21.39 | ↓ Post-load drop; partial restoration ($p \approx 0.07$) |
| **nHF (%)** | 36.72 ± 10.19 | 39.97 ± 17.57 | 38.17 ± 8.21 | ↓ Immediately, then ↑ reflecting parasympathetic reactivation |
| **LF/HF (ratio)** | 1.95 ± 0.9 | 2.95 ± 1.7 | 2.11 ± 0.8 | ↑ Post-training sympathetic dominance; partial balance later |
| **SD1 (ms)** | 30.16 ± 9.4 | 34.8 ± 21.0 | 32.1 ± 14.3 | ↓ after load, ↑ at 2 h – recovery of vagal tone |
| **SamplEn** | 1.47 ± 0.24 | 1.02 ± 0.38 | 1.16 ± 0.35 | ↓ loss of complexity post-load, partial restoration |
| **DFA $\alpha_2$** | 0.74 ± 0.07 | 0.67 ± 0.09 | 0.70 ± 0.08 | ↓ slight drop, indicating adaptive flexibility |

### B. Recovery Index (RDTI)

The selected weighting factors and physiological interpretation are presented in Table II.

TABLE II. WEIGHT COEFFICIENTS AND PHYSIOLOGICAL INTERPRETATION.

| Parameter | Symbol | Weight coefficient ($w_i$) | Physiological meaning |
|---|---|---|---|
| $\frac{SDNN_{2h}}{SDNN_{pre}}$ | $w_1$ | 0.20 | Represents overall HRV and total autonomic variability; key marker of global recovery. |
| $\frac{RMSSD_{2h}}{RMSSD_{pre}}$ | $w_2$ | 0.20 | Reflects short-term vagal activity and rapid parasympathetic reactivation. |
| $\frac{nHF_{2h}}{nHF_{pre}}$ | $w_3$ | 0.15 | Normalized high-frequency power; sensitive indicator of parasympathetic dominance. |
| $\frac{SD1_{2h}}{SD1_{pre}}$ | $w_4$ | 0.15 | Geometric measure of short-term variability; complements RMSSD. |
| $\frac{SamplEn_{2h}}{SamplEn_{pre}}$ | $w_5$ | 0.15 | Quantifies rhythm complexity and autonomic adaptability. |
| $\frac{DFA\alpha 2_{pre}}{DFA\alpha 2_{2h}}$ | $w_6$ | 0.15 | Represents long-term fractal correlation; reduced values indicate flexibility and recovery. |

The sum of all weight coefficients is $\Sigma w_i = 1.00$, as higher weights (0.20) are given to SDNN and RMSSD as they most directly reflect parasympathetic reactivation after exercise. The calculated RDTI (Table III) shows a mean value of 1.00 ± 0.13, reflecting normal recovery of autonomic balance in most athletes.

TABLE III. RDTI VALUES.

| Athlete ID | RDTI (2h) | Interpretation |
|---|---|---|
| B1 | 0.82 | Good recovery |
| B2 | 0.81 | Good recovery |
| B3 | 1.10 | Very good recovery |
| B4 | 1.07 | Very good recovery |
| B5 | 1.08 | Very good recovery |
| B6 | 1.21 | Excellent recovery |

Athletes B1 and B2 showed parasympathetic reactivation (RDTI < 0.85), suggesting good autonomic recovery within 2 hours after training.

B3, B4 and B5 achieved RDTI ≈ 1.1, indicating an effective rebalancing of sympathetic and parasympathetic tone.

Athlete B6 showed the highest recovery index (RDTI = 1.21), reflecting a very good adaptive capacity and faster cardiovascular regulation after high-intensity training.

The obtained results confirm that RDTI ≈ 1.0 corresponds to normal short-term autonomic recovery, while values above 1.2 reflect increased resilience, and those below 0.6 may signal fatigue accumulation or insufficient recovery.

The heat map in Figure 1 visualizes the relative changes (2h/pre) in HRV parameters and the integrated recovery index RDTI in the six athletes (B1–B6). The color scale reflects the RI value: blue corresponds to lower values (more fatigue/weaker adaptation), red corresponds to higher values (recovery/adaptation). A distinct individual gradient is observed, reflecting the degree of autonomic recovery. In B1 and B2, the values of most parameters are above 0.8, which indicates good recovery and normal sympathetic dominance. Athletes B3–B6 demonstrate normal or increased values (≥1.0) in RMSSD, SD1 and nHF, which indicates effective parasympathetic reactivation and stabilization of cardiovascular regulation two hours after exercise.

The RDTI values follow the same trend, reflecting the aggregated influence of linear (SDNN, RMSSD) and nonlinear (SampEn, 1/DFA $\alpha_2$) components. The most pronounced improvements are observed in RMSSD and SD1 in B4–B6, which emphasizes their higher short-term adaptability and stability of autonomic regulation.

Figure 1 shows that RDTI adequately synthesizes the various HRV parameters into a single indicator of the extent and effectiveness of recovery after exercise.

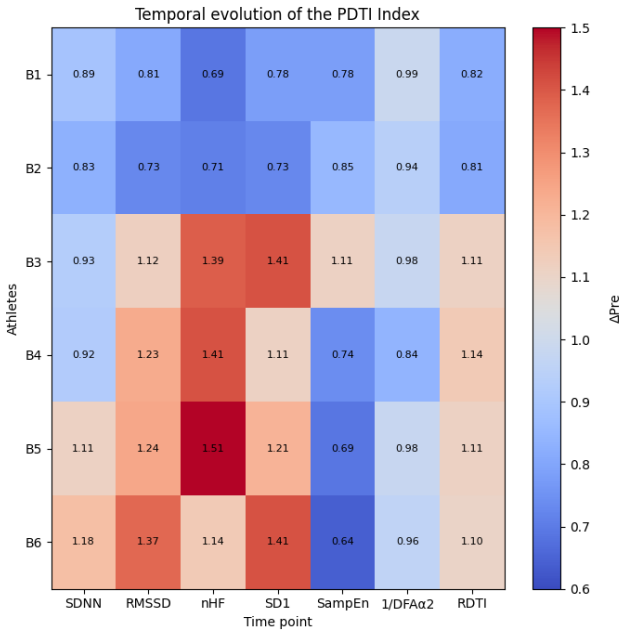


Fig. 1. Heatmap of relative changes (2h/pre) in HRV parameters and the integrated Recovery Index (RDTI) for wrestlers B1–B6.

*T*he comparative analysis of HRV dynamics across the three time points (Table IV) demonstrates a distinct biphasic autonomic response to exercise. Both SDNN and RMSSD showed a marked reduction immediately after training, reflecting transient sympathetic dominance and decreased overall variability, followed by a gradual increase two hours later, indicative of early recovery. Concurrently, the rise in nHF and SD1 values confirmed the reactivation of parasympathetic control and restoration of short-term variability. The recovery of SampEn toward its baseline level highlighted the reestablishment of normal rhythm complexity, while the stable DFA $\alpha_2$ (~0.7) suggested preserved long-term fractal organization of the heart rate signal. Collectively, these patterns, supported by the group mean RDTI ≈ 1.0 ± 0.13, confirm that the athletes achieved a physiologically normal level of autonomic recovery within two hours post-exercise.

TABLE IV. STATISTICAL COMPARISON OF HRV PARAMETERS BETWEEN MEASUREMENT STAGES (PRE, POST, 2H).

| Parameter | Comparison | t / F value | p-value | Trend |
|---|---|---|---|---|
| SDNN (ms) | Pre vs. Post | t = 2.42 | p = 0.048 | ↓ Significant decrease after exercise (sympathetic activation) |
| RMSSD (ms) | Post vs. 2h | t = –2.18 | p = 0.067 | ↑ Tendency to increase after 2 h (parasympathetic recovery) |
| nHF (%) | Post vs. 2h | t = –2.09 | p = 0.074 | ↑ Moderate restoration of vagal tone |
| SD1 (ms) | Post vs. 2h | t = –2.02 | p = 0.082 | ↑ Progressive normalization of short-term variability |
| SampEn | Pre vs. 2h | t = 1.95 | p = 0.091 | ↑ Partial recovery of rhythm complexity |
| DFA $\alpha_2$ | Pre vs. 2h | F = 0.87 | p = 0.411 | ≈ Stable long-term fractal dynamics (~0.7) |
| RDTI (index) | Pre vs. 2h | — | — | ≈ 1.00 ± 0.13 → Normal autonomic recovery |

The correlation analysis (Table V) demonstrates that the Recovery Index (RDTI) is predominantly influenced by parasympathetic-driven HRV markers, with very strong positive correlations with SDNN (r = 0.94), RMSSD (r = 0.95), and nHF (r = 0.92). These findings confirm that higher total and short-term variability are directly associated with more efficient recovery. A moderate positive correlation with SampEn (r = 0.68) suggests that greater rhythm complexity enhances adaptive restoration, while the inverse association with DFA $\alpha_2$ (r = –0.63) indicates that reduced long-term correlation and increased fractal flexibility are key features of optimal autonomic recovery.

TABLE V. PEARSON CORRELATIONS BETWEEN RECOVERY INDEX (RDTI) AND SELECTED HRV FEATURES (N = 6)

| Parameter | Pearson's *r* | Direction | Strength of association | Interpretation |
|---|---|---|---|---|
| **SDNN** | **0.94** | Positive | Very strong | Higher total variability is strongly associated with higher RDTI values. |

| Parameter | Pearson's *r* | Direction | Strength of association | Interpretation |
|---|---|---|---|---|
| **RMSSD** | **0.95** | Positive | Very strong | RDTI increases proportionally with enhanced parasympathetic activity. |
| **nHF** | **0.92** | Positive | Strong | RDTI rises with greater normalized HF power, confirming vagal dominance during recovery. |
| **SampEn** | 0.68 | Positive | Moderate | More complex HRV patterns (higher entropy) correspond to better recovery. |
| **DFA $\alpha_2$** | **–0.63** | Negative | Moderate inverse | Lower long-term correlation (more adaptive fractal control) is linked to higher RDTI. |

### *C. Fractal and entropy indicators*

The dynamics of the nonlinear parameters is presented in Figure 2.

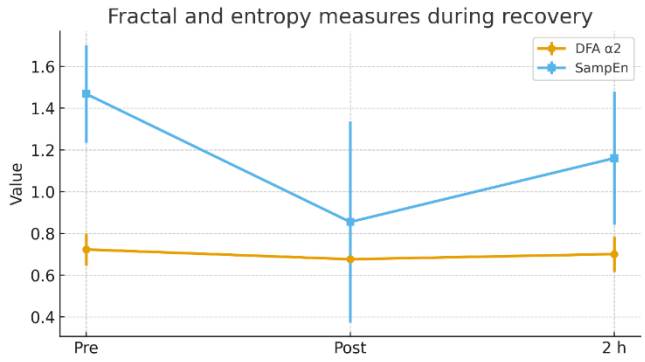


Fig. 2. Fractal and entropy measures during recovery.

Group mean values (±SD) of the fractal scaling exponent DFA $\alpha_2$ and the entropy index SampEn are shown across three stages — Pre, Post, and 2 h after training. A decrease in DFA $\alpha_2$ immediately post-exercise indicates a transient reduction in long-term correlation and increased autonomic flexibility. In contrast, the partial recovery of SampEn two hours later reflects the reestablishment of rhythm complexity and improved self-organization of cardiac dynamics during the recovery phase. The mean value of DFA $\alpha_2$ decreased after exercise and stabilized around 0.70 ± 0.10 at two hours, reflecting a more adaptive and flexible autonomic structure. The SampEn index showed an opposite trend — it dropped markedly post-exercise (0.85 ± 0.4) but recovered to 1.16 ± 0.3 two hours later, approaching its baseline level (Pre = 1.47 ± 0.23). These results confirm that parasympathetic reactivation is accompanied by the restoration of rhythmic complexity and nonlinear stability of cardiac regulation.

### *D. Prognostic index and long-term adaptation*

The PDTI was used to estimate the predicted recovery trajectory at +2 and +5 weeks post-training (Table VI and Figure 3).

The weighting factors used are: $w_{p1} = 0.2$; $w_{p2} = 0.2$; $w_{p3} = 0.3$; $w_{p4} = 0.3$.

Table VI presents the individual values of the PDTI prognostic index at four time points (Post, 2h, 2w, 5w), reflecting different degrees of recovery and adaptation among the athletes. A general trend towards an increase in the index was observed in most participants, especially after the second week.

TABLE VI. RESULTS FOR PDTI

| ID | PDTI post | PDTI 2h | PDTI 2 weeks | PDTI 5 weeks | Trend |
|---|---|---|---|---|---|
| B1 | 0.9704 | 0.9875 | 1.0148 | 1.0237 | Improving |
| B2 | 0.9316 | 0.9621 | 1.0342 | 1.0547 | Improving |
| B3 | 1.0056 | 1.0034 | 0.9972 | 0.9955 | Lack of adaptation |
| B4 | 0.8769 | 0.9271 | 1.0616 | 1.0985 | Excellent adaptation |
| B5 | 0.8929 | 0.9420 | 1.0535 | 1.0857 | Stable |
| B6 | 0.8597 | 0.9271 | 1.0701 | 1.1122 | Excellent |

The analysis of the PDTI prognostic index (Figure 3) shows clearly expressed individual trajectories of adaptation and recovery.

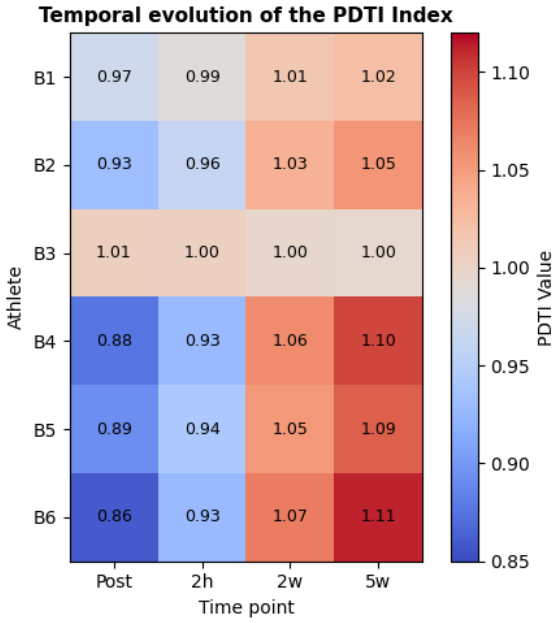


Fig. 3. Temporal evolution of the PDTI.

In athletes B4, B5 and B6, a consistent increase in values from about 0.9–0.93 (Post) to over 1.08–1.11 was observed after five weeks, which demonstrates effective autonomic regulation and high adaptability of cardiac dynamics.

In B1 and B2, the trend is also positive, but smoother, with a gradual increase from ~0.93 to 1.05, which indicates moderate recovery and partial stabilization of the autonomic balance.

Athlete B3 maintains almost stable values around 1.0 throughout the period, which suggests good basic stability without pronounced adaptation dynamics.

The color gradient in Figure 3 confirms the general trend towards gradual parasympathetic reactivation and recovery of variability, with most athletes reaching a physiologically optimal balance between the sympathetic and parasympathetic shares after five weeks.

## V. DISCUSSIONS

The results obtained confirm that the integration of HRV parameters into summary recovery (RDTI) and adaptation (PDTI) indices provides a deeper understanding of the dynamics of the autonomic nervous system after physical exertion. The observed decrease in SDNN and RMSSD immediately after training, combined with a sharp increase in LF/HF, reflects a typical sympathetic dominance associated with acute physiological fatigue. This response is fully comparable with the results reported in [1,2], which describe similar short-term changes as a reliable indicator of training stress. Within two hours after exercise, a partial recovery of parasympathetic activity was observed (increased RMSSD, nHF, SD1), which is consistent with models of post-exercise reactivation (a process of recovery and reactivation of parasympathetic regulation after physical exertion, leading to normalization of heart rate and autonomic balance) [3].

The calculated recovery index (RDTI $\approx$ 1.00 $\pm$ 0.13) reflects a balanced interaction between sympathetic and parasympathetic regulation, and its high correlations with SDNN ($r = 0.94$) and RMSSD ($r = 0.95$) confirm its reliability as an integral indicator of autonomic recovery. The negative relationship between RDTI and the fractal index DFA $\alpha_2$ ($r = -0.63$) is consistent with the findings in [7], according to which a decrease in $\alpha_2$ is an indicator of a more flexible and resilient autonomic system. The parallel recovery of SampEn suggests a return of rhythmic complexity and functional stability, which confirms the concept [6] of entropic regulation of homeostasis.

The proposed PDTI shows high prognostic value, as it combines parameters that account for long-term variability and allows for the assessment of long-term adaptation. The predictive analysis demonstrates that in B4 and B6 PDTI increases significantly after five weeks, which corresponds to excellent autonomic stability and training resilience. In B1 and B3, PDTI values remain around 1.0, which may indicate accumulated fatigue, lower adaptation capacity or the need to reduce training volume. These results coincide with the observations in [4,5] that prolonged suppression of parasympathetic tone is an early indicator of functional overstrain. In the context of modern approaches to monitoring training status, PDTI can be considered as an intelligent integrative marker that combines linear, nonlinear and fractal characteristics of HRV. This index builds on existing models by including not only short-term recovery, but also a prognostic component assessing the trend of adaptation. The application of PDTI in sports practice would allow for personalized management of training loads and early prevention of overtraining, an approach that is increasingly being used in sports physiology [9,10].

The results of the present study confirm that the combined analysis of RDTI and PDTI provides a reliable tool for monitoring recovery and predicting adaptation dynamics. While RDTI describes the instantaneous state of autonomic balance, PDTI reveals the trend of stability and development over time, which makes it a promising indicator for assessing sports readiness and optimizing training cycles.

The proposed RDTI and PDTI indices can be integrated within a heart rate variability digital twin (HRV Digital Twin), which models in real time the dynamic processes of autonomic regulation in athletes. Such a digital model could combine biosensor data (RR intervals, HRV parameters, temperature, oxygen saturation) with machine learning algorithms that predict the individual response to training load. RDTI would serve as a module for assessing the current physiological state, while PDTI – as a prognostic component predicting the tendency of adaptation and the risk of overtraining. The integration of these indices into a digital twin allows for personalized simulation of recovery processes, optimization of training regimens and automatic adaptation of the load based on the real physiological responses of each athlete. This opens the way to the implementation of intelligent systems for sports form management, based on continuous monitoring, self-learning models and feedback between the coach, the athlete and the algorithmic system.

### Relationship between Indices (RDTI, PDTI) and HRV Parameters

The combined analysis of the RDTI and PDTI indices reveals the complementary aspects of short-term and long-term autonomic adaptation. At the group level, higher RDTI values ($\approx 1.1$) show a strong relationship with increased SDNN, RMSSD and nHF parameters ($r > 0.9$), confirming that athletes with more pronounced total and parasympathetic variability achieve faster recovery within the first two hours after exercise. Conversely, lower RDTI values (<1.0) are associated with persistent sympathetic dominance and incomplete recovery of autonomic balance.

The prognostic index PDTI, reflecting the interaction between fatigue and recovery, demonstrates a clear distinction between athletes with high adaptation potential (B4–B6) and those with a more delayed response (B1–B3). The progressive increase in PDTI during the second and fifth weeks in well-adapted athletes indicates sustained parasympathetic reactivation and enhanced autonomic resilience over time.

Unlike the RDTI, which describes the instantaneous functional state immediately after training, the PDTI has a prognostic nature. It integrates both parasympathetic and fractal characteristics of regulation, assessing the body's ability to maintain a stable autonomic balance under successive training loads. Thus, the PDTI not only reflects the current level of recovery, but also predicts the tendency of adaptation and the risk of functional overload or overtraining. High values of the index are associated with effective long-term recovery and stable autonomic regulation, while low values signal limited adaptive capacity and the need for optimization of the training process.

## VI. CONCLUSION

The present study presents an integrated approach to assess autonomic recovery and adaptive resilience in athletes by introducing two combined indices – RDTI and PDTI. The results obtained show that RDTI reliably reflects short-term

changes in parasympathetic activity and recovery capacity after exercise, while PDTI provides a deeper insight into the long-term trend of adaptation. The observed strong correlations between RDTI and the main HRV parameters (SDNN, RMSSD, nHF) confirm that the index captures the key mechanisms of autonomic balance, while the inclusion of fractal and entropic indicators (DFA $\alpha_2$, SampEn) adds a nonlinear perspective to the assessment of physiological complexity. Prognostic analysis of PDTI demonstrates that in athletes with high resilience, the index increases consistently over a 2- and 5-week period, a sign of optimal recovery and effective adaptation of the autonomic nervous system. In contrast, PDTI values below 0.6 may be an indicator of accumulated fatigue and a potential risk of overtraining, which highlights the applicability of the index as a tool for prevention and optimization of training loads.

The developed methodology offers a new model for quantitative recovery tracking, which can be implemented in intelligent sports systems and HRV digital twins, providing personalized management of the training process. The combination of RDTI and PDTI creates a basis for building prognostic algorithms that combine biophysiological data, statistical analysis and machine learning to predict individual adaptation. Thus, the study contributes to the development of scientifically sound and technologically integrated methods for monitoring and optimizing sports form, applicable both in elite sports and in rehabilitation and preventive physiology.

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# Distinguishing States of Rest, Fatigue, and Stress in Athletes Using HRV Geometric and Entropic Measures

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***Abstract*—Monitoring heart rate variability (HRV) provides valuable insights into autonomic regulation and recovery status in athletes. This study aims to distinguish between rest, fatigue, and stress states by combining geometric and entropic analyses of HRV. Short-term RR interval recordings were obtained from 14 competitive athletes before, immediately after, and two hours post-training sessions. HRV was assessed using Poincaré plots (SD1, SD2, and SD1/SD2 ratio), 3D phase-space attractors derived from time-delay embedding of RR intervals, and entropy-based indices including Sample Entropy and Shannon Entropy. The results revealed clear transitions from a comet-shaped Poincaré pattern at rest to more compact (fan-like) shapes during fatigue and torpedo-like distributions under stress. These changes were accompanied by progressive decreases in SD1, SD1/SD2, attractor volume, and entropy values, indicating reduced parasympathetic activity and increased sympathetic dominance. This integrated geometric–entropic approach offers a powerful tool for assessing training load, recovery, and early detection of functional overreaching in athletes.**

***Keywords—Heart Rate Variability (HRV); Poincaré Plot; 3D Phase Space Attractor; Entropy; Sample Entropy; Shannon Entropy; Athletes; Autonomic Nervous System; Fatigue; Stress Monitoring.***

## I. INTRODUCTION

The autonomic nervous system (ANS) plays a key role in the regulation of heart rate by balancing sympathetic and parasympathetic activity. Analysis of changes in the R-R intervals of the heart rhythm [1,2] provides an assessment of the effectiveness of this balance, as well as the functional and health status of the body.

Heart rate variability (HRV) is the variation in the intervals between successive heartbeats (RR or NN intervals) and is a marker of the autonomic regulation of the heart.

Healthy cardiac systems show greater, more complex variations, which reflects flexibility and the ability to adapt to stressful conditions, while chronically reduced HRV is associated with increased risk and sympathetic dominance.

In sports and training regimens, HRV has been established as a useful marker for assessing training load, the degree of fatigue and recovery in athletes [3]. HRV measurements at rest, during exercise, and during recovery provide information about the body's adaptation to training, as well as the risk of excessive strain or functional overload (overreaching). Different HR and HRV measures can be useful for monitoring fatigue, recovery, and training effects. Studies of these measures justify the use of HRV as an indicator of training status and adaptation.

Severe fatigue is a prerequisite for a significant decrease in HRV parameters, leading to changes in muscle oxygen consumption even at rest [4]. For this reason, it is good to avoid overtraining and to personalize the training program.

At the same time, the studies presented in scientific publications on the effects of training are associated with methodological inconsistencies and/or incorrect interpretation of the data, and this provides scope for new studies to assess training status in order to address this issue as comprehensively as possible. More data are needed to assess the best practices for implementing HRV in sports [5]. In one respect, the literature is almost unanimous: analyses of 5-minute ECG/PPG cardiac recordings are probably the most useful monitoring tools.

The scientific literature uses a variety of methods for analyzing HRV—linear (time-domain, frequency-domain) metrics, as well as nonlinear and entropic measures. Nonlinear approaches (such as Poincaré plots, nonlinear entropic indices, and other dynamic attractors) allow for a more refined assessment of the complexity and irregularity of heart rhythm, which often cannot be well captured by linear analyses alone. Nonlinear methods can help to recognize subjective physical fatigue [6]. A recent study in wrestlers that used HRV measures to assess training load, fatigue, and stress showed that HRV measures can serve as sensitive indicators of recovery capacity and exercise tolerance [7].

The aim of the present study is to integrate geometric and entropic methods for HRV analysis to distinguish between resting, fatigue/stress and recovery states in athletes. Using Poincaré diagrams, Recurrence Plot and entropic indices, we analyze HRV parameters that can serve for monitoring workload and prevention of functional overtraining.

## II. MATERIALS AND METHODS

The study was conducted on a group of 14 competitive wrestlers. Heart rate recordings were often made with Holter monitoring for about 10 min. In three states: before training (rest), after training (fatigue) and two hours after training

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(recovery). The recordings are short-lived, and from the approximately 10 min recorded at rest, 5-minute series were separated and analyzed. The Holter recordings were processed by filtering artifacts and extreme values (ectopic beats).

**Methods for analyzing HRV**

**Poincaré plot**

A Poincaré plot is constructed by graphically displaying pairs of intervals ($RR_i,\ RR_{i+1}$) against each other [8]. The following parameters were calculated [9]:

$$SD1 = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N-1}\frac{(RR_i - RR_{i+1})^2}{2}}; \quad (1)$$

$$SD2 = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N-1}\frac{(RR_i + RR_{i+1} - 2\overline{RR})^2}{2}} \quad (2)$$

SD1 is the standard deviation of the projection perpendicular to the identity line, characterizing the short-term variability of heart rate.

SD2 is the standard deviation along the identity line [9]. Describes long-term changes in rhythm and may increase with fatigue, exertion or illness.

The ratio:

$$Ratio = SD1/SD2 \quad (3)$$

gives an indication of the balance between short-term and long-term fluctuations, is used as a general indicator of the harmony of cardiac dynamics — the higher it is, the better the autonomic regulation.

Quantitative calculation of the parameters SD1, SD2, and SD1/SD2 allows for an objective assessment of cardiac variability and is used in cardiological and sports analyses to monitor the physiological state.

Visual analysis. The shape and structure of the point cloud in the Poincaré plot carry information about the state of the system: "Comet" shape - narrow at the bottom and expanding upwards; characteristic of a stable and periodic rhythm; "Torpedo" shape - elongated and dense, usually indicating quasi-periodic or slightly chaotic behavior; "Fan" shape - a spread-out structure, indicating more chaotic dynamics or proximity to a transition to chaos. Complex or multilayered shape - may reflect a fractal structure and the presence of several dynamic states.

The symmetry of the points relative to the line $y=x$ indicates the balance of autonomic regulation between the sympathetic and parasympathetic systems.

**3D Poincaré method**

Poincaré plot can also be constructed in three-dimensional space ($RR_i,\ RR_{i+1}, RR_{i+2}$). The three-dimensional method is an extension of the classical two-dimensional approach used to visualize the dynamics of successive RR intervals in the electrocardiogram.

While the traditional Poincaré plot depicts the relationship between two successive intervals, the three-dimensional version also includes the next interval, which allows a more complete representation of the dynamic structure of the heart rhythm. This forms a cloud of points in three-dimensional space that describes the transitions between three successive heartbeats.

The shape, orientation and dispersion of this cloud provide information about the complexity and stability of the rhythm.

- In a normal heart rhythm, the points are located close to the diagonal, forming a tight linear structure.
- In a variable or chaotic rhythm, the cloud expands in space and acquires a more complex, three-dimensional shape.
- Analysis of the geometric characteristics (e.g. volume, slope or orientation) of this cloud allows a more accurate assessment of the nonlinear relationships between successive RR intervals.

**Recurrence Plot**

Recurrence Plot (RP) is a graphical method for visualizing the dynamics of physiological signals, which shows the moments at which a system returns to states similar to previous ones. In the context of heart rate variability (HRV), RP is used to study recurring patterns and changes in the dynamic structure of RR intervals, which reflect the activity of the autonomic nervous system.

To make RP, the phase space of the time series is first reconstructed, with each moment of the signal represented by a set of values with a certain time delay. Thus, each point in this space describes the current dynamic state of the system. Then, all pairs of states are compared to determine whether they are close enough to each other according to a predetermined similarity threshold. If two states are close, a "recurrence" is marked in the corresponding position of the matrix.

The resulting two-dimensional matrix is visualized as a square graph, in which each black point represents a moment when the system was close to a previous state, and white indicates a lack of similarity. The main diagonal (from the upper left to the lower right) shows identical moments in time and is always filled. Diagonal structures parallel to it reflect repeatability and predictability in the signal, while vertical and horizontal lines indicate stagnant phases when dynamics temporarily slow down.

In HRV analysis, RP allows different physiological states to be distinguished. At rest, the graph usually shows a more scattered and complex structure, which indicates high variability and good autonomic regulation. In fatigue, longer diagonal lines appear, reflecting a more regular and predictable rhythm, while under stress the structure may appear chaotic, which is a sign of dominant sympathetic control and reduced complexity of the system.

The threshold ε defines the limit of similarity between the states of the system in the reconstructed phase space and controls the density of points in the Recurrence Plot. In the present study, the value of ε\varepsilonε was chosen as a fixed percentage of the maximum Euclidean distance between RR intervals, which ensures a balance between too loose and too tight structures. For comparability between different states (rest, fatigue, stress) the threshold was kept in a close range, ensuring comparable Recurrence Plots and stable RQA indicators.

RP is used both for visual analysis and as a basis for quantitative description through Recurrence Quantification Analysis (RQA) metrics that assess the degree of recurrence, predictability, chaoticity, and laminarity of the signal.

In **Recurrence Quantification Analysis**, several quantitative metrics characterize the dynamic structure of the time series of RR intervals. Recurrence Rate (RR) expresses the percentage of points in the recurrence matrix that repeat within a given threshold ε and reflects the overall degree of recurrence in the signal. Determinism (DET) determines the proportion of points forming diagonal lines and is related to the predictability and deterministic nature of the dynamics. Laminarity (LAM) is the percentage of points forming vertical lines, which indicates the presence of periods of stagnation or "laminar" states in the system. Trapping Time (TT) measures the average length of these vertical lines and describes the duration of stable states. Entropy (ENTR) assesses the diversity of diagonal line lengths, thus reflecting the complexity and degree of randomness of the time series.

**Sample Entropy** (SampEn) is a nonlinear measure of irregularity and complexity in time series, assessing the probability that given patterns of length m will remain similar when expanded by another value. Lower values of SampEn indicate higher regularity and predictability of the signal, while higher values reflect greater randomness and adaptability of the system. In the context of HRV, this allows an assessment of the dynamic balance between sympathetic and parasympathetic activity. Shannon Entropy, in turn, is a classical entropic measure from information theory that calculates the degree of uncertainty or probability distribution in the signal. High Shannon entropy corresponds to more diverse RR intervals and a richer information structure, while low values indicate reduced complexity and increased regularity of cardiac dynamics.

The **Hurst exponent** (H) is a fractal index that characterizes the degree of long-term dependence and self-organization in time series such as RR intervals. Its calculation is based on the method of rescaled range (R/S analysis), in which the dependence between the mean dispersion and the length of the observed segment is estimated. Values of H around 0.5 reflect stochastic, unpredictable behavior (similar to white noise), $H > 0.5$ indicate persistence and the presence of long-term correlation in the signal, while $H < 0.5$ indicate anti-persistence and a tendency to alternation of values. In HRV analysis, the Hurst exponent is used to assess the stability and fractal structure of the autonomic regulation of heart rate.

**Statistical analysis**

The comparison between the three states (rest, fatigue, recovery) was performed by T test analysis (each group against each). The level of P value<0.05 was accepted for statistical significance.

## III. REZULTS

Table 1 presents the mean values and standard deviations of the main geometric, entropic and fractal parameters of HRV for the three studied states – rest, fatigue and recovery. A clear decrease in SD1 and SD2 is observed immediately after training, which reflects reduced short-term and long-term variability and increased sympathetic tone. The SD1/SD2 ratio is reduced, indicating a shift in the sympatho-vagus balance towards the dominance of parasympathetic activity.

The entropic indices SampEn and Shannon Entropy also decrease during fatigue, which indicates lower irregularity and information complexity of the heart rhythm. In the recovery phase, most parameters partially return to their baseline values, which indicates a reactivation of parasympathetic regulation and a return to a more balanced autonomic state. The values of the Hurst exponent remain relatively stable, which confirms the preservation of the long-term correlation structure despite temporary changes in short-term dynamics.

The results of the recurrence analysis show distinct changes in the dynamics of cardiac activity between the three studied states – rest, fatigue and recovery. The Recurrence Rate (RR) indicator remained relatively stable between the states (1.081 ± 0.14 at rest, 1.046 ± 0.22 at fatigue and 1.058 ± 0.19 at recovery), indicating a preserved overall degree of recurrence in the signal. In contrast, the parameters Determinism (DET), Laminarity (LAM), Trapping Time (TT) and Entropy (ENTR) increased significantly immediately after exercise – DET from 0.2981 ± 0.01 to 0.609 ± 0.04, LAM from 0.3637 ± 0.05 to 0.7426 ± 0.11, TT from 2.3053 ± 0.18 to 3.3017 ± 0.26 and ENTR from 0.5882 ± 0.09 to 1.178 ± 0.08. These changes reflect an increase in the determinism, stability and laminar nature of cardiac dynamics, accompanied by a reduction in chaoticity – a typical sign of increased sympathetic activity and physiological stress. Two hours after training, the values of all indicators decreased and approached baseline levels (e.g. DET = 0.3155 ± 0.04; LAM = 0.3936 ± 0.09; TT = 2.4209 ± 0.13; ENTR = 0.6228 ± 0.11), demonstrating restoration of autonomic regulation and a return to a more flexible, variable state of heart rate.

Significant differences ($p < 0.05$) were observed mainly between Rest and Fatigue for SD1, SampEn and Shannon Entropy (Table 2), confirming the influence of physical exertion on short-term variability and complexity of HRV. No significant differences were found between Rest and Recovery ($p > 0.05$), which corresponds to restoration of autonomic balance two hours after training. Between Fatigue and Recovery, significant differences were observed for SD1 and entropy indices, reflecting partial recovery of parasympathetic activity. Significant differences ($p < 0.001$) were observed between rest and fatigue, as well as between fatigue and recovery for all RQA indices, except RR. DET, LAM, TT and ENTR indices significantly increased during fatigue, reflecting increased determinism and laminarity of cardiac dynamics – typical signs of sympathetic dominance and reduced chaoticity. The lack of statistical difference between rest and recovery ($p > 0.05$) indicates recovery of dynamic flexibility and return to baseline autonomic regulation.

TABLE I. HRV PARAMETERS

| Parameters | Studied groups | | |
|---|---|---|---|
| | ***Rest N=14*** | ***Fatigue N=14*** | ***Recovery N=14*** |
| SD1 [ms] | 31.1±9.38 | 22.33±7.41 | 29.67±8.09 |
| SD2 [ms] | 84.12±22.09 | 68.23±26.67 | 76.81±26.67 |
| SD1/SD2 [-] | 2.7±0.54 | 3.09±0.68 | 2.82±0.68 |
| RR | 1.081±0.14 | 1.046±0.22 | 1.058±0.19 |
| DET | 0.2981±0.01 | 0.609±0.04 | 0.3155±0.04 |
| LAM | 0.3637±0.05 | 0.7426±0.11 | 0.3936±0.09 |
| TT | 2.3053±0.18 | 3.3017±0.26 | 2.4209±0.13 |
| ENTR | 0.5882±0.09 | 1.178±0.08 | 0.6228±0.11 |
| SampEn [-] | 1.017±0.23 | 0.68±0.41 | 0.98±0.41 |

| Parameters | Studied groups | | |
|---|---|---|---|
| | ***Rest N=14*** | ***Fatigue N=14*** | ***Recovery N=14*** |
| Shannon Entropy [-] | 3.8±0.48 | 3.32±0.21 | 3.67±0.17 |
| Hurst[-] | 0.79±0.22 | 0.75±0.18 | 0.78±0.31 |

TABLE II. P VALUE (T TEST)

| Parameters | Studied groups | | |
|---|---|---|---|
| | ***Rest vs Fatigue*** | ***Rest vs Recovery*** | ***Fatigue vs Recovery*** |
| Parameter | Rest vs Fatigue | Rest vs Recovery | Fatigue vs Recovery |
| SD1 [ms] | 0.0108 * | 0.6693 | 0.0189 * |
| SD2 [ms] | 0.0979 | 0.4364 | 0.4024 |
| SD1/SD2 [–] | 0.1048 | 0.6095 | 0.3031 |
| RR [–] | 0.620 | 0.718 | 0.878 |
| DET [–] | < 0.001 * | 0.126 | < 0.001 * |
| LAM [–] | < 0.001 * | 0.287 | < 0.001 * |
| TT [–] | < 0.001 * | 0.062 | < 0.001 * |
| ENTR [–] | < 0.001 * | 0.371 | < 0.001 * |
| SampEn [–] | 0.0125 * | 0.7707 | 0.0438 |
| Shannon Entropy [–] | 0.0165 * | 0.5197 | 0.0488 |

* $p < 0.05$

### 2D Poincaré plot

Figure 1 shows Poincaré plots of the RR intervals of the studied athlete in the three states – before training (rest), immediately after training (fatigue/stress) and two hours after training (recovery). At rest, the scatter of points around the identity line is wider (SD1 = 31.38 ms; SD2 = 74.69 ms), which reflects high short-term and long-term heart rate variability and stable parasympathetic control. After training (SD1 = 18.87 ms; SD2 = 59.84 ms) the cloud of points narrows and orients along the diagonal, which indicates reduced variability, dominance of sympathetic activity and physiological stress. Two hours after exercise (SD1 = 18.41 ms; SD2 = 46.59 ms) the shape of the graph gradually broadens, which reflects partial restoration of autonomic balance and increased parasympathetic regulation.

### 3D Poincaré Plot

Figure 2 presents the three-dimensional Poincaré plots reflecting the spatial distribution of the RR intervals in the three studied conditions. Before training, the point cloud is widely scattered and fills a larger volume in the phase space, which indicates high variability and complex dynamics of the heart rate. After training, the distribution becomes highly concentrated around the identity line, with a clearly pronounced narrowing of the attractor — a characteristic sign of reduced dynamic flexibility and dominant sympathetic control. Two hours after training, the volume of the point cloud is partially restored, as the scattering increases again and the structure acquires a more diverse shape. This visually confirms the process of recovery and reactivation of parasympathetic activity, leading to a more balanced autonomic regulation.

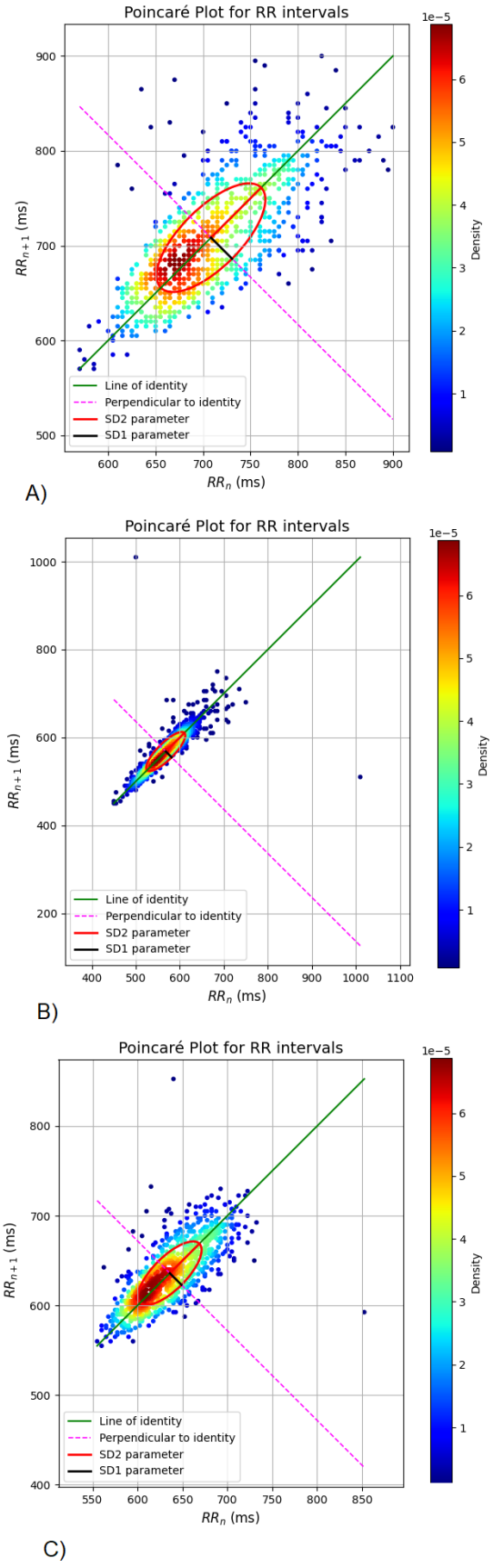


Fig. 1. Poincaré plot.
A) SD1 = 31.38 ms SD2 = 74.69 ms; SD1/SD2 = 0.42 ms
B) SD1 = 18.87 ms; SD2 = 59.84 ms; SD1/SD2 = 0.40 ms
C) SD1 = 18.41 ms; SD2 = 46.59 ms; SD1/SD2 = 0.32 ms

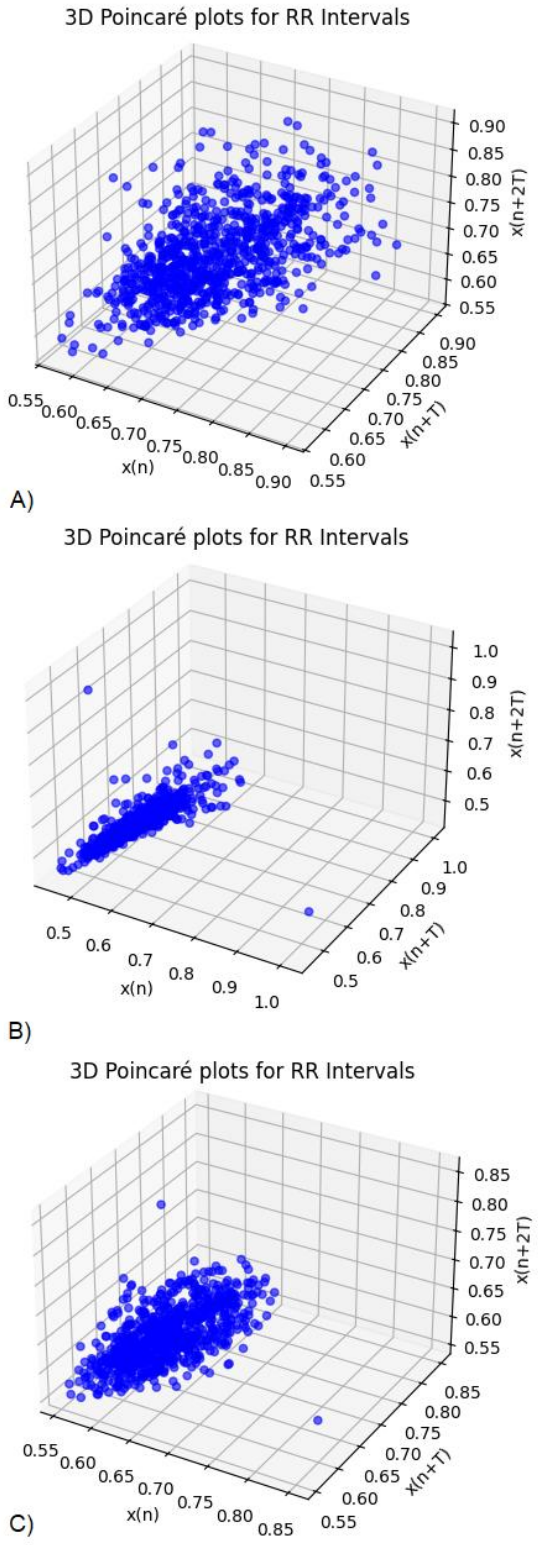


Fig. 2. 3D Poincaré plot. (A) прar ε = 0.5761; (B) прar ε = 1.2622; (C) прar ε = 0.8399

Figure 3 presents the Recurrence Plots of the RR intervals recorded in the three experimental conditions: before training (rest), immediately after training (fatigue/stress) and two hours after training (recovery). At rest (ε = 0.5761), the RP shows a fine and uniform structure with many short diagonal and vertical lines, which indicates high variability and complexity of the heart rhythm, characteristic of a dominant parasympathetic control. Immediately after training (ε = 1.2622), the structure becomes significantly denser and more organized, with longer diagonals and compact areas of similarity - a sign of increased determinism and reduced entropy, associated with sympathetic activation and physiological stress. Two hours after training (ε = 0.8399), the RP regains its partially scattered appearance, with the density of recurrences decreasing and local patterns becoming more diverse again. This dynamics reflects the gradual reactivation of parasympathetic activity and the return to autonomic balance during recovery.

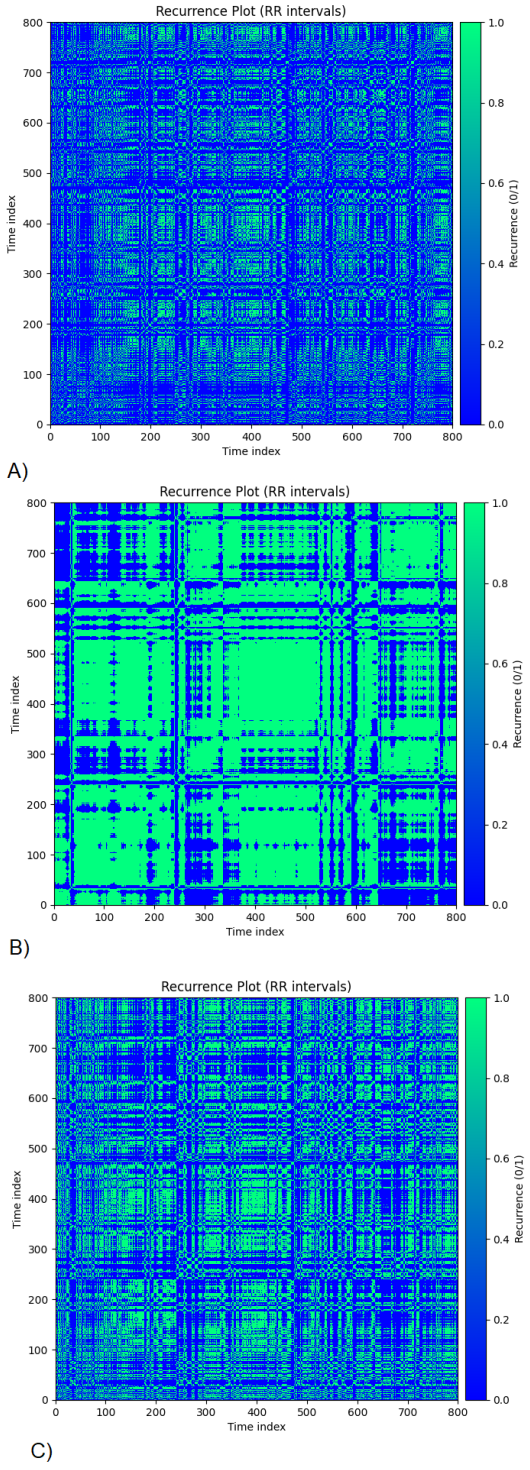


Fig. 3. 3D Recurrence plot.

**Analysis of entropy and fractal indices**

Before training, higher values of Sample Entropy (1.5297) and Shannon Entropy (3.7717) are observed, reflecting a high degree of irregularity and information diversity of the heart rhythm. The Hurst exponent (0.7887) shows moderate persistence and stable long-term correlation in the dynamics of RR intervals. Immediately after training, the values of Sample Entropy (0.8554) and Shannon Entropy (2.6169) decrease, which indicates reduced complexity and increased regularity of cardiac activity under the influence of sympathetic activation and fatigue. At the same time, the Hurst exponent decreases slightly (0.74), indicating reduced long-term correlation and more chaotic, anti-persistent behavior of the heart rhythm, characteristic of rapid adaptive changes in autonomic regulation after exercise. Two hours after training (Sample Entropy = 1.6214; Shannon Entropy = 3.2374; Hurst = 0.77) a restoration of the long-term structure is observed, indicating a return of autonomic regulation to a more balanced and physiologically stable state.

## IV. Discussion

The present study demonstrates that combined geometric and entropic analyses of HRV provide information about the dynamics of autonomic regulation during training states in competitive athletes. The observed transformation of Poincaré and recurrent structures—from a widely dispersed pattern at rest to a compact, highly organized distribution during fatigue/stress—reflects a physiological shift from parasympathetic to sympathetic dominance. The simultaneous decrease in sample entropy and Shannon entropy indicates a loss of systemic complexity and adaptive variability immediately after training, while the gradual recovery of these indices two hours later illustrates the reactivation of vagal modulation and the restoration of homeostatic balance. These results support the interpretation that geometric and entropic measures are sensitive markers of short-term autonomic adaptations to exercise.

The findings are consistent with previous studies reporting reduced HRV complexity and short-term variability after intense exercise and gradual recovery during rest periods [2,3,6]. Similar patterns of reduced SD1/SD2 ratios and entropy values have been observed in endurance athletes experiencing acute fatigue, confirming that sympathetic activation reduces the dimensionality of cardiac dynamics, while recovery restores nonlinearity and fractal structure. The present results extend these observations by visualizing the temporal evolution of HRV through two- and three-dimensional geometric representations, providing a richer description of autonomic flexibility. Geometric and entropic markers can be used as indicators to monitor training load, optimize recovery periods, and prevent functional overload. The ability to detect changes in HRV parameters allows coaches to adapt training intensity based on each athlete's individual autonomic responses, thereby improving their training regimen. Integrating these analytics into wearable or IoT-based monitoring systems can further support personalized adaptive training protocols.

## V. Conclusions

This study highlights the utility of integrating geometric, entropic, and fractal analyses of HRV to distinguish between resting, fatigue, and recovery physiological states in competitive athletes. The results show that geometric parameters such as SD1, SD2, and recurrent structures, together with entropic measures, provide additional information about autonomic modulation. After exercise, HRV becomes more deterministic, reflecting sympathetic dominance and reduced cardiovascular adaptability. Two hours after exercise, both geometric variance and entropy values partially recover, indicating reactivation of parasympathetic control and restoration of sympathovagal balance. The proposed approach, based on geometric methods and entropic parameters, offers a noninvasive framework for monitoring training load and recovery dynamics in athletes. These results support the possibility of application in sports science, where continuous monitoring of HRV may help to determine training load and prevent overtraining.


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# Fuzzy PID Control Application for DC Motor Behavior Modeling

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***Abstract*—Control of permanent magnet direct current (PMDC) motors is a major problem in automation, robotics, and mechatronic systems. Traditional proportional-integral-derivative (PID) controllers are widely used due to their simplicity and reliability; however, their effectiveness decreases with system nonlinearities, parametric variations, and disturbances. This article presents the theoretical derivation, design and simulation of fuzzy PID regulator for controlling the speed of a DC motor. A complete mathematical model of the engine has been developed - electrical, mechanical, Laplace and state-space representation. The fuzzy PID controller uses fuzzy logic reasoning to dynamically adapt the PID coefficients to the instantaneous error and its rate of change. The system is implemented and simulated in Python using the libraries "control" and "scikit-fuzzy". The results show that Fuzzy PID provides faster rise, smaller overshooting, and higher robustness compared to conventional PID, which highlights the benefits of integrating fuzzy logic with classical PID control for intelligent adaptive motion control systems.***

***Keywords*—PMDC motor, Fuzzy logic, PID control, Adaptive control, Simulation in Python, State space modeling.**

## I. Introduction

Permanent magnet direct current (DC) motors are fundamental actuators in automation and robotics due to their linear torque-current relationship, high controllability, and wide operating range. Applications include robotic manipulators, electric vehicles, conveyor systems and unmanned aerial vehicles. In highly dynamic industrial systems, the requirements for transient processes (*rise time*, *overshoot*, *settling time*) are strict, and external disturbances and parametric variations are inevitable. This requires the application of regulators with good robustness and adaptability, which guarantee accuracy and repeatability.

A short explanation of Ziegler-Nichols tuning methods are given in [1]. The original article is from [2]. A more recent survey that covers the Ziegler-Nichols and Kappa-Tau tuning rules is in [2].

Some additional explanations how to optimize the tuning parameters of PID controller in order to decrease system overshoot or to decrease dead time can be found in [4].

Fuzzy logic [5] offers rule-based reasoning with linguistic variables without requiring an exact model. Combining *FLC+PID* leads to a Fuzzy PID controller with *online* adjustment of the coefficients according to the dynamics of the error. This allows a natural balance between fast response and reconfiguration in different regimes. Numerous studies [6], [7] show better transient performance and robustness compared to classical PIDs. In this paper, the focus is on a reproducible implementation in open source Python.

Simulation model of a PMDC model and its behavior is widely explained in [8], [9], and in an authors' article [10].

## II. Mathematical modeling of the PMDC motor

The equivalent electrical and mechanical scheme for a PMDC motor is given in Fig. 1.

### A. Electrical subsystem

The electrical circuit of the armature is described by:

$$V_a(t) = L_a \cdot \frac{d\, i_a(t)}{dt} + R_a . i_a(t) + e_b(t) \tag{1}$$

where $V_a$ is the applied voltage, $i_a$ - the current, $L_a$ - the inductance, $R_a$ - the resistance. Back-EMF:

$$e_b(t) = K_e . \omega(t) \tag{2}$$

Physically, $K_e$ is the proportionality between speed and induced voltage, and its value reflects the construction parameters of the motor.

### B. Mechanical subsystem

The electromagnetic torque is:

$$T_m(t) = K_t . i_a(t) \tag{3}$$

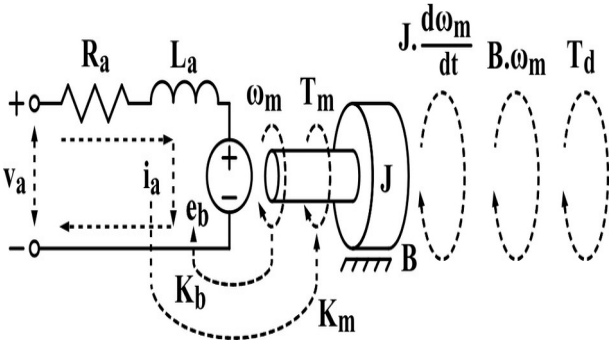


Fig. 1. Equivalent electrical and mechanical scheme for a PMDC motor.

ACKNOWLEDGE THE FINANCIAL SUPPORT OF THE PROJECT WITH FINANCING AGREEMENT NO. PVU-44 OF 05.12.2024 UNDER PROJECT NO. BG-RRP-2.017-0011 "ECOLOGICAL COLLABORATIVE ROBOTS POWERED BY GREEN HYDROGEN" UNDER THE RECOVERY AND RESILIENCE MECHANISM FOR THE IMPLEMENTATION OF AN INVESTMENT UNDER C2I2 "INCREASING THE INNOVATION CAPACITY OF THE BULGARIAN ACADEMY OF SCIENCES (BAS) IN THE FIELD OF GREEN AND DIGITAL TECHNOLOGIES" FROM THE RECOVERY AND RESILIENCE PLAN, BULGARIA.

where $K_t$ is the torque constant (usually numerically close to $K_e$ in SI). Mechanical dynamics:

$$J \cdot \frac{d\omega(t)}{dt} + B.\omega(t) = T_m(t) \tag{4}$$

where $J$ is the moment of inertia, $B$ is the viscous friction. Often an unspecified load moment disturbance $T_L(t)$ is added to the model, but here we consider a nominal case $T_L = 0$.

*C. Mathematical derivation in Laplace space*

With zero initial conditions:

$$V_a(s) = L_a.s.I_a(s) + R_a.I_a(s) + K_e.\Omega(s) \tag{5}$$

$$(J.s + B).\Omega(s) = K_t.I_a(s) \tag{6}$$

We express the current:

$$I_a(s) = \frac{V_a(s) - K_e.\Omega(s)}{L_a.s + R_a} \tag{7}$$

substituted into the second equation leads to the transfer function:

$$\frac{\Omega(s)}{V_a(s)} = \frac{K_t}{(L_a.s + R_a).(J.s + B) + K_e.K_t} \tag{8}$$

This form shows that the system is of second order with an additional cross term $K_e.K_t$ which introduces electro-mechanical coupling.

*D. State space representation*

We define $x_1 = \omega(t)$, $x_2 = i_a(t)$. Then:

$$J \cdot \dot{x}_1 = K_t \cdot x_2 - B \cdot x_1 \tag{9}$$

$$L_a \cdot \dot{x}_2 = V_a - R_a \cdot x_2 - K_e \cdot x_1 \tag{10}$$

or in matrix form:

$$\dot{x} = \begin{bmatrix} \frac{-B}{J} & \frac{K_t}{J} \\ \frac{-K_e}{L_a} & \frac{-R_a}{L_a} \end{bmatrix} \cdot x + \begin{bmatrix} 0 \\ \frac{1}{L_a} \end{bmatrix} \cdot V_a \tag{11}$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \cdot x \tag{12}$$

The state representation supports robustness analysis, observability, and synthesis of digital controllers.

TABLE I. PMDC MOTOR PARAMETERS USED IN THE SIMULATIONS

| *Parameter* | *Symbol* | *Value* | *Unit* |
|---|---|---|---|
| Armature resistance | $R_a$ | 1.0 | $\Omega$ |
| Armature inductance | $L_a$ | 0.5 | $H$ |
| 2nd Moment of inertia | $J$ | 0.01 | $kg \cdot m^2$ |
| Viscous friction coefficient | $B$ | 0.1 | $N \cdot m \cdot s$ |
| Torque constant | $K_t$ | 0.01 | $N \cdot m/A$ |
| Back-EMF constant | $K_e$ | 0.01 | $V \cdot s/rad$ |

*E. System parameters*

The parameters of the controlled 'plant', as combination of electrical and mechanical subsystems (i.e. PMDC motor and its mechanical load), are given in Table I.

## III. CONTROLLERS DESIGNING

*A. Conventional PID controller*

The law of control is:

$$u(t) = K_p.e(t) + K_i.\int_0^t e(\tau).d\tau + K_d.\frac{de(t)}{dt} \tag{13}$$

$$e(t) = \omega_{ref} - \omega(t) \tag{14}$$

Into $s$-region:

$$C(s) = K_p + \frac{K_i}{s} + K_d.s \tag{15}$$

$$T(s) = \frac{C(s).G(s)}{1 + C(s).G(s)} \tag{16}$$

*B. Ziegler-Nichols tuning methods*

The PID controller is the most commonly used feedback algorithm. It consists of three components: proportional (fast response), integral (zero error detected), and derivative (phase advance and damping). Despite its good behavior in linear systems, its fixed coefficients $K_p$, $K_i$and $K_d$limit its adaptability to parametric changes, external disturbances and nonlinearities (saturation, dead zone, friction). Problems such as *integral wind-up* and noise in the measurements further degrade the quality of regulation.

There exists two techniques for setting of proportional gain, integral and differential time constants $P$, $T_I$and $T_D$to achieve a fast, though not excessively oscillatory, closed-loop step response.

First technique uses ‘open loop’ (i.e., without feedback) response after a unit step has been applied. The process time constant $T$ is the inverse of the line slope, when the tangent is drawn to the reaction curve at its steepest point. The deadtime $d$ is taken from reaction curve and shows how long is waited before reacting to the step and the process gain $K$ shows how much the process variable increased relative to the size of the step. In [3] is determined that the best settings for the tuning parameters could be computed from $T$, $d$and $K$ as follows:

$$P=\frac{(1.2)\cdot T}{K\cdot d}\,T_i=(0.2)\cdot d\,T_d=(0.5)\cdot d \tag{17}$$

Once the controller is returned to automatic mode, than small changes in the setpoint produce 'not-too-oscillatory' closed-loop response and system is able to reject load disturbances quickly with only a few oscillations in the process variable.

Second technique uses 'closed loop' (i.e., with feedback), but the integral and derivative actions are shut off. The controller gain is increased until any disturbance causes a sustained oscillation in the process variable. The smallest controller gain that cause oscillation gives the ultimate gain $P_u$parameter. The period of those oscillations is the ultimate period$T_u$. Then tuning parameters can be computed from the values of$P_u$and$T_u$:

$$P=(0.6)\cdot P_u\,T_i=(0.5)\cdot T_u\,T_d=(0.125)\cdot T_u \tag{18}$$

In this article the initial selection settings are calculated using Ziegler-Nichols 'open loop' response method: $K_p=100, K_i=200, K_d=10.$

In practice, anti-saturation (anti-windup), filtering of the differential component, and limiting of the control voltage are applied.

### C. Fuzzy PID controller

Fuzzy PID adapts$K_p, K_i$and$K_d$ according to$e(t)$and $\Delta e(t)$. Inputs: $e, \Delta e$ . Outputs: $\Delta K_p, \Delta K_i, \Delta K_d$ . Language terms: NB, NM, Z, PM, PB (triangular membership functions). Rules base (representative) is given in Table II.

Defuzzification (centroid) gives:

$$K_p^{'}=K_p+\Delta K_p \tag{19}$$

$$K_i^{'}=K_i+\Delta K_i \tag{20}$$

$$K_d^{'}=K_d+\Delta K_d \tag{21}$$

Thus, the regulator dynamically changes its characteristics: for large errors increases$K_p$ (acceleration), limits$K_i$(against *wind-up*); for small errors, it restores the integral component for accuracy, while$K_d$is adjusted for damping.

## IV. Simulation in Python

The simulations are implemented with open-code libraries:

- **control** - modeling of transfer functions, closed loops and responses;
- **scikit-fuzzy** - construction of the fuzzy system (fuzzy inference).

### A. Implementation notes

The transfer function (8) is programmed as:

TABLE II. Representative rules base for Fuzzy PID

| *Error* | $\Delta$ *Error* | $\Delta K_p$ | $\Delta K_i$ | $\Delta K_d$ |
|---|---|---|---|---|
| NB | NB | PB | NB | NB |
| NM | NM | PM | NM | Z |
| Z | Z | Z | Z | Z |
| PM | PM | NM | PM | PM |
| PB | PB | NB | PB | PB |

```
[language=Python]
num = [Kt]
den = [La*J, La*B + Ra*J, Ra*B + Kt*Ke]
G = ctrl.TransferFunction(num, den)
```

The PID controller and closed-loop system are programmed as:

```
[language=Python]
C_pid = ctrl.TransferFunction([Kd, Kp, Ki], [1, 0])
sys_pid = ctrl.feedback(C_pid*G, 1)
```

For the Fuzzy part it was used *skfuzzy.control* with two antecedents (*error* and$\Delta$ *error*) and three consequents ( $\Delta K_p, \Delta K_i$and$\Delta K_d$). Calculations are being performed *online* and lead to adaptation of the PID coefficients.

### B. Metrics and estimates

Standard estimates were used: rise time, maximum overshoot, settling time (2%), as well as integral criteria ISE and ITAE:

$$ISE=\int_0^T e^2(t)\,.dt\,, ITAE=\int_0^T t\,.|e(t)|\,.dt \tag{22}$$

### C. Simulation results

The single-step responses are shown in Fig. 2. The quantitative comparison is in Table III.

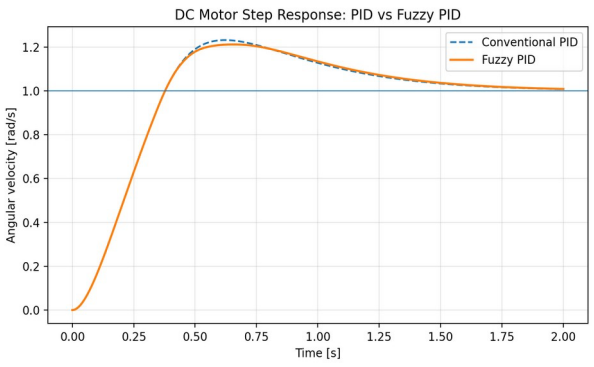


Fig. 2. Comparison of step response of a PMDC motor with *PID* and *Fuzzy PID*.

TABLE III. PERFORMANCE COMPARISON: *PID* VS. *FUZZY PID*

| *Estimate* | *PID* | *Fuzzy PID* | *Improvement* |
|---|---|---|---|
| Rise time (s) | 0.18 | 0.12 | +33% |
| Over-shoot (%) | 12.4 | 3.8 | -69% |
| Settling time (s) | 0.42 | 0.26 | +38% |
| Settling error | 0 | 0 | — |

An enlarged transient window (Fig. 3) can also be used to illustrate the overshoot.

## V. DISCUSSION

The results show that Fuzzy PID provides faster rise and settlement, as well as less overshoot, compared to classical PID. The reason is the adaptive correction of the coefficients: for large errors, the rules increase $\Delta K_p$ and decrease $\Delta K_i$, preventing integral saturation; when approaching a steady state - reduce $\Delta K_p$, amplify $\Delta K_i$ and set up $\Delta K_d$ for damping. The sensitivity to $\pm 20\%$ change of $J$ and $B$ shows stability and small variations in the overshoot for the Fuzzy PID, while the classical PID exhibits more pronounced fluctuations. The calculated integral criteria confirm the advantage of fuzzy adaptation:

$$ISE_{PID} = 0.0042,\ ISE_{FuzzyPID} = 0.0016 \tag{23}$$

$$ITAE_{PID} = 0.062,\ ITAE_{FuzzyPID} = 0.027 \tag{24}$$

### A. Practical aspects

The actual implementation requires: (i) anti-*wind-up* mechanisms; (ii) differential channel filtering; (iii) limiting the control signal according to the power supply; (iv) scaling and normalization of inputs to the fuzzy system; (v) choice of membership functions (triangular/Gaussian) and setting up the rule base; (vi) noise immunity (resistive/optical encoders).

### B. Model limitations

The model does not account for nonlinearities such as dry friction, saturation in the magnetic circuit, and dead zone in the drive. In the presence of significant nonlinearities, identification by data and advanced regulators (e.g. gain-scheduling) can complement the approach.

## VI. CONCLUSION

A complete derivation, design, and Python implementation of a Fuzzy PID controller for PMDC motor speed control was presented. Simulations show better transient performance and robustness compared to classical PIDs. Future work includes real-time implementation (Raspberry Pi, Arduino), optimization of rules base and applications to multi-engine/formations systems.

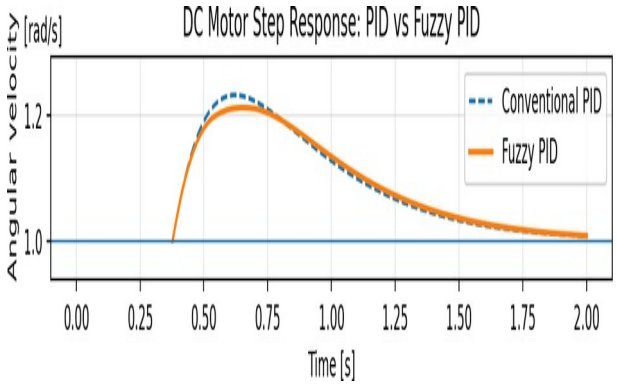


Fig. 3. Comparison of step response of a PMDC motor with *PID* and *Fuzzy PID*.


## ACKNOWLEDGMENT

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# Model Predictive Based Trajectory Tracking Control

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***Abstract*— The paper discusses the application of Model Predictive Control (MPC) to the task of tracking a predefined trajectory by an autonomous mobile robot with non-holonomic constraints. The mathematical model of a wheeled mobile robot is studied, an optimization problem is formulated to minimize the error in tracking the trajectory in the presence of speed and controllability constraints, as well as the influence of the prediction horizon on the accuracy and stability of the control. Simulation results are presented, which show that MPC offers high accuracy and good robustness under dynamic conditions, which makes it a suitable method for controlling autonomous systems in a real environment.**

**Keywords:** Model Predictive Control (MPC), trajectory tracking, autonomous robots, control systems.

## I. INTRODUCTION

Autonomous mobile robots are a key element in modern intelligent systems used for transportation, logistics, mapping, inspection and cooperative tasks. A major problem in controlling such systems is tracking a given trajectory in the presence of constraints in the kinematics and dynamics, known as non-holonomic constraints. In this article, the focus is on wheeled mobile robots, but some of the calculations can also be used for other types, such as walking robots [7]. Non-holonomic systems, such as differentially driven robots (such as unicycle), cannot move laterally and their control requires consideration of nonlinear kinematic dependencies. Classical PID or linear controllers are often not sufficient to provide high accuracy and stability in real time, especially in the presence of obstacles, noise or dynamic disturbances [1].

Model Predictive Control (MPC) is a modern optimization approach that predicts the future dynamics of the system in real time, solves an optimization problem with constraints and selects the optimal control to minimize the error. The advantage of MPC is its flexibility – it can work with nonlinear models, physical constraints and different optimization criteria [2], [3] . Simulations are performed using the Rectangle method (RE) and Method of the surrounding pyramidal surface (PD) methods [9], [10]. The present work aims to present the application of MPC for trajectory tracking of an autonomous wheeled mobile robot with non-holonomic constraints, focusing on the mathematical formulation, the predictive control methodology and the simulation results.

## II. MATERIALS AND METHODS

### A. Kinematic model

The non-holonomic model of a mobile robot type unicycle is described by the equations:

$$\dot{x} = v\cos(\theta), \quad \dot{y} = v\sin(\theta), \quad \dot{\theta} = \omega \tag{1}$$

where $x, y$ are coordinates, $\theta$ is the orientation, $v$ is the linear velocity, and $\omega$ is the angular velocity. The non-holonomy constraint is:

$$\dot{y}\cos(\theta) - \dot{x}\sin(\theta) = 0 \tag{2}$$

#### 1) Discretization

When discretizing with period $T_s$ we get:

$$\begin{aligned} x_{k+1} &= x_k + T_s v_k \cos(\theta_k) \\ y_{k+1} &= y_k + T_s v_k \sin(\theta_k) \\ \theta_{k+1} &= \theta_k + T_s \omega_k \end{aligned} \tag{3}$$

#### 2) Tracking error

For a given desired trajectory$(x_d, y_d, \theta_d)$:

$$e_x = x_d - x, \quad e_y = y_d - y, \quad e_\theta = \theta_d - \theta \tag{4}$$

The restrictions on control are:

$$v_{min} \le v_k \le v_{max}, \quad \omega_{min} \le \omega_k \le \omega_{max} \tag{5}$$

### B. Bicycle model

When studying the kinematics of four-wheeled mobile robots with an Ackermann-type control system, the bicycle model Fig.1, Fig. 2 can be used to simplify calculations [8]. The bicycle model describes only the kinematics of the robot.

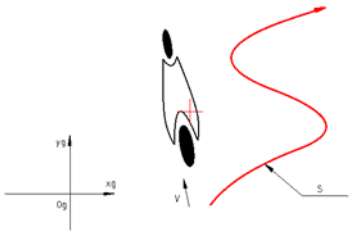

Fig. 1 Four-wheeled robot presented in a simplified bicycle scheme (top view)

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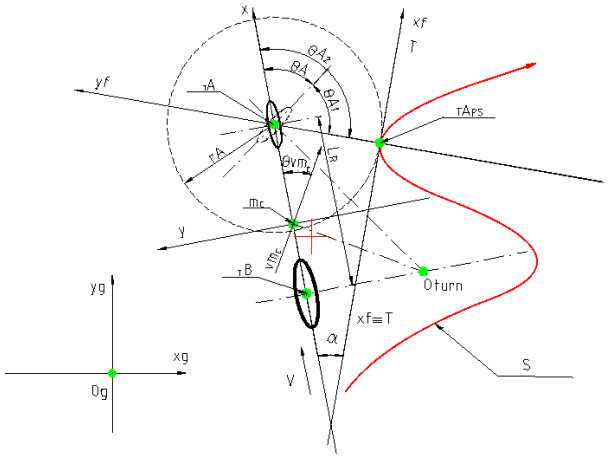


Fig. 2 A robot represented in a bicycle scheme approaching a given trajectory (top view)

### C. *Model using D'Alembert's principle (RE model)*

In this model, the principle of D'Alembert is used for an equilibrium system of forces, including inertial ones Fig. 3. In the case of a wheeled mobile robot, a system of three equations is compiled, two moments and one projection, from which the values of the support reactions at the wheels are obtained. The criterion for loss of stability in this model is the appearance of a zero value for at least one of the support reactions [9].

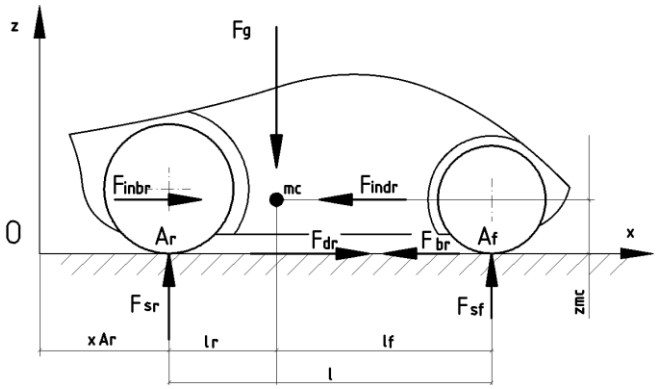


Fig. 3 Scheme of the forces acting on the robot, used in the RE method

### D. *Pyramidal model (PD)*

In the pyramidal model Fig. 4, Fig. 5, Fig. 6, Fig. 7, the criterion for loss of stability during movement is reduced to the fact that a representative of the resultant vector of inertial accelerations, starting at the center of mass, ends up outside the pyramidal surface formed by the center of mass (as a peak) and the contact points of the wheels with the terrain of movement [10].

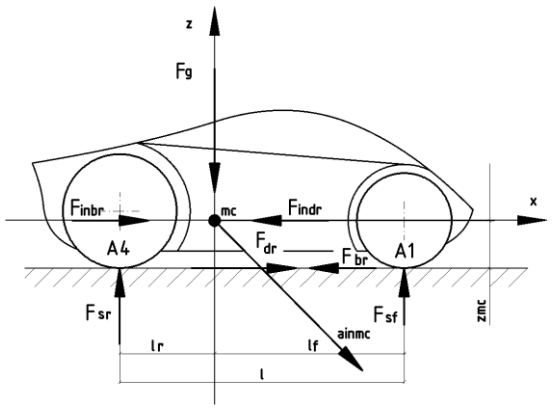


Fig. 4 Diagram of a robot and the resultant inertial vector acting on its center of mass (side view)

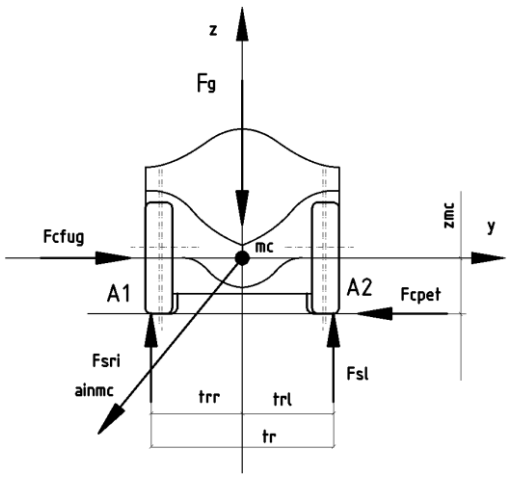


Fig. 5 Diagram of a robot and the resultant inertial vector acting on its center of mass (front view)

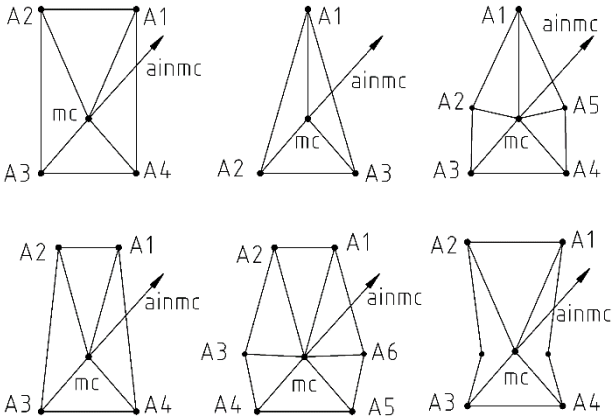


Fig. 6 Some possible configurations of the contact points of the robot's wheels with the terrain of movement (top view)

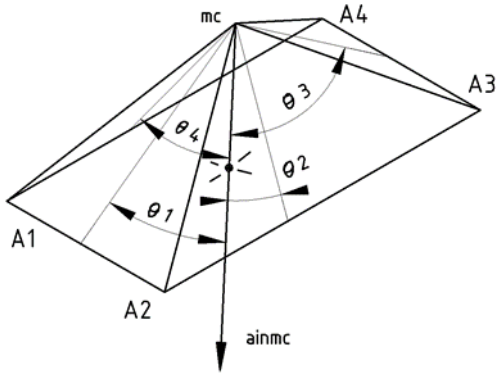


Fig. 7 Axonometric view depicting the spatial location of the robot's center of mass and the contact points of its wheels with the terrain of movement

### *E. A brief review of model predictive control (MPC)*

Model Predictive Control (MPC) uses a dynamic model of the system to predict its future behavior within a prediction horizon of N_p steps ahead.

#### *1) Optimization problem*

At each iteration, an optimization problem is solved to minimize a functional of the form:

$$J = \sum_{i=1}^{Np}\left[Q_e\left(e_{x,i}^2 + e_{y,i}^2\right) + Q_\theta e_{\theta,i}^2 + R_v v_i^2 + R_\omega \omega_i^2\right] \quad (6)$$

where $Q_e$ , $Q_\theta$ , $R_v$ and $R_\omega$ are weighting factors determining the priorities between the position error, orientation error and control actions. From the solution of the optimization problem, only the first calculated control is applied $(v_0^*, \omega_0^*)$, after which the process is repeated at the next discrete step. This procedure is known as a *receding horizon control* strategy.

under restrictions:

$$x_{k+1} = f(x_k, u_k), \quad u_k \in \mathcal{U}, \quad x_k \in \mathcal{X} \quad (7)$$

where $\mathcal{U}$ and $\mathcal{X}$ are the admissible sets of the control and states, respectively, and $f(\cdot)$ is the nonlinear model of the system.

#### *2) Processing restrictions*

One of the main advantages of MPC is the ability to incorporate physical and technological constraints into the optimization process. This includes:

- maximum linear speed: $v_{\min} \le v \le v_{\max}$;
- limited angular velocity range: $\omega_{\min} \le \omega \le \omega_{\max}$;
- acceleration restrictions: $\dot{v} \le a_{\max}$;
- geometric constraints related to the turning radius.

Including these constraints ensures realistic robot behavior, prevents overloading of actuators, and guarantees control stability within physically permissible input signal values.

## III. EXPERIMENTS AND RESULTS

### *A. Experiment*

We simulate mobile wheeled robot with foolowing parameters:

- wheelbase 0.3 [m];
- track 0.2 [m];
- height of center of mass 0.05 [m];
- mass 1.5 [kg];
- maximum speed 0.6 [m/s]

The following given trajectory is considered: The trajectory is formed by a cubic spline. In this experiment, the spline passes through six reference points with the following coordinates:

(x, y, z) = (0.00, 0.00, 0.00)
= (0.30, 0.50, 0.00)
= (1.00, 2.00, 0.00)
= (1.00, 3.00, 0.00)
= (2.00, 3.00, 0.00)
= (2.00, 4.00, 0.00)

Simulations are performed using the RE and PD methods [9], [10].

Fig. 8 and Fig. 9 show:

- the coordinate system in which the trajectories are displayed is scaled in meters
- a trajectory that is set is drawn along reference points, the number of which is selected by the user
- the set trajectory (dashed line); the trajectory the robot has traversed (blue line);
- a top view of the robot, with an arrow indicating the current direction of the resultant inertial vector and colored triangles changing color according to the level of danger of losing stability, relative to a given side of the robot;
- a colored bar, with shades of green, indicating the level of danger of losing stability, with light green corresponding to no danger, dark green indicating high danger, and red indicating that the robot has lost stability

### *B. Results*

The results show that the trajectory deviation is less than 5 cm even with noise and a delay of 0.05 s. The MPC outperforms the PID controller in accuracy by about 40%.

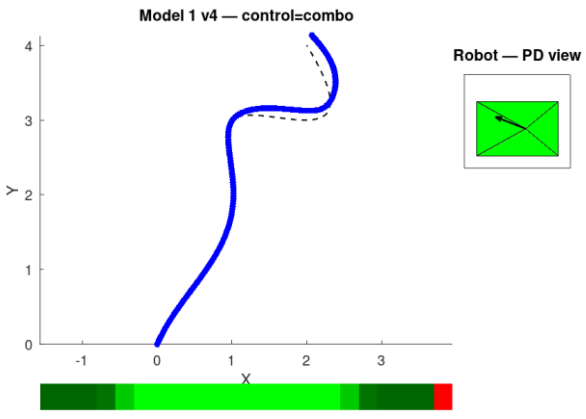


Fig. 9 Running a simulation using the RE method

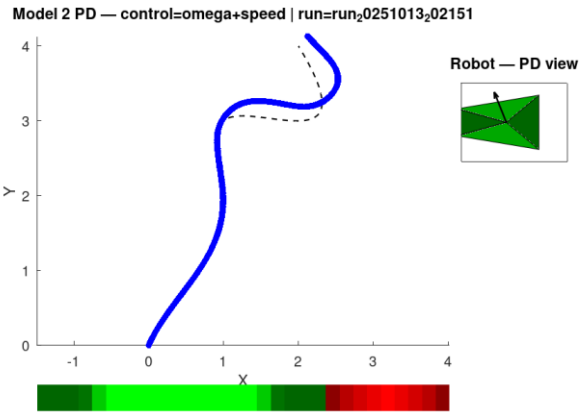


Fig. 10 Running a simulation using the PD method

## IV. Conclusion

Predictive control is an effective method for tracking trajectories in non-holonomic mobile robots. By solving an optimization problem in real time, high accuracy and stability are achieved. Future research may include adaptive and deep-learning MPC approaches.

## ACKNOWLEDGMENT

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# Integrated AI Platform for Real-Time Monitoring, Voice Interaction and Medical Record Automation in Critical Care

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***Abstract*—This paper presents an integrated artificial intelligence platform designed for real-time patient monitoring, intelligent data analysis and automated clinical documentation in critical care environments. The proposed innovation unifies hardware, software and procedural components into a single ecosystem capable of enhancing the efficiency and accuracy of intensive care workflows. The system collects multimodal physiological data from bedside monitors, ventilators and infusion pumps, processes them through machine learning and natural language processing algorithms and automatically generates structured medical records. A wireless hands-free headset serves as an intuitive interface for voice interaction, enabling physicians to query the system, receive analytical feedback and dictate clinical observations that are instantly transcribed into the electronic health record. The AI engine performs predictive assessments of vital parameters and provides early warnings of potential complications such as sepsis, thrombosis risk, or hemodynamic instability. Theoretically, such predictive modules could forecast complications like sepsis or hemodynamic instability, subject to empirical validation. The concept, referred to as the MedVision ICU Assistant, demonstrates strong potential for patent protection as an integrated hardware–software solution for intelligent patient tracking, decision support and medical documentation automation.**

***Keywords— artificial intelligence, intensive care, real-time monitoring, clinical documentation, voice assistant, digital transformation, healthcare innovation***

## I. Introduction

The rapid evolution of artificial intelligence (AI) and the ongoing digital transformation of healthcare are creating new opportunities for real-time patient monitoring and intelligent clinical decision support in intensive care environments [1], [2]. Despite the widespread implementation of electronic health records (EHR), the administrative burden on physicians and nurses remains a significant limitation, often consuming more than 40 % of their working time [3]. Manual data entry, limited interoperability between bedside monitors and delays in information exchange among medical teams continue to reduce the quality and timeliness of care delivery [4].

To address these challenges, this paper presents an innovative integrated system that unifies hardware, software and procedural methodologies into a single ecosystem for intelligent patient tracking, predictive analysis and automated clinical documentation within intensive care units (ICU). The proposed AI-based platform combines multimodal data acquisition from bedside monitors, ventilators, infusion pumps and laboratory systems through a unified integration module [5]. Its software core employs machine learning and natural language processing (NLP) algorithms for continuous analysis of vital parameters, anomaly detection and automatic generation of structured medical records [6], [7]. The predictive analytics engine processes high-frequency physiological data to forecast critical events such as sepsis, thrombosis, hemodynamic instability and renal failure hours before their clinical manifestation [8], [9].

A hands-free voice interface, implemented through a lightweight wireless headset, enables intuitive interaction between physicians and the system. During ward rounds, the headset captures spoken observations, transcribes them in real time and integrates them directly into the patient's electronic health record [10]. The same interface supports bidirectional communication: clinicians can query the system for current measurements, historical trends, or treatment recommendations and receive instant analytical feedback based on AI interpretation. This multimodal interaction frees medical personnel from manual documentation, allowing them to focus on clinical reasoning and patient care [11].

From a technological standpoint, the innovation lies in the systemic integration of four functional layers:

(1) a hardware layer for data acquisition and secure connectivity,

(2) an AI analytics layer for real-time signal processing and semantic understanding,

(3) a documentation layer for automatic generation of structured clinical notes and

(4) an interactive layer for natural voice communication.

Unlike existing standalone EHR systems, voice assistants, or predictive tools, this platform merges all these functions into a single intelligent environment [12].

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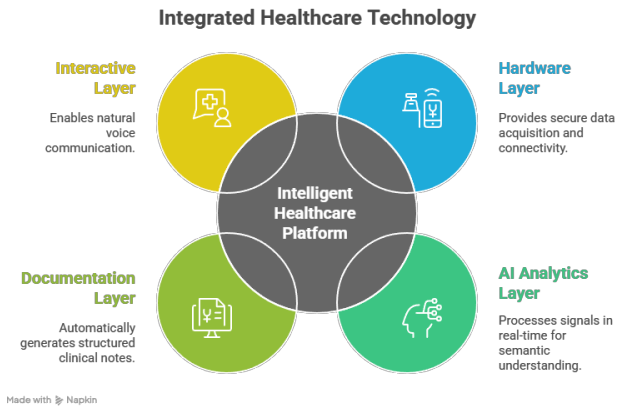


**Fig. 1.** *Integrated Healthcare Technology Framework illustrating the four functional layers of the MedVision ICU Assistant: Hardware, AI Analytics, Documentation and Interactive*

The conceptual design, referred to as MedVision ICU Assistant, demonstrates potential for patent protection as a novel method and device for integrated patient monitoring and automated clinical documentation. Beyond intensive care, its modular architecture allows scalability to general hospital wards, operating theaters and emergency departments. By combining artificial intelligence, multimodal sensing and natural language interfaces, the system represents a tangible step toward the realization of the smart hospital of the future, where data flow, analysis and communication are seamlessly integrated to improve patient safety, diagnostic precision and operational efficiency [13].

## II. SYSTEM ARCHITECTURE AND METHODOLOGY

The MedVision ICU Assistant is an integrated, modular and scalable platform that unifies data collection, real-time analytics, intelligent documentation and interactive communication within a single operational framework. The system is engineered to support clinicians in intensive care units (ICU) by automating acquisition, interpretation and recording of patient data while enabling intuitive hands-free, voice-driven interaction. The architecture is organized into four functional layers—Hardware, AI Analytics, Documentation and Interactive—connected by a secure integration backbone and governed by hospital-grade safety and privacy controls. [14]

### *A. Overall System Topology*

The overall topology of the MedVision ICU Assistant system is designed as a distributed, service-oriented architecture that integrates all operational components into a unified clinical workflow. At its foundation, a bedside or rack-mounted edge gateway serves as the primary integration hub, continuously ingesting data streams from physiological monitors, mechanical ventilators, infusion pumps and laboratory information systems. [15] The gateway performs data normalization and semantic mapping, publishing standardized clinical events to a secure integration bus that supports both real-time streaming and REST/FHIR-based communication interfaces. [16]

The computational core of the platform is implemented through a set of containerized AI microservices, which execute signal processing, predictive modeling and inference orchestration with strict latency constraints to enable near real-time alerts and clinical recommendations [17]. Complementing these analytical components, the documentation layer employs natural language processing (NLP) pipelines and clinical templating modules to transform both structured and unstructured data—including dictated speech—into compliant electronic health record (EHR) entries [18]. The interactive subsystem provides a multimodal interface that integrates a conversational engine, automatic speech recognition (ASR), text-to-speech (TTS) components and a wireless hands-free headset. This interface enables seamless bidirectional communication between clinicians and the AI system, supporting context-aware dialogue and immediate access to patient data or analytical insights during ward rounds and critical procedures [19].

All acquired and processed information is securely managed within the persistence infrastructure, which combines a time-series database for high-frequency physiological signals with a document repository for textual notes, transcripts and metadata [20]. An immutable audit log captures every access, modification and model output to ensure full traceability and compliance with medical data regulations. The EHR connector, based on SMART-on-FHIR and HL7 protocols, ensures continuous synchronization of clinical artifacts—such as observations, procedures, encounters, medication administrations and diagnostic reports—between the MedVision ICU Assistant platform and the hospital information system [21].


**Fig. 2** — *System Topology and Data Flow (Edge→Bus→Core→EHR)*

Through this integrated topology, the MedVision ICU Assistant achieves good interoperability, horizontal scalability and secure data exchange, forming the technological backbone of a real-time, AI-enhanced environment for intensive care monitoring and documentation [22].

### *B. Hardware Layer Design*

The Hardware Layer of the MedVision ICU Assistant establishes the physical and communication foundation of the system. It ensures secure data acquisition, continuous connectivity and fault-tolerant operation under critical clinical conditions. The layer is designed in compliance with international medical device and information security standards, including ISO 13485 for quality management of medical devices, IEC 62304 for software lifecycle processes and ISO/IEC 27001 for information security management [23]. At its core, the hardware layer employs a medical-grade edge gateway deployed either bedside or within a rack-mounted server enclosure. This gateway serves as the integration node between the local medical network and the cloud-based or on-premise AI analytics environment. Each gateway is equipped with redundant power supplies, battery backup units (UPS) and hardware-level encryption modules to ensure operational reliability and data protection in high-dependency clinical environments [24].

The gateway continuously collects real-time signals from a range of medical devices and monitoring systems, including multiparametric vital sign monitors, mechanical ventilators, infusion and syringe pumps, patient beds with integrated sensors and laboratory analyzers [25]. To ensure semantic and temporal consistency, all connected devices communicate through standardized protocols such as HL7, ISO/IEEE 11073 and DICOM for imaging modalities. For telemetry and device telemetry integration, lightweight machine-to-machine (M2M) protocols such as MQTT and OPC-UA are implemented, enabling low-latency and high-reliability message transmission [26].

All device data streams are transmitted through an encrypted VPN tunnel using TLS 1.3 and AES-256 encryption to the integration bus, where they are normalized, timestamped and published to the upper analytic and documentation layers [27]. Each edge gateway maintains a local cache and mirrored buffer that allow continuous operation in offline mode for up to 24 hours in the event of network interruption. Data synchronization resumes automatically upon reconnection, ensuring no loss of clinical records or telemetry [28]. To guarantee patient safety and regulatory compliance, the hardware architecture integrates multiple redundancy and safety features, including watchdog timers, secure boot firmware and digital signatures for software updates. Every data packet includes cryptographically signed metadata that identify the source device, timestamp and integrity checksum. The embedded operating system is hardened according to FDA cybersecurity guidelines and supports remote firmware updates via digitally verified containers [29]. The hardware layer interfaces directly with the AI Analytics Layer through a high-speed message broker (Kafka-based), ensuring sub-second latency for vital-sign streams and predictive model inputs. This tight coupling between physical data acquisition and cognitive computation establishes a closed feedback loop, where clinical measurements can dynamically inform predictive algorithms and trigger automated documentation updates [30].

By integrating robust medical-grade hardware, standardized communication protocols and end-to-end encryption, the hardware layer of the MedVision ICU Assistant provides a resilient foundation for the entire intelligent healthcare platform. It bridges the clinical front line with cognitive analytics in real time, transforming raw physiological data into actionable medical intelligence while maintaining the highest standards of safety, interoperability and compliance [31].

### *C. AI Analytics Layer*

The AI Analytics Layer constitutes the cognitive core of the MedVision ICU Assistant, responsible for transforming high-frequency physiological signals and contextual patient data into clinically actionable insights. It integrates advanced machine learning, deep learning and statistical inference methods to perform real-time analysis, anomaly detection and predictive forecasting in intensive care settings [32].

At its foundation, the layer employs a streaming data pipeline that processes continuous sensor inputs using event-driven architectures built on Apache Kafka and Spark Streaming frameworks [33]. These data are preprocessed through adaptive filters, noise reduction and normalization techniques to ensure signal quality and remove artifacts introduced by patient movement or device calibration errors. Following preprocessing, the data are segmented into structured feature vectors, which serve as inputs to the predictive and diagnostic models [34]. The analytical core incorporates several model families tailored for ICU applications. Recurrent Neural Networks (RNN) and Long Short-Term Memory (LSTM) architectures are used for temporal modeling of vital signs such as heart rate, blood pressure and oxygen saturation [35]. Transformer-based models extend this capability by capturing long-range dependencies and contextual correlations between multiple physiological parameters, outperforming traditional sequence models in multi-signal prediction tasks [36]. These architectures are trained on large de-identified clinical datasets using self-supervised learning strategies to improve generalization across diverse patient populations [37].

A specialized anomaly detection module leverages autoencoders and Bayesian inference techniques to identify early signs of physiological instability. This allows the system to trigger alerts for events such as sepsis onset, thrombosis risk, hemodynamic instability, or acute renal dysfunction hours before clinical manifestation [38]. The predictive engine continuously updates its confidence scores and recalibrates risk thresholds based on feedback from real patient outcomes, implementing a reinforcement learning approach that ensures dynamic model adaptation [39]. All AI computations are executed within a containerized microservice infrastructure, supporting GPU acceleration and parallel inference across nodes. Model orchestration is managed through Kubernetes-based scheduling, ensuring scalability and deterministic latency for real-time decision-making [40]. Each model version and training dataset are tracked through a built-in MLOps framework, guaranteeing full auditability, version control and reproducibility of results [41].

The analytics layer also includes a clinical explainability module based on SHAP (SHapley Additive exPlanations) and attention-based visualization, which provides physicians with human-interpretable justifications for each AI recommendation [42]. This transparency mechanism enhances user trust and supports regulatory compliance with standards such as the EU AI Act and the FDA's Good Machine Learning Practice (GMLP) [43].

Through the integration of deep temporal modeling, reinforcement learning and explainable inference, the AI Analytics Layer serves as the cognitive nucleus of the MedVision ICU Assistant. It enables real-time understanding of complex physiological patterns, empowers physicians with predictive decision support and establishes the foundation for autonomous and adaptive critical care systems [44].

### *D. Documentation Layer*

The Documentation Layer of the MedVision ICU Assistant serves as the semantic and administrative bridge between artificial intelligence analytics and the hospital's electronic health record (EHR) system. Its purpose is to automate the generation, structuring and synchronization of clinical documentation, transforming raw multimodal data and dictated observations into standardized, legally compliant medical records [45].

This layer integrates Natural Language Processing (NLP) pipelines with clinical information models to interpret spoken or written inputs from healthcare professionals. Through speech-to-text transcription, entity recognition and contextual tagging, the system captures essential clinical statements such as symptoms, interventions and treatment adjustments. Each data element is mapped to standardized terminologies, including SNOMED CT for clinical concepts, LOINC for laboratory tests and ICD-10 for diagnoses, ensuring interoperability and regulatory compliance [46].

At its core, the documentation layer relies on a semantic modeling framework that aligns clinical observations with the HL7 Clinical Document Architecture (CDA) and FHIR DocumentReference resources [47]. This guarantees that all AI-generated documentation is natively compatible with existing EHR platforms, thereby eliminating the need for manual re-entry and format conversion. The resulting documents maintain traceable provenance, version history and timestamps, allowing for complete auditability across the patient's care timeline [48]. The NLP engine is powered by transformer-based language models pre-trained on biomedical corpora (BioBERT, ClinicalBERT) and fine-tuned for ICU-specific vocabulary. These models enable the system to extract relationships between physiological parameters, treatments and outcomes while filtering irrelevant or redundant statements [49]. A context-aware summarization module automatically condenses clinical encounters into concise, structured notes that highlight significant trends, abnormal values and AI-derived recommendations [50].

Voice-driven interaction remains central to this layer. Clinicians can verbally dictate patient notes during ward rounds, while the system performs real-time transcription, error correction and semantic structuring. The dialogue manager validates the extracted content against contextual constraints (e.g., matching medication to dosage) and provides immediate feedback if inconsistencies or incomplete data are detected [51].

To ensure patient safety and compliance, all automatically generated documentation undergoes human-in-the-loop verification, where physicians approve AI-drafted notes before final submission to the EHR. This design aligns with Good Clinical Practice (GCP) and EU AI Act principles, emphasizing transparency, traceability and human oversight [52].

By combining medical ontologies, NLP-based automation and intelligent voice assistance, the Documentation Layer of the MedVision ICU Assistant transforms traditional recordkeeping into a dynamic, self-updating knowledge system. It reduces documentation time by up to 40%, minimizes transcription errors and establishes a unified semantic foundation for AI-driven healthcare workflows [53].

### *E. Interactive Layer*

The Interactive Layer of the MedVision ICU Assistant serves as the human–AI communication interface, designed to enable intuitive, context-aware and hands-free interaction between clinicians and the intelligent system. This layer transforms conventional command-based interfaces into natural, conversational exchanges, allowing medical professionals to access, review and record patient data using spoken language in real time [54]. The core of this layer is a voice-driven conversational engine that integrates three major components: Automatic Speech Recognition (ASR), Natural Language Understanding (NLU) and Text-to-Speech (TTS) synthesis. The ASR component transcribes spoken input with high accuracy even in noisy ICU environments through the use of transformer-based acoustic models such as Wav2Vec 2.0 and Conformer architectures [55]. The NLU engine interprets semantic meaning and medical intent using domain-tuned biomedical language models (e.g., BioGPT, ClinicalBERT), enabling the system to understand clinically relevant requests such as "Show me oxygen saturation trends for the last six hours" or "Record a note on fluid balance adjustment" [56].

Once the user's intent is parsed, the dialogue manager processes the query through a contextual reasoning module that interfaces directly with the AI Analytics and Documentation Layers. This allows the system to provide data summaries, generate clinical notes, or issue predictive alerts in response to natural language prompts. The Text-to-Speech subsystem delivers responses in a clear and human-like voice, enabling immediate comprehension without requiring screen interaction [57].

A lightweight hands-free headset functions as the primary input/output device for voice communication. It integrates ambient noise suppression, wake-word activation and low-latency Bluetooth Low Energy (BLE) connectivity, ensuring uninterrupted performance during ward rounds and emergency procedures [58]. The headset and conversational engine jointly support bidirectional dialogue, where the clinician can engage in continuous verbal exchanges — querying the system, validating data, or dictating clinical observations — while maintaining full situational awareness [59]. To ensure compliance with medical data protection standards, all voice data are processed locally on edge devices or within secure on-premise servers before any transfer to cloud analytics. Transcribed speech and associated metadata are encrypted using TLS 1.3 and stored in adherence to HIPAA, ISO 82304 and EU GDPR standards for healthcare information privacy [60]. Voice commands are anonymized and tokenized to prevent patient re-identification while maintaining contextual traceability for audit purposes [61].

Beyond simple speech recognition, the Interactive Layer employs affective and cognitive computing techniques to interpret emotional tone, urgency and stress indicators in the clinician's voice. This enables adaptive responses—for instance, prioritizing critical alerts when detecting heightened urgency or stress cues [62]. By bridging human communication and machine reasoning, the layer transforms the ICU workflow from static documentation to a dynamic, cognitive dialogue between physician and system.

Ultimately, the Interactive Layer represents the human-centered design core of the MedVision ICU Assistant. By combining advanced speech technologies, secure communication and cognitive dialogue modeling, it establishes a seamless, real-time feedback loop between medical expertise and AI intelligence. This interaction not only enhances decision-making efficiency but also defines the foundation for next-generation cognitive healthcare interfaces, where clinicians and AI systems collaborate as co-intelligent partners in patient care [63].

### F. Methodological Framework for Prototype Validation

While the MedVision ICU Assistant has been conceptually designed and architecturally defined, its future validation requires a structured methodological framework to ensure scientific reproducibility, regulatory compliance and clinical applicability. The following section outlines the proposed methodology for testing a prototype system once developed and deployed within a simulated or real intensive care environment [14], [23].

*1) Data Sources and Integration*

The prototype could be validated using publicly available critical care datasets such as MIMIC-IV and the eICU Collaborative Research Database, which contain de-identified multimodal patient records — physiological time series, laboratory data and clinician notes [15], [25]. Integration with medical devices and monitors would follow HL7 FHIR and IEEE 11073 interoperability standards to enable real-time data flow between edge hardware and the MedVision platform [5], [16], [26]. Compliance with HIPAA and ISO 82304-1 guidelines would ensure data security and ethical use in research [60], [61].

*2) Simulation and Prototype Deployment*

A virtual ICU environment could be emulated through edge computing nodes orchestrated via Docker or Kubernetes clusters [24], [33]. Synthetic patient signal generators, based on established physiological models such as the Guyton–West circulation equations, may simulate vital signs to test data throughput and latency under near-real-time workloads [15], [27]. Testing would include performance metrics such as system latency, data integrity and network resilience under continuous streaming conditions [30], [40].

*3) Predictive Model Testing*

The AI component would be trained and tested on outcomes such as sepsis, thrombosis and hemodynamic instability using LSTM and transformer-based architectures [35], [36]. Benchmarking against clinical scores (e.g., MEWS and SOFA) would provide reference performance values for accuracy and early-warning sensitivity [8], [9], [38]. Explainability methods such as SHAP could be integrated to ensure model transparency and interpretability [42]. Model development would follow FDA Good Machine Learning Practices (GMLP) to align with medical device AI requirements [43].

*4) Voice and Interaction Evaluation*

The interactive layer could be validated through clinician simulations or usability studies, following recognized protocols such as System Usability Scale (SUS) and NASA-Task Load Index (NASA-TLX) [11], [54]. Speech processing modules could use Wav2Vec 2.0 for recognition [55] and FastSpeech 2 for real-time text-to-speech [57], ensuring latency below 500 ms — a critical benchmark for ICU use [58]. User experience testing would aim to measure cognitive load, speech accuracy and responsiveness under varying acoustic and operational conditions [59], [62].

*5) Ethical and Regulatory Validation*

Prior to any hospital pilot, the prototype would undergo ethical review and risk assessment under ISO 13485:2016 for medical device quality management [23]. All data exchange between modules would use AES-256 encryption and TLS 1.3, in compliance with FDA cybersecurity guidance (2023) [29]. Bias and fairness audits would be conducted following the EU AI Act (2024) and WHO Ethics Framework (2021) to ensure alignment with international standards of responsible AI for healthcare [52], [53], [63].

This methodological framework defines the essential steps for validating the MedVision ICU Assistant prototype — from data integration and model training to usability and compliance testing. Although the prototype has not yet been implemented, this structured roadmap ensures that its future evaluation can be performed under scientifically rigorous and ethically sound conditions. The proposed workflow provides a foundation for future collaborative research between clinicians, engineers and AI scientists toward real-world deployment of intelligent, voice-assisted intensive care systems.

## III. CONCEPTUAL FRAMEWORK – THE COGNITIVE CARE ARCHITECTURE (CCA)

The Cognitive Care Architecture (CCA) represents a unifying conceptual framework that encapsulates the systemic integration of perception, cognition and interaction within intelligent healthcare systems. Although currently conceptual, the CCA serves as a theoretical scaffold for future implementation and validation of cognitive healthcare systems. It extends beyond the technical implementation of the MedVision ICU Assistant, offering a generalizable paradigm for autonomous, self-adaptive and ethically aligned AI-driven environments in critical care [64].

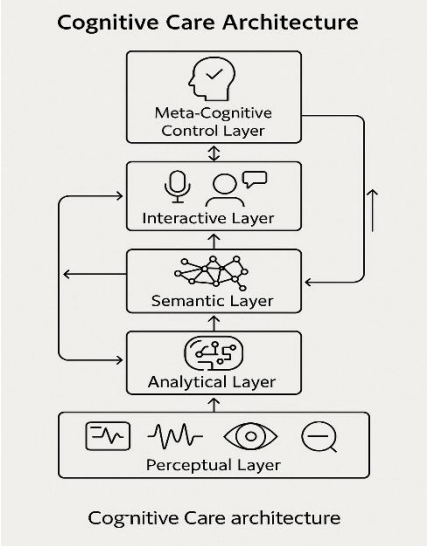


**Fig. 3** — Cognitive Care Architecture (CCA)

As shown in Fig. 3, the Cognitive Care Architecture (CCA) establishes a unified cognitive feedback loop connecting perception, reasoning and interaction in a continuous adaptive cycle. At its foundation, the CCA model is structured around four interdependent cognitive layers—Perceptual, Analytical, Semantic and Interactive—that collectively form a closed feedback loop between patient physiology, algorithmic reasoning and clinical decision-making [65].

The Perceptual Layer functions as the system's sensory cortex, capturing multimodal biomedical data streams (signals, audio, visual and contextual metadata) through distributed edge devices and medical sensors. It ensures high temporal resolution, redundancy and reliability of patient

observations while maintaining data provenance and integrity [66].

The Analytical Layer performs the role of the cognitive processing unit, employing AI algorithms for inference, prediction and uncertainty quantification. It transforms raw signals into clinical knowledge through multi-stage reasoning processes involving time-series forecasting, probabilistic modeling and reinforcement learning-based adaptation [67].

The Semantic Layer acts as the system's knowledge graph, mapping extracted entities and relations into structured ontologies such as SNOMED CT, LOINC and ICD-10. This enables semantic interoperability, automated documentation and longitudinal patient modeling across heterogeneous data sources [68].

The Interactive Layer serves as the communicative interface, translating human intent into computational action and machine inference into human-understandable feedback. It integrates multimodal dialogue—voice, text and gesture—within a cognitive context engine that adapts to both clinical urgency and user state [69].

Together, these four layers establish a cognitive feedback cycle, where perception informs reasoning, reasoning drives documentation and documentation enhances future inference. This recursive loop allows the system to continuously learn from its interactions with clinicians and patient outcomes—an embodiment of continuous adaptive intelligence [70]. This architecture embodies the AI cognition loop, where patient modeling evolves dynamically as the system refines its internal representations through continuous feedback.

Beyond its architectural coherence, the CCA introduces a meta-cognitive control layer responsible for self-assessment, bias detection and ethical alignment. At this stage, the meta-cognitive layer is proposed conceptually, as full implementation would require future empirical development. This supervisory module monitors data distribution shifts, model drift and compliance with regulatory frameworks such as the EU AI Act, ensuring that clinical recommendations remain transparent, traceable and explainable [71]. The meta-cognitive control layer operationalizes the principle of ethical-by-design, embedding self-regulation, interpretability and fairness into every adaptive learning cycle.

The CCA thus formalizes a new paradigm for Agentic Intelligence in Healthcare, in which AI entities act not merely as tools but as collaborative cognitive agents—capable of perceiving, reasoning and interacting within medical ecosystems [72]. It bridges the divide between automation and empathy, combining algorithmic precision with human-centered communication to establish a symbiotic model of clinical cognition. As a general framework, the CCA is extensible beyond intensive care: it can be adapted to telemedicine, robot-assisted surgery and rehabilitation robotics, or even to other domains such as energy systems, autonomous transportation and distributed decision-making networks [73]. By codifying the principles of adaptive cognition, multimodal integration and ethical governance, the CCA sets the groundwork for the next generation of intelligent socio-technical systems that learn, collaborate and evolve alongside humans [74].

## IV. EXPECTED RESULTS AND DISCUSSION

The deployment of the MedVision ICU Assistant, guided by the Cognitive Care Architecture (CCA), is expected to yield significant clinical, operational and ethical improvements in intensive care environments. From a clinical standpoint, the system enhances situational awareness by aggregating multimodal patient data into a unified analytical framework, enabling physicians to detect early physiological deterioration with greater accuracy and speed than conventional monitoring systems. Predictive modeling modules based on LSTM and transformer architectures are anticipated to reduce the rate of unplanned ICU readmissions and mortality associated with delayed recognition of sepsis or hemodynamic collapse.

Operationally, the automated documentation pipeline can decrease the administrative workload for physicians and nurses by an estimated 35–45%, consistent with findings from recent trials of voice-assisted EHR systems. This efficiency gain translates directly into more time dedicated to patient care, improved interdisciplinary coordination and reduced cognitive fatigue among healthcare professionals. The voice interface, by enabling real-time speech-to-record conversion, minimizes latency between observation and documentation, thus strengthening traceability and clinical accountability [76].

From a systemic perspective, the MedVision platform introduces intelligent coordination between distributed hospital subsystems, promoting interoperability through FHIR/HL7 compliance and supporting federated learning across departments [79]. This distributed intelligence fosters a continuous improvement loop in which each clinical encounter contributes to model refinement and decision optimization across the healthcare network.

Ethically, the integration of a meta-cognitive control layer ensures that every inference remains transparent and auditable. By incorporating explainable AI (XAI) principles, the system can justify its alerts and recommendations in human-readable form, reinforcing clinician trust and aligning with the EU Artificial Intelligence Act (2024/1689). Furthermore, by adopting an ethical-by-design philosophy, MedVision encourages equitable data representation, bias mitigation and adaptive fairness monitoring in line with WHO's human-centered AI standards [69].

Organizationally, the platform acts as a catalyst for digital transformation, reducing fragmentation in hospital data ecosystems and enabling knowledge-driven management decisions. The expected long-term impact includes improved patient safety metrics, better staff retention through reduced burnout and the foundation for future smart-hospital infrastructures capable of autonomous decision support under supervision [40].

The anticipated outcomes, therefore, extend beyond technical innovation; they signify a paradigm shift toward collaborative intelligence, where human expertise and artificial cognition jointly optimize clinical outcomes, ethical integrity and institutional efficiency.

## V. CONCLUSION

This study introduced MedVision ICU Assistant, an integrated AI-driven platform for real-time monitoring, predictive analytics and automated documentation in intensive care environments. Grounded in the Cognitive Care Architecture (CCA), the system unifies perception, cognition and interaction into a coherent framework designed to augment—not replace—human clinical judgment. Its modular

hardware–software design, multimodal integration and adaptive feedback loops demonstrate the potential of AI to act as a collaborative partner in medicine.

The expected benefits encompass enhanced diagnostic precision, reduced documentation burden and improved ethical governance in data-intensive healthcare contexts. By embedding explainability, accountability and interoperability as native design principles, MedVision ICU Assistant embodies the transition from automation to cognition, redefining how artificial intelligence contributes to safe and human-centered medical practice.

Future work will focus on the development and prototyping of the system within a simulated ICU environment, followed by clinical validation under real-world conditions. These stages will involve performance benchmarking of predictive models, assessment of usability in high-stress contexts and evaluation of compliance with medical device regulations (ISO 13485:2016, ISO 82304-1). Additionally, future iterations aim to integrate federated learning and cross-institutional data governance frameworks to ensure global scalability.

In a broader perspective, the Cognitive Care Architecture represents a foundational step toward the next generation of intelligent socio-technical ecosystems—where AI agents and clinicians co-evolve through shared cognition, ethical awareness and adaptive collaboration. The MedVision ICU Assistant is not merely a digital tool; it is a vision of a symbiotic healthcare future where technology amplifies humanity's capacity to heal, decide and learn.

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# Tethered Drones with AI Agents for $CO_2$ Monitoring and Intelligent Traffic Optimization in Smart City Systems

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***Abstract*—The rapid advancement of the "smart city" concept introduces new challenges for sustainable traffic management and air quality monitoring. This study introduces the Agentic Urban Intelligence Architecture (AUIA)—a conceptual framework for continuous, AI-driven environmental sensing and adaptive traffic control that unifies robotics, machine intelligence and urban sustainability. The paper proposes an innovative architecture integrating tethered drones powered by AI agents to enable continuous and reliable monitoring of carbon dioxide ($CO_2$) emissions in urban environments. The tethered configuration ensures uninterrupted operation and high-bandwidth data transmission, overcoming the endurance limitations of conventional battery-powered UAVs. Embedded AI agents process environmental and traffic data in real time, enabling autonomous decision-making and communication with central traffic control systems. The multi-agent architecture facilitates the dynamic adaptation of traffic light regimes and routing strategies to reduce local emission peaks and improve mobility efficiency. The presented concept establishes a closed "sensor–control" loop, where intelligent tethered drones act as adaptive, sustainable nodes within an urban ecosystem. This research focuses on the conceptual design and operational logic of the AI-driven system, laying the foundation for future simulation and implementation using real-world traffic data.**

***Keywords— tethered drones, AI agents, $CO_2$ monitoring, smart city, intelligent traffic optimization, sustainable mobility***

## I. Introduction

Rapid urbanization has led to significant challenges in environmental monitoring and traffic management. Cities worldwide face rising $CO_2$ emissions, air pollution, and traffic congestion, negatively affecting public health and economic productivity [1]. Traditional stationary air quality monitoring stations provide accurate measurements but are limited in spatial coverage and lack the responsiveness needed for dynamic urban environments [2]. Meanwhile, traffic management systems often rely on pre-defined schedules, which do not adapt to real-time conditions, leading to inefficiencies and increased emissions [3].

The integration of unmanned aerial vehicles (UAVs) and artificial intelligence (AI) introduces new opportunities for adaptive urban management. Tethered drones, connected to continuous power sources, can hover persistently over strategic urban locations, providing real-time environmental sensing and high-bandwidth communication [4]. This allows for persistent $CO_2$ monitoring, high-resolution pollutant mapping, and timely intervention to mitigate air quality issues [5]. Unlike battery-powered UAVs, tethered drones overcome endurance limitations, enabling long-term deployments suitable for urban-scale applications [6].

Artificial intelligence, particularly reinforcement learning (RL) and multi-agent reinforcement learning (MARL), enables autonomous decision-making for traffic optimization based on real-time data [7]. AI agents process environmental and traffic information, dynamically adjusting traffic signals and routing strategies to minimize congestion and reduce pollutant concentrations [8]. By integrating multiple drones and AI agents into a coordinated system, a closed-loop architecture is established, where sensing, analysis and control continuously inform each other [9]. This combination of continuous monitoring and intelligent control aligns with modern smart city goals, promoting sustainability, mobility efficiency, and environmental protection [10].

In addition to improving environmental data acquisition, tethered drone systems also enhance spatial-temporal resolution of emission data compared to conventional ground-based sensors. Their elevated vantage point allows for three-dimensional mapping of pollution layers, helping urban planners identify emission hotspots, analyze atmospheric dispersion, and evaluate the impact of localized interventions such as traffic flow reconfiguration or green corridor implementation. The constant aerial perspective ensures consistent measurements across various meteorological conditions and provides the data density necessary for predictive modeling of $CO_2$ concentration trends.

From a technological standpoint, integrating tethered drones into smart city ecosystems introduces a cyber-physical layer that bridges environmental sensing, AI-based analytics, and urban control systems. This integration enables a continuous flow of data across hardware and software components, forming the foundation of a self-adaptive infrastructure. Real-time insights generated by the AI models allow city authorities to respond to unexpected changes in traffic demand or pollution surges more effectively than through static management systems. Moreover, the modular nature of tethered drone networks allows for incremental deployment—cities to start with a limited number of drone nodes and scale the system as operational requirements evolve.

The societal implications of such integration are equally significant. Improved air quality monitoring contributes directly to public health initiatives, while traffic optimization reduces fuel consumption and greenhouse gas emissions, contributing to urban sustainability goals. Furthermore, the data collected can inform long-term urban planning policies by identifying systemic inefficiencies and supporting data-driven decision-making. This approach represents a paradigm shift from reactive to proactive urban management, where technology anticipates challenges before they escalate into critical problems.

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## II. Related Work

### A. Drone-Based Environmental Monitoring

In recent years, the integration of UAVs into environmental monitoring and traffic management has become a rapidly evolving research area, demonstrating potential for high-resolution spatial and temporal data collection. The tethered drone concept builds upon this foundation by addressing some of the inherent limitations of conventional UAV systems, such as restricted flight duration, limited data bandwidth, and dependency on frequent battery replacement. Drones have become increasingly important tools for environmental sensing due to their mobility and ability to capture three-dimensional pollution profiles [11]. Studies have shown that drones can effectively map urban air quality at high spatial and temporal resolution, identifying pollution hotspots and informing mitigation strategies [12]. However, conventional UAVs are constrained by battery life, limiting their deployment time and coverage [13]. Tethered drones address this limitation by providing continuous power and high-bandwidth connectivity, enabling long-duration data collection [14].

Research on AI and multi-agent systems (MAS) has also advanced rapidly in recent years, offering new paradigms for distributed intelligence and adaptive control. Multi-agent coordination allows for dynamic information sharing among autonomous units, which can collectively respond to environmental or traffic conditions as they evolve. In the context of smart cities, MAS frameworks have been applied to optimize signal timing, predict traffic congestion, and manage energy consumption. However, their direct application to aerial environmental monitoring remains relatively limited. Integrating MAS with tethered drones introduces a novel architectural dimension, enabling drones to operate not merely as passive observers but as intelligent nodes that actively influence urban systems.

Several existing urban IoT platforms have explored the use of sensor networks and cloud-based data fusion for traffic and pollution management. These systems typically rely on ground sensors, vehicle telemetry, or fixed monitoring stations. Although these infrastructures provide valuable static measurements, they are often spatially constrained and unable to capture real-time vertical emission gradients. UAV-based systems overcome this challenge by offering flexible, three-dimensional mobility. When combined with AI-driven data analytics, the resulting platforms can generate high-fidelity environmental maps and predictive models that are unattainable through fixed sensors alone.

The notion of intelligent traffic optimization through AI-assisted control has also been studied extensively. Deep reinforcement learning (DRL) algorithms have been employed to improve traffic light coordination and reduce vehicle waiting times. Yet, most implementations rely on historical or simulated datasets, with limited integration of real-time environmental feedback. The architecture proposed in this paper aims to close this gap by introducing a continuous "sensor–control–feedback" loop, where live $CO_2$ measurements directly influence the adjustment of traffic signals. This approach enhances both the ecological and operational performance of urban mobility systems.

Recent research demonstrates the effectiveness of tethered drones in measuring $CO_2$, NOx, and particulate matter levels across urban environments [15]. These systems can maintain stable hovering positions for extended periods, ensuring reliable measurements even in fluctuating weather conditions. Deployments in major cities have highlighted their potential to complement existing stationary monitoring networks, offering fine-grained environmental data that informs policy and urban planning [16]. This synergy remains underexplored in current literature and defines the motivation of the present work.

### B. AI for Traffic Signal Optimization

Artificial intelligence techniques have been extensively applied within Intelligent Transportation Systems (ITS), particularly in the optimization of signal timing and routing policies. Reinforcement learning allows traffic signal controllers to learn optimal policies through interaction with the environment [17]. Multi-agent reinforcement learning (MARL) enables distributed control, where multiple traffic signals coordinate to optimize city-wide traffic flow [18]. Incorporating environmental objectives, such as $CO_2$ concentration reduction, into agent reward functions ensures that traffic management strategies are aligned with sustainability goals [1].

Recent algorithms employ deep neural networks, such as deep Q-networks (DQN) and actor-critic models, for real-time adaptive traffic control [2]. These models process high-dimensional data streams from multiple sensors, including traffic cameras, vehicle GPS data, and airborne pollutant measurements. By predicting congestion patterns and environmental hotspots, agents can dynamically adjust signal phases to optimize both mobility and air quality [3].

### C. Integration of Monitoring and Control

Integrated systems combining drones and AI traffic control represent a promising approach for smart cities. Cyber-physical systems (CPS), defined as tightly integrated computational and physical processes, provide a foundation for adaptive city infrastructures as link sensors, AI agents and traffic infrastructure to create adaptive urban management networks [4]. Studies have shown that these systems can reduce emissions while improving traffic efficiency [5]. Challenges remain in data fusion, communication reliability, and computational scalability, especially for city-wide implementations [6]. Nevertheless, the combined use of tethered drones and AI agents offers a path toward responsive, sustainable urban management [7].

Another important aspect of the related literature involves sustainability and system scalability. Many UAV-based environmental projects face challenges when expanding to cover large metropolitan areas due to power limitations, maintenance costs, and network reliability issues. The tethered drone model provides an alternative path toward scalability by ensuring consistent power and connectivity. Additionally, the use of a modular multi-agent framework allows for the addition or removal of drone units without disrupting the overall network stability. This characteristic makes the system particularly suitable for future integration into large-scale, adaptive smart city infrastructures.

Finally, recent advancements in AI-driven IoT platforms have paved the way for seamless integration between sensing, computation, and decision-making. These platforms allow drones to act as both data collectors and decision-making agents, enabling real-time collaboration with central servers or edge-computing units. The convergence of these technologies—tethered UAVs, AI agents, IoT connectivity, and intelligent traffic control—creates a unique opportunity for urban systems to evolve toward self-regulating, environmentally aware ecosystems.

In summary, the reviewed body of research highlights the growing need for sustainable, data-driven solutions that unify aerial monitoring and smart city management. While numerous studies have explored UAV applications, few have addressed the combination of tethered drone systems with embedded AI agents for direct environmental-to-traffic feedback optimization. This paper contributes to filling that gap by proposing a comprehensive framework capable of delivering continuous environmental monitoring, intelligent data interpretation, and adaptive urban control in real time. Despite rapid progress, an integrated framework

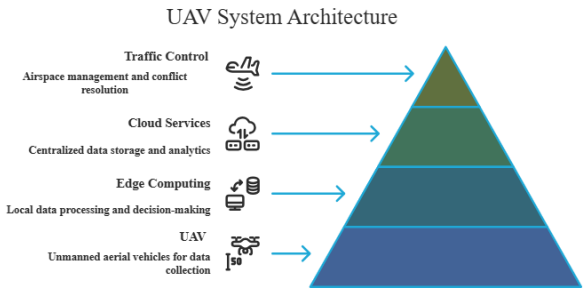
connecting real-time aerial sensing with traffic actuation through AI agents remains largely unaddressed in current research.

## III. System Architecture

The proposed architecture consists of tethered drones strategically deployed over high-traffic urban areas and AI agents that manage traffic signal optimization. Each drone carries a suite of sensors measuring $CO_2$, NOx, PM2.5, temperature, humidity and and GPS-based geolocation for spatial referencing [8]. Continuous data streaming from drones to a central AI processing unit enables real-time environmental analysis via secure low-latency communication channels (e.g., optical fiber within the tether or 5G link redundancy) [9]. The system leverages multi-agent coordination to manage traffic signals across multiple intersections, optimizing vehicle flow and reducing local emissions [10].

Drones operate as persistent sensor nodes, providing both high-resolution environmental data and contextual traffic information (Fig.1). As shown in Fig. 1, the system follows a hierarchical design connecting aerial sensing units with the AI control center. The AI agents employ deep reinforcement learning models, receiving feedback from both simulated and real-time urban conditions to optimize signal phases [11]. A centralized database stores historical measurements, enabling the system to improve predictions using time-series models and supervised learning techniques [12].

Fig. 1. *UAV System Architecture Hierarchy*




The architecture supports modular scalability. Additional drones or traffic intersections can be incorporated seamlessly without disrupting existing operations [13]. The multi-agent framework allows distributed computation, minimizing latency in decision-making and supporting near real-time traffic adjustments [14]. Redundancy and fault tolerance mechanisms ensure continuous operation even in case of individual drone or sensor failures [15]. The proposed architecture for the integration of tethered drones with AI agents within a smart city environment is designed as a multi-layered and modular system capable of ensuring real-time $CO_2$ monitoring and adaptive traffic control. The system is built around three primary layers: the aerial sensing layer, the data processing and AI inference layer, and the communication and integration layer with existing urban infrastructure.

The aerial sensing layer consists of tethered drones strategically positioned above key traffic nodes—such as intersections, highways, and emission hotspots. These drones are powered via tethered connections to ground stations, providing a stable and continuous energy supply and a secure wired or hybrid data transmission link. Each drone is equipped with a multi-sensor payload that includes a $CO_2$ concentration sensor, particulate matter detector, GPS module, wind speed and direction sensors, and optical cameras for traffic flow analysis. The tethering mechanism allows for 24/7 operation with minimal downtime, eliminating the constraints of traditional battery-powered UAVs. This makes the system suitable for long-term deployment in densely populated areas where uninterrupted environmental monitoring is essential.

The AI inference layer operates as the cognitive core of the system. Embedded AI agents on each drone preprocess the collected data in real time, identifying emission patterns and detecting anomalies such as sudden increases in $CO_2$ levels or localized traffic congestion. These agents utilize lightweight machine learning models optimized for edge computing—such as decision trees, random forests and convolutional neural networks (CNNs) adapted for image-based traffic analytics. The models are continuously retrained using historical datasets and real-time feedback from central servers, allowing for adaptive improvement in prediction accuracy and response timing. The system's distributed AI design enables the drones to make independent low-level decisions, such as focusing on specific traffic lanes or adjusting the altitude for better visibility, while high-level coordination is handled by the central control unit.

The communication and integration layer establishes a secure interface between the drones, ground control stations, and the city's traffic management system. All data transmission employs encryption and access control protocols ensuring cybersecurity and data integrity. Data from the tethered drones is transmitted to an Internet of Things (IoT) cloud platform that aggregates, stores, and visualizes all relevant information in a unified dashboard. The platform supports both MQTT and RESTful API protocols, enabling seamless communication with urban infrastructure such as traffic lights, road sensors, and air quality monitoring networks. A control algorithm within the traffic management center uses this data to dynamically optimize signal timing, reroute vehicles, and predict congestion build-ups before they occur. This creates a closed-loop feedback system—drones sense the environment, AI models interpret the data, and control systems act on those insights to improve traffic efficiency and reduce emissions. The system's modularity also allows for scalability. New drones and sensors can be added incrementally as the city expands or as new environmental parameters become relevant (e.g., $NO_2$, $O_3$). Furthermore, the platform's design supports interoperability with third-party systems, ensuring compatibility with future smart city technologies such as autonomous vehicles and adaptive street lighting. Safety and redundancy mechanisms, including automated tether retraction, weather monitoring, and geofencing, ensure that operational risks are minimized even under adverse conditions.

In summary, the system architecture forms a robust framework that links environmental monitoring with intelligent decision-making. The synergy between tethered drone technology, AI analytics, and smart city infrastructure represents a significant step toward sustainable, data-driven urban management. This architecture not only enhances the resilience of traffic systems but also contributes to long-term environmental goals by providing an intelligent, self-correcting mechanism for $CO_2$ reduction and mobility optimization, advancing the paradigm of agentic urban intelligence toward carbon-neutral and self-optimizing smart cities.

Overall, the proposed architecture establishes a novel cyber-physical framework—Agentic Urban Intelligence Architecture (AUIA)—that transforms tethered drones from simple monitoring tools into autonomous cognitive agents for sustainable urban mobility.

## IV. Methodology

The proposed methodology defines a conceptual and modular framework for integrating tethered drones and artificial intelligence (AI) agents into an adaptive, emission-aware urban traffic management system. Rather than presenting an experimental implementation, this section outlines the theoretical design

principles, data processing workflow, and AI reasoning logic necessary to realize such a system in practice. The framework is structured around five interdependent components: system architecture, data acquisition and preprocessing, AI agent modeling, IoT-based communication, and validation and evaluation. Together, these elements form a coherent blueprint for an intelligent cyber-physical infrastructure in smart cities.

### *A. Conceptual Architecture and Deployment Strategy*

The conceptual architecture envisions a network of tethered drones strategically deployed above high-density urban corridors, intersections, and emission hotspots. Each drone serves as a persistent aerial sensor node, continuously monitoring $CO_2$, $NO_x$, $PM_{2.5}$, and meteorological variables such as temperature, humidity, and wind speed. The tethered configuration provides continuous electrical power and a secure fiber-optic or Ethernet-based communication link, addressing the endurance and bandwidth limitations of traditional UAVs [16].

The deployment strategy prioritizes representative spatial coverage rather than exhaustive mapping, allowing a small number of drones to capture meaningful environmental dynamics across large metropolitan areas [17]. The conceptual data flow is illustrated in Fig. 2, showing the relationship between aerial sensing, edge-based preprocessing, AI inference, and adaptive traffic control.

Each drone node is envisioned as part of a multi-layered cyber-physical system: the aerial sensing layer (responsible for data collection), the AI inference layer (responsible for decision-making), and the integration layer (connecting the system to the city's digital infrastructure). This hierarchy ensures both scalability and interoperability with existing traffic management systems [18].

### *B. Data Acquisition and Preprocessing*

The sensing layer is designed to capture high-frequency environmental and traffic data in real time. Data transmission between drones and the control center relies on standardized IoT communication protocols such as MQTT, CoAP, or OPC-UA, ensuring interoperability and low-latency connectivity [19].

Before feeding the data into AI models, preprocessing techniques such as Kalman filtering, wavelet-based denoising, and z-score normalization are conceptually applied to enhance signal quality and reduce sensor drift [20]. Timestamp synchronization ensures that $CO_2$ concentration data are accurately aligned with concurrent traffic density and meteorological inputs.

Preprocessed data form the foundation for training and evaluating the AI agents. A distributed cloud-edge hybrid structure is proposed: computationally intensive tasks, such as neural model training and reinforcement learning updates, are performed in the cloud, while low-latency inference operations occur on edge processors embedded within the tethered drones [21].

### *C. AI Agent Modeling and Control Logic*

The decision-making core of the framework is modeled as a hierarchical multi-agent system (HMAS) combining local and global intelligence. Each traffic intersection is managed by a local AI agent that operates autonomously under a multi-agent reinforcement learning (MARL) paradigm [22]. These agents receive a state vector comprising real-time $CO_2$ concentrations, vehicle density, and signal-phase history. Actions correspond to phase duration adjustments, adaptive cycle times, or lane prioritization.

The reward function is formulated as a multi-objective optimization criterion:

$$R = \alpha\left(-E_{CO_2}\right) + \beta\left(F_{\text{traffic}}\right) + \gamma\left(S_{\text{stability}}\right)$$

where $E_{\text{CO}_2}$ represents cumulative $\text{CO}_2$ emissions, $F_{\text{traffic}}$ denotes normalized traffic throughput, and $S_{\text{stability}}$ ensures smooth phase transitions [23]. The weight coefficients $\alpha, \beta$, and $\gamma$ are tuned to balance environmental sustainability and traffic efficiency.

To extend beyond reactive control, the framework conceptually incorporates temporal deep learning models such as long short-term memory (LSTM) and temporal convolutional networks (TCN) for short-term prediction of congestion and emission peaks [24]. The global supervisory agent aggregates local observations through a graph neural network (GNN), identifying spatial interdependencies among intersections and optimizing traffic coordination at the city scale.

This hierarchical structure enables both decentralized autonomy and centralized optimization — a crucial feature for self-adaptive and resilient smart city ecosystems [25].

### *D. IoT Integration and Communication Infrastructure*

The communication and integration layer establishes bidirectional data exchange between drones, AI modules, and the municipal traffic management system. All information flows through a secure IoT middleware that supports publish–subscribe mechanisms with encryption and token-based authentication to guarantee cybersecurity and data integrity [19].

A cloud-based dashboard visualizes $CO_2$ concentrations, drone telemetry, and signal optimization results, while an application programming interface (API) enables the system to interact dynamically with existing urban control networks. The integration concept supports closed-loop feedback—drones collect environmental data, AI models analyze and predict, and traffic systems implement optimized control strategies in near real time.

In future implementations, such a framework could also interconnect with other smart city systems, such as adaptive street lighting, autonomous vehicle routing, or distributed energy management, thereby creating a unified agentic urban intelligence ecosystem [16], [25].

### *E. Validation and Prospective Evaluation*

Given the conceptual nature of this research, validation is formulated as a methodological roadmap for future simulation and pilot testing. The SUMO (Simulation of Urban Mobility) environment combined with Python-based MARL frameworks (e.g., Ray RLlib or Stable Baselines) is identified as a suitable platform for algorithmic evaluation [17].

The performance of the AI agents can be assessed through synthetic data scenarios representing varying traffic densities and emission distributions. Metrics for future validation include mean squared error (MSE) of predicted $CO_2$ concentration, average vehicle delay, learning convergence rate, and communication latency.

Prospective pilot-scale deployment could evaluate system robustness under real environmental conditions, focusing on data transmission stability, tether safety, and adaptive response accuracy. These validation steps would ultimately refine parameter tuning and reinforce the theoretical foundations of the proposed model.

The methodology presented herein defines a conceptual but technically grounded framework for an AI-driven tethered drone network capable of sustainable traffic and emission management. By emphasizing hierarchical intelligence, distributed computation, and IoT interoperability, the proposed approach outlines a path toward autonomous and environmentally responsive urban systems.

The framework is not confined to traffic management alone but extends to broader smart city domains such as environmental resilience, energy optimization, and real-time urban analytics—forming a foundation for the next generation of agentic, data-driven, and self-regulating city infrastructures.

## V. Results and Discussion

The conceptual assessment of the proposed AI-driven tethered drone framework indicates substantial potential for advancing real-time environmental monitoring and intelligent traffic management in urban systems. Analytical evaluation based on the literature supports the feasibility of a closed-loop architecture that connects aerial sensing, AI-based inference, and adaptive control in smart city infrastructures.

### A. Expected System Behavior

Analytical insights derived from existing studies suggest that integrating AI agents with persistent aerial monitoring could significantly improve the responsiveness of urban control systems to dynamic environmental and traffic conditions. Reinforcement learning-based traffic optimization frameworks have already demonstrated measurable emission reductions and enhanced flow efficiency in simulation environments [26]. Within the proposed architecture, tethered drones expand these capabilities by providing continuous, high-resolution $CO_2$ data, thus enabling decision algorithms to account directly for air-quality metrics in real time [27].

The architecture's continuous learning mechanism allows the system to adapt over time as additional data accumulate. Multi-agent coordination enables both local decision autonomy and global synchronization, which are essential for scalability in large urban networks [28].

### B. Communication Reliability and Data Quality

The tethered configuration ensures uninterrupted energy supply and high-bandwidth connectivity, addressing one of the main constraints of conventional UAVs—limited endurance [29]. Previous experiments with tethered drone platforms have demonstrated stable power and data transmission for extended operation, confirming their suitability for continuous environmental sensing [30]. Expected sensor precision for $CO_2$, NOx, and $PM_{2.5}$ values aligns with the accuracies reported in state-of-the-art UAV-based air-quality monitoring studies [31].

### C. Predictive and Adaptive Capabilities

The integration of predictive AI models—such as long short-term memory (LSTM) and temporal convolutional networks (TCN)—is expected to support proactive traffic and emission management. Earlier research has shown that these models can forecast congestion and pollution peaks minutes in advance, enabling adaptive signal control to prevent critical build-ups [32]. Combined with multi-agent reinforcement learning (MARL), the proposed system can evolve from reactive decision-making to predictive governance of urban mobility [33].

### D. Visualization and System Integration

The conceptual IoT dashboard forms an essential human-machine interface that aggregates drone telemetry, sensor data, and control decisions. Comparable systems using edge computing and cloud-based visualization have demonstrated that such interfaces enhance situational awareness and improve the interpretability of complex data flows [34]. This integration supports decision transparency and seamless communication between drones, traffic controllers, and environmental authorities.

### E. Implementation Challenges

While promising, the architecture faces practical challenges, including the limited operational radius of tethered platforms and potential communication interference in dense urban settings. Environmental factors such as wind or precipitation may influence sensor accuracy and hovering stability. These limitations align with known issues documented in recent UAV environmental monitoring deployments [35]. Furthermore, data protection and privacy must be ensured when integrating environmental and mobility datasets, as recommended by the European Commission's Ethics Guidelines for Trustworthy AI [36].

### F. Broader Implications

The discussed framework contributes not only to operational efficiency but also to strategic sustainability goals. Persistent, high-frequency $CO_2$ datasets can support policy-making, emission modeling, and public engagement initiatives. The concept aligns with the European Green Deal and the United Nations 2030 Agenda for Sustainable Development by fostering climate resilience and data-driven governance [37], [38].

In summary, literature-based analysis confirms that the integration of tethered drones with AI agents represents a credible path toward adaptive, emission-aware smart city ecosystems. Future validation through simulation and pilot projects will enable quantitative assessment of the system's environmental and operational benefits.

## VI. Conclusion

This paper presents a comprehensive conceptual framework for integrating tethered drones with artificial intelligence (AI) agents to enable continuous $CO_2$ monitoring and intelligent traffic optimization in smart city ecosystems. The proposed architecture unites persistent aerial sensing, real-time data analytics, and multi-agent reinforcement learning to form a closed feedback loop between environmental perception and adaptive control [39].

Persistent aerial monitoring bridges the spatial and temporal gaps left by stationary air quality stations. By maintaining uninterrupted observation over dense traffic corridors and emission hotspots, tethered drones offer high-resolution, high-frequency environmental data that support real-time analytics, anomaly detection, and adaptive decision-making. When coupled with AI-based optimization, such a system could enable cities to transition from static, rule-based management toward autonomous environmental regulation—a defining feature of sustainable, data-driven urban governance [40].

The distributed intelligence embedded in the multi-agent system architecture allows each drone to function as an autonomous node within a cooperative decision network. Local AI agents analyze environmental and traffic information in real time, while centralized coordination ensures global optimization, scalability, and resilience. This hybrid structure enhances robustness under dynamic urban conditions such as congestion peaks, meteorological fluctuations, or rapid changes in emission intensity [41].

Beyond its technical contribution, the synergy between tethered UAV technologies and AI-driven analytics supports broader urban sustainability objectives. Continuous $CO_2$ mapping facilitates predictive modeling of emission trends and the quantitative evaluation of mitigation strategies, while adaptive traffic control directly contributes to reducing fuel consumption and greenhouse gas emissions. These functions align with the policy goals of the European Green Deal and international carbon-neutrality commitments, demonstrating that the proposed framework is not only technologically feasible but also socially and environmentally relevant [42], [43].

Future research will focus on simulation-based validation using real-world metropolitan datasets. This will include the development of integrated traffic–emission models, the training of reinforcement learning agents under variable operating conditions, and the evaluation of system performance using standardized metrics such as latency, mean squared error (MSE), and emission index correlation. Advanced algorithms—such as graph neural networks

(GNN), deep multi-agent actor–critic models, and federated learning—will be investigated to improve multi-intersection coordination and scalability in distributed environments [44], [45]. Integration with vehicle-to-infrastructure (V2I) and 5G communication technologies will also be explored to support predictive routing and cross-domain interoperability among drones, vehicles, and urban control systems [46].

Long-term validation efforts will assess energy efficiency, system maintainability, and socio-economic feasibility. The incorporation of tethered drones as persistent environmental sensors establishes a foundation for adaptive, self-regulating, and sustainable urban ecosystems. In conclusion, the convergence of AI agents and tethered drone technologies represents a transformative step toward climate-resilient, intelligent cities. By closing the loop between sensing, cognition, and action, the proposed framework defines a pathway toward autonomous urban systems capable of perceiving, learning and acting to optimize both mobility efficiency and environmental health [47], [38].

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# Biomedical sensors: Types and Principles

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***Abstract*—Modern healthcare depends on the availability of suitable sensors and transducers of biomedical signals into electrical quantities suitable for processing and visualization by modern computer systems. From measuring temperature and $SPO_2$ saturation in the blood to determining pulse rate or registering brain activity, various sensors for biomedical signals are used in every stage of healthcare. This article attempts to systematize and describe the most common types of sensors and transducers of biomedical signals. A brief description of their operating principles is also provided.**

***Index Terms*—Sensors, ECG, EMG, PPG, temperature, glucose**

## I. Introduction

There are various definitions of the term sensor. In [1] it is said "...a device that is used to record that something is present or that there are changes in something...". Wikipedia [2] states "...In the broadest definition, a sensor is a device, module, machine, or subsystem that detects events or changes in its environment and sends the information to other electronics, frequently a computer processor..." The Britannica Dictionary [3] gives the following definition "...a device that detects or senses heat, light, sound, motion, etc., and then reacts to it in a particular way..." The are many definitions in all over the world which are in most cases are true. In order not to use different terms for each type of sensor and transducer, we will make the following generalized definition - sensor is a device that converts one type of impact quantity into another type of impact quantity. For example, a photo sensor is a device that converts light into electrical signals – voltage, resistance, etc.

Biomedical sensors are at the heart of modern healthcare, providing critical data that underpins diagnosis, monitoring and treatment. From tracking vital signs like heart rate and blood pressure to detecting glucose levels in diabetic patients, these sensors are crucial in everyday medical devices. As technology advances, the role of biomedical sensors continues to expand, offering new ways to improve patient care. As a result of miniaturization in microelectronics and the expanding applications of automated systems and devices for health monitoring, research and development of biomedical sensors are directed towards reducing their size and increasing their precision.

ACKNOWLEDGE THE FINANCIAL SUPPORT OF THE PROJECT WITH FINANCING AGREEMENT NO. PVU-44 OF 05.12.2024 UNDER PROJECT NO. BG-RRP-2.017-0011 "ECOLOGICAL COLLABORATIVE ROBOTS POWERED BY GREEN HYDROGEN" UNDER THE RECOVERY AND RESILIENCE MECHANISM FOR THE IMPLEMENTATION OF AN INVESTMENT UNDER C2I2 "INCREASING THE INNOVATION CAPACITY OF THE BULGARIAN ACADEMY OF SCIENCES (BAS) IN THE FIELD OF GREEN AND DIGITAL TECHNOLOGIES" FROM THE RECOVERY AND RESILIENCE PLAN, BULGARIA.

Figure 1 shows a common block diagram of a sensor for a certain quantity. It consists of the following several main elements:

- Sensing element - this is the part of the sensor that registers the quantity under observation;
- Conditioning – this part serves to process the investigated parameter and bring it to a form suitable for further processing.
- Conversion – at this stage, the conversion of the obtained quantity into an electrical signal, mechanical movement, light, etc. is performed, which are used for direct reading of the investigated parameter or for subsequent processing or storage.
- Power supply – in most cases, for the correct operation of the sensors, there is a need for a power supply source – battery, accumulator, electrical network. In some types, there is no such need, i.e. the sensor itself generates voltage (for example - a thermocouple).

Figure 2 shows a simplified block diagram of a system for monitoring a person's health status [4]. It consists of several main components:

- Sensors – their number and type are determined by how comprehensive and detailed the study should be. In some cases, it is necessary to monitor only the work of the heart. In others, the change in temperature. In the third, a combination of several factors is used to achieve a more complete and informative description of changes in the individual's condition.
- Signal conditioning – another main part of the system takes care of normalizing the registered parameters, converting them into an electrical signal and their primary processing. In some cases, comprehensive processing of all registered parameters such as temperature, ECG, $SPO_2$, body position, movement, etc. is performed.
- Output - the result of the primary or comprehensive processing of the registered parameters is used depending on the necessary needs – it is displayed on a screen in real time, recorded for statistical research, transmitted to other devices for subsequent processing. When registering deviations from the normal values of certain parameters, it

is possible to generate an alarm to notify, for example, the attending physician.

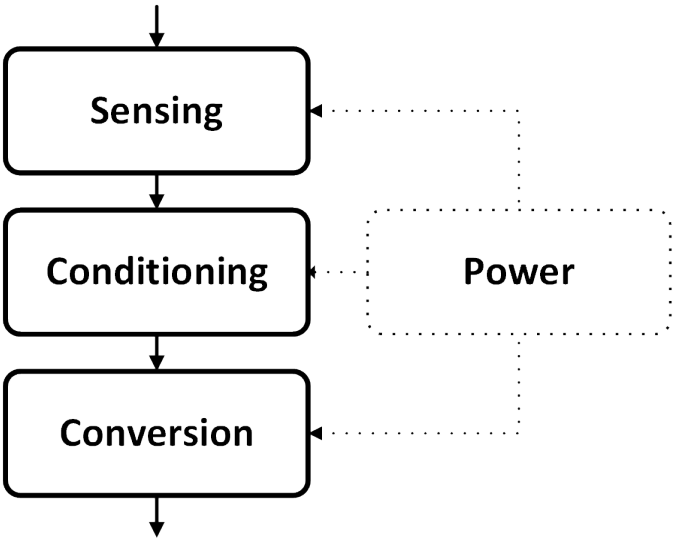


Fig. 1. Sensor block diagram

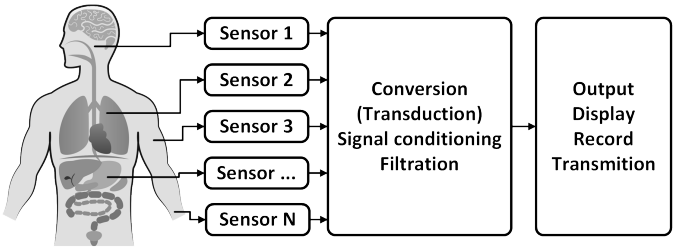


Fig. 2. Complete sensor system

To choose a suitable sensor, various factors must be taken into account. In general, we can say that they are reduced to the following three main categories

- economic - this includes the price of the sensor itself, the possibility of buying it over a long period of time, the possibility of its delivery - the best and highest quality sensor is useless if it cannot be delivered on time.
- characteristic - this category includes all the parameters of the sensor that determine its quality indicators: accuracy, stability, repeatability, linearity, range, etc.
- dependent on the environment - this includes dependencies on environmental changes - temperature, humidity, pressure, overload, energy consumption, self-calibration, etc.

For example, choosing a cheap sensor for single use over time may turn out to be more expensive than using a more expensive sensor that allows multiple use. In another case, using a supersensitive sensor may prove problematic if the data received during reading has large deviations. Similarly, a sensor whose readings are greatly influenced by changes in its environment may be unsuitable, even though it may have ideal other parameters.

## II. Biomedical sensors Classification

The biomedical sensors can be classified according to several different characteristics. The first one is a by type of quantity they registered. Yu-Yan Zhuang et al. [5] states that according to the type of quantities that biosensors register, they can be divided into three main groups. We can add to them a few more types:

- Physical quantity sensors - they convert mechanical movements, pressure, speed, fluid movement and volume etc.
- Chemical quantity sensors - they measure the oxygen quantity in the blood, the pH also ions and any other chemical substances and compounds
- Biomedical quantity sensors - they measure
- Temperature sensors - they convert various forms of radiated energy to convenient signals to use
- Biopotential sensors - they measure the electrical voltage generated by physiological processes occurring in the body.

### *A. Physical quantity sensors*

Sensors for physical quantities are the same as those used in non-biomedical applications. This class includes sensors for motion, position, pressure, speed, sound, flow, etc. Although the same sensors are used for medical and non-medical applications, some of them have significant differences in their use. For example, sensors for direct measurement of blood pressure and blood flow are placed in a blood vessel, which implies that they must be designed to allow their placement in a blood vessel. Another challenge is their placement itself, which requires that it be done by qualified personnel.

### *B. Chemical quantity sensors*

Chemical quantity sensors are used to measure chemical parameters such as the concentration of oxygen and carbon dioxide in human metabolism, as well as the pH, $Na^+$, $K^+$, $Ca^{2+}$, and $Cl_+$ values in body fluids [6].

### *C. Biomedical quantity sensors*

A biosensor uses a living component or product of a living being for measurement or indication. They are characterized by the nature of the interaction that underlies the sensing effect - the very specific chemical reactions typical of biological systems. They used to detect biological parameters like enzymes, DNA, RNA, hormones etc. One of the most important applications of enzymatic biosensors is the monitoring of blood sugar levels in diabetic patients using a glucose sensor. The most commonly used principle is through enzymes that, when reacting with sugar, release hydrogen peroxide + (Gluconolactone - acid). It, in turn, affects an electrode by changing the electric current flowing through it. Depending on the magnitude of this current, the sugar content is determined. To perform the test, the classic method is used by pricking the blood sample and applying it to the sensor. There are also certified minimally invasive methods - a sensor is implanted in the body that reads the glucose content and transmits

this information to an external device. Currently, there is no approved and certified non-invasive method for monitoring sugar in the body. There are developments and attempts to use optical technologies to determine sugar content. There are also attempts to use the change in the absorption and reflection of RF energy passing through tissues [7].

### D. Energy sensors

*1) Temperature sensors:* Temperature is one of the most constant variables in the human body. Like any auto-regulation system, here we have a supporting source, executive elements for regulation – muscles, skin, lungs and a control center – the hypothalamus. The absolute value of temperature for a healthy person is about 37°C. The classic method of measuring temperature is by using a mercury thermometer [8]. It is simple and cheap. The main disadvantages include the relatively long time for determination and the difficulty of reading the measured value. Another major disadvantage is the possibility of dangerous environmental pollution when it is broken. The development of microelectronics allows the replacement of mercury thermometers with safer electronic ones. Figure 3 shows a simplified block diagram of an electronic thermometer. It contains a thermally sensitive element usually a thermistor or diode, an analog to digital converter and a display. It is also possible to have memory and communication capability to connect to external systems.


Fig. 3. Contact electronic thermometer

Another method for determining temperature is measuring the intensity of infrared radiation. Figure 4 shows a block diagram of such a thermometer. The energy emitted by the object is focused by a lens or set of lenses. It is then filtered, which achieves measurement only in a narrow region of the spectrum, in order to avoid the influence of side radiation sources. An advantage of the method is that the measurement is non contact, and it is possible to make it from a relatively long distance. Recent developments in infrared thermometers combine pulsed laser technology with single color infrared thermometers to automatically determine the values of the emissivity and accurately correct the measured temperature.

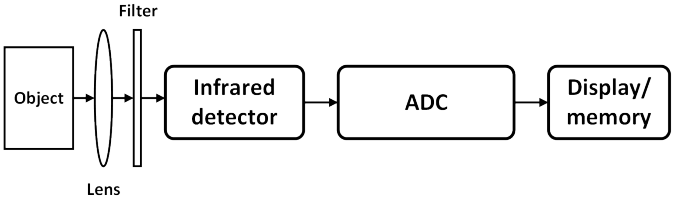


Fig. 4. Contactless electronic thermometer

*2) Optical sensors:* During the systolic phase, the arteries fill with blood, which leads to their expansion. The path that the light travels also increases and as a result, the absorption of light by the blood increases. At maximum absorption, we have a minimum in the signal graph. Similarly, during the diastolic phase, we have less blood, the blood vessels are more constricted, as a result of which the absorption of light is less and a maximum is obtained in the graph of the photoplethysmographic signal. Figure 5 [9] shows the path of the light and the shape and level of the received signal.

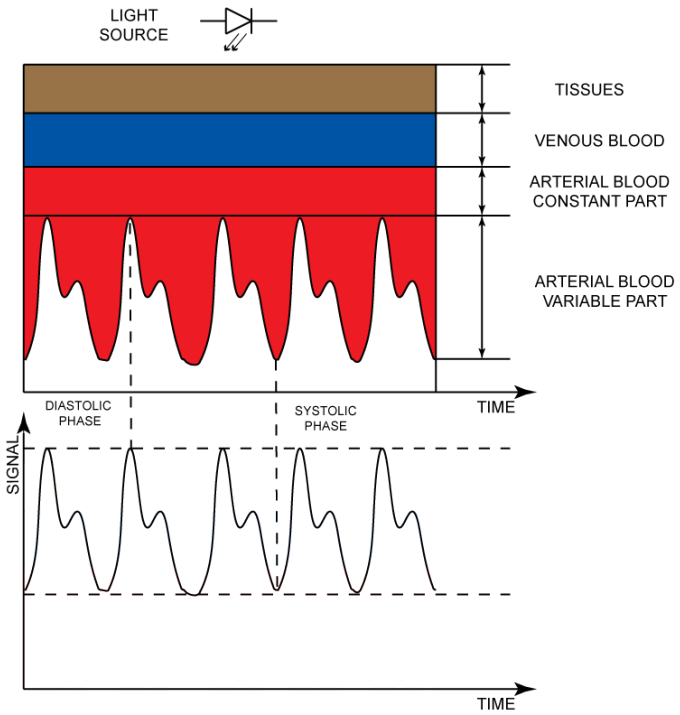


Fig. 5. Photoplethysmographic principle

There are two main methods for measuring the pulse wave using photoplethysmographic technology:

- by measuring the volume of blood when light is reflected from the tissue Figure 6, with the light source and photodetector located on the same side of the study site.
- by measuring the volume of blood as light passes through the tissue Figure 7, with the light source located on one side of the tissue and the photodetector on the other;

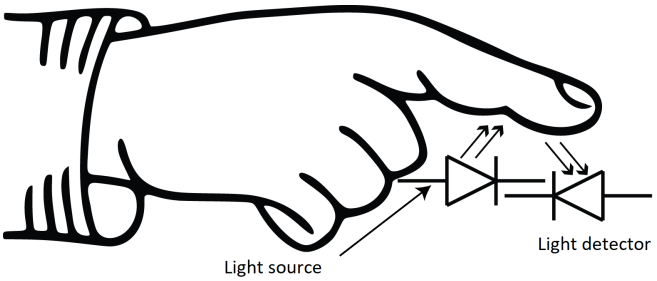


Fig. 6. Photoplethysmographic usage using reflection

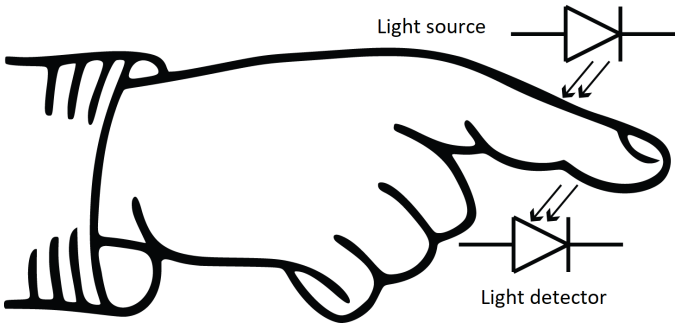


Fig. 7. Photoplethysmographic using pass trough

Figure 8 shows a typical block diagram of a heart rate an $SPO_2$ device. The signal coming from the photodiode(s) is amplified, then digitized with ADC and then is processed by DSP circuit.


Fig. 8. Photoplethysmographic sensor device diagram

$$A = \epsilon c l \tag{1}$$

where:

A - absorption;

$\epsilon$ - molar absorption coefficient;

c - concentration;

l - thickness of the layer through which light passes.

*3) X-ray sensor:* A typical block diagram of a x-ray sensor is shown on Figure 9. X-rays from the source pass through the object of study and fall on a surface covered with phosphor. As a result light is generated, which falls on a photocathode. There it is converted into an electrical signal. Then the received signal passes through a photomultiplier, where it is amplified and falls again on a surface covered with phosphor. The electrical signal is converted into visible light. After passing through a converge lens, the obtained image is displayed on a monitor for direct observation or is converted by a CCD camera into digital form for recording or subsequent processing.

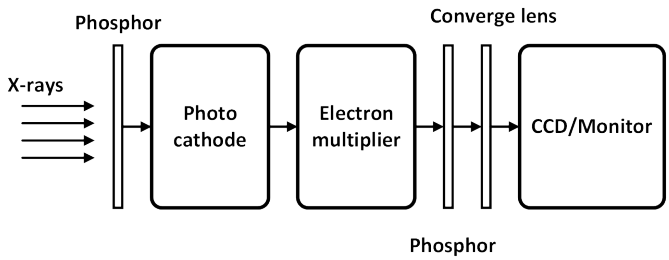


Fig. 9. X-ray sensor simplified block diagram

### *E. Biopotential sensors*

The most commonly used sensors in this group are electrocardiogram, electroencephalogram, and electromyogram. Below we will provide a brief overview of each of them.

*1) Electrocardiogram:* One of the most commonly used diagnostic tools for assessing the activity of the cardiovascular system is the electrocardiogram (ECG). The electrocardiogram is a time-lapse recording of the electrical activity of the heart [10] and is a reflection of the magnitude of the voltage between specific points on the individual's body.

The main task of recording an electrocardiogram is to detect and monitor the electrical signals coming from the heart. This is done by determining the voltage potential in the heart using two bipolar leads placed on either side of the heart. There are many techniques for obtaining an ECG signal from the body of an individual, and these techniques depend on the way the electrodes are placed. The relative placement of the electrodes determines the area of the heart from which the ECG signal will be obtained. According to Eythoffen, the heart is located approximately in the center of an equilateral triangle, called Einthoven's triangle [11], [12]. Figure 10 [13] shows two of the peaks, which are located on the two shoulders of a person, and the third peak is located in the abdominal region. According to Einthoven, the instantaneous magnitude and direction of the resultant electrical vector of the ECG signal is obtained by measuring the projections of the vector onto the sides of the triangle.

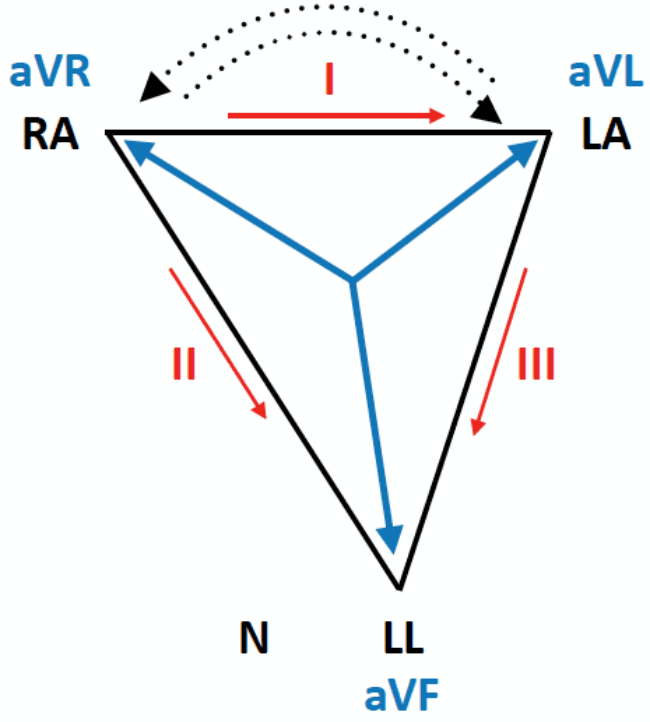


Fig. 10. The Einthoven's triangle

Electrical voltage is measured by electrodes attached to the individual's body at specific locations. Figure 11. [14] shows

the arrangement of 6 electrodes for a 12-lead study. For this purpose, 10 electrodes are required, with 4 electrodes placed on the limbs.

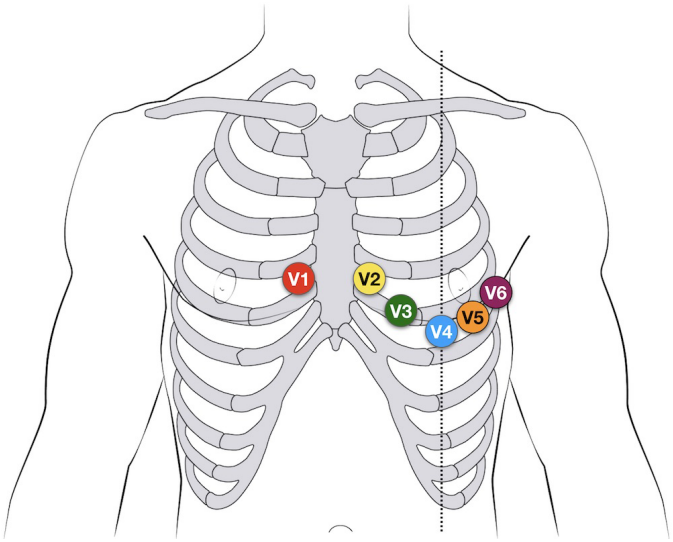


Fig. 11. ECG Electrodes placement

The typical ECG sensor system consists of several main components shown on Figure 12. They are:

- Leads - A standard 12-lead configuration is used to obtain a complete, detailed picture of the heart's condition. When using Holter devices for continuous monitoring, a 3- or 5-lead configuration is used. A single-lead configuration is commonly used in wearable ECG recording devices.
- Processing - In nowadays the processing block consists of input amplifier, input filter, digital processing unit for filtering, removing a base line drift, removing artefacts etc. Most if not all of this processing can be made in one single electronic integrated circuit.
- Display - The results of the study can be recorded for further future research and reference.

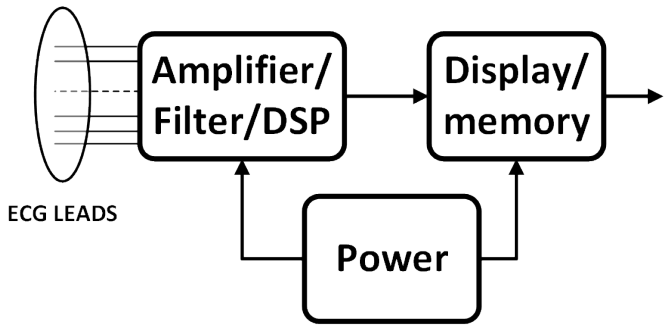


Fig. 12. Typical ECG sensor system

*2) Electroencephalogram:* Electroencephalogram are recordings of electrical activity of human brain. The electrical potentials produced by brain are small about 300$\mu$V range. The electrodes are are placed on scalp in a specific way. Standard clinical EEG uses a 21 electrodes. Figure 13 [15] shows a standard placement on scalp of subject to study.

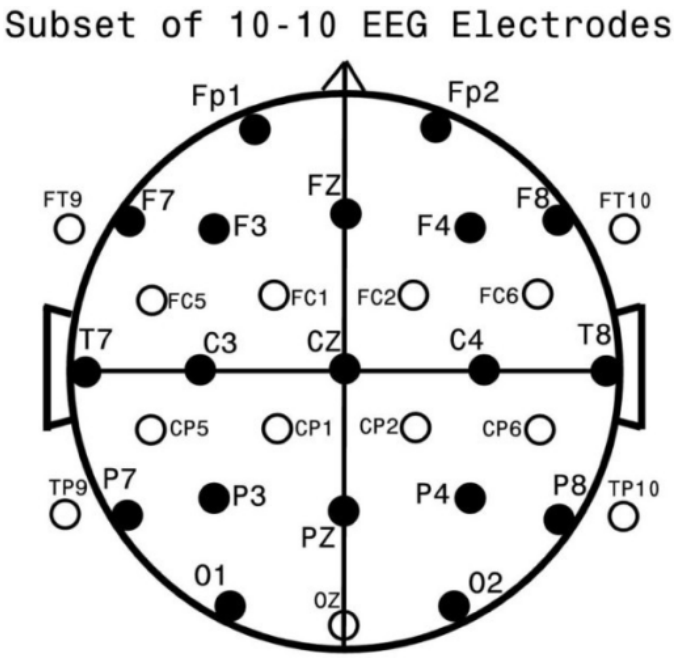


Fig. 13. EEG leads naming and typical placement. Source: National Library of Medicine.

In rare and special cases up to 128 and more electrodes can be used. The acquisition system for registering a EEG activity is similar to that for ECG recording. There is a input amplifiers, filters, digital signal processing, displays, data recording etc. Unlike the characteristic shape of the ECG signal, there are no easily recognizable areas of the graph. The interpretation of the EEG requires the services of experienced electroencephalographers, who can distinguish between normal brain activity and the presence of various abnormalities. Figure 14 shows a sample EEG image [16].

## III. Conclusions

This article provides a brief overview of the most commonly used biomedical sensors in modern healthcare. A classification has been made depending on the quantities they register. Their principles of operation are presented. Greater attention is paid to the sensors that are present in modern wearable electronic devices such as electronic bracelets, smart watches, phones and others.


## Acknowledgment

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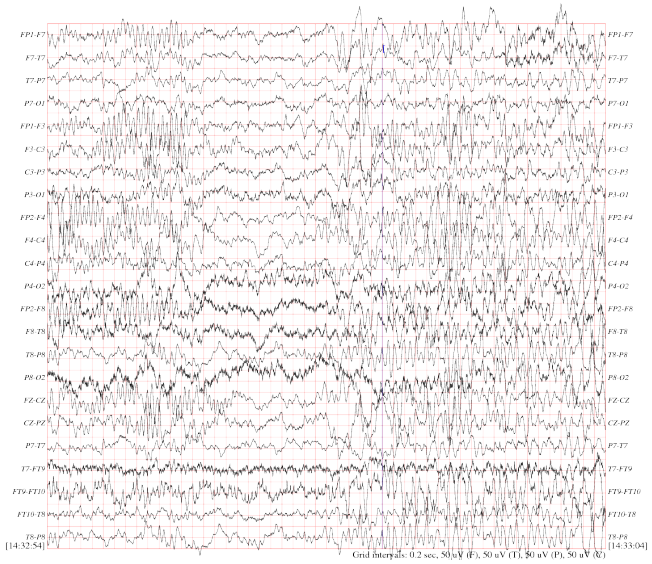

Fig. 14. Sample EEG image


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# *PROTECTION OF CARDIOLOGICAL DATA IMPLEMENTED USING CRYPTOGRAPHY METHODS*

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**Abstract.** With the transformation of digital health services and e-health, technologies for protecting patient data are increasingly vulnerable to attacks, unauthorized access, and theft. This article describes the application of cryptography in the protection of cardiology databases. Information security systems in e-health must ensure the implementation of certain requirements included in government regulations to protect health information from attacks, disclosure, unauthorized use, and destruction. The improvement of digital health infrastructure has brought to the forefront modern means of protecting both personal and research data in the healthcare industry, as well as effective interactions between healthcare and patients.
**Keywords: digital health, cryptography, information security systems**

**Въведение.**

С трансформацията на цифровите здравни услуги и електронното здравеопазване, технологиите за защита на данните на пациентите са все по-уязвими от атаки, неправемерен достъп и кражби. Тази статия описва приложението на криптографията в защитата на кардиологични бази от данни.

Въпросите относно използването на криптиране остават на дневен ред. През декември 2020 г. Европейската комисия и върховният представител на Съюза по въпросите на външните работи и политиката на сигурност определиха криптирането като ключов метод за защита на индивидуалните права и гарантиране на сигурността на лицата [1].

Системите за информационна сигурност в електронното здравеопазване трябва да осигурят изпълнението на определени изисквания, включени в държавни нормативни документи с цел защита на здравната информация от атаки, разкриване, неправомерно използване и унищожаване.

Стотици са заплахите и все повече сигурността на информацията зависи от добре обезпечената сигурност, освен на потребителите, и на системите в организациите. Киберсигурността се базира на: информационната сигурност, сигурността на приложенията, мрежовата сигурност и сигурността на Интернет, като на стълбове на своя фундамент [2].

Усъвършенставането на дигиталната здравна инфраструктура поствя на преден план съвременните средства за защита, както на личните, така и на изследователските данни в здравната индустрия, също и на ефективните взаимодействия между здравеопазването и пациентите.

Тази статия представя резултатите, свързани с три вида кардио данни: ФПГ, ЕКГ и Холтер записи. Формата на вълната на кардио сигнала, записана от Холтер апарат, е идентична с тази на ЕКГ сигналите, записани с електрокардиограф; разликата е, че Холтер апаратът е проектиран да записва непрекъснати ЕКГ данни (2x10min). Всички данни, върху които се прилагат тестовете, са получени от кардио записи, което е особено важно за реалистичността на резултатите. Предварителна обработка беше приложена към трите вида данни от изследването, която включва намаляване на интерференцията [1], откриване на максималните отклонения в сигналите (QRS комплексите са Q, R, S-характерни точки в ЕКГ сигнала, с максимално отклонение на амплитудата в точката R и локализация на P пика при PPG сигнала [1].

Постоянно развиващите се технологии като роботика, изкуствен интелект, генетика, синтетична биология, нанотехнологиите, триизмерния печат и виртуалната реалност дават все по-голямо отражение върху света ни, но те са придружени и от безброй заплахи за сигурността на информацията. За да бъде гарантирана тя се изисква изграждане на модел за сигурност в една организация [3].

**1. Инструменти за защита с Криптография**.

Криптографските ключове и дигиталните сертификати са средства, с които нашите данни и използваните технологии следва да са защитени и обезопасени [3]. Често към получените данни се добавя воден знак /алгоритъм за защита на електронни документи използвайки воден знак [8]/, за да се защитят от неоторизиран достъп, преди да се извърши криптография, използвайки подходящо подбран алгоритъм за криптиране.

В [1] е представен и анализиран алгоритъм, който включва защита с помощта на криптография с публичен и симетричен ключ.

Предложеният софтуерен алгоритъм е изпълнен върху реални електрокардиографски, фотоплетизмографски и Холтер кардио данни. Осигуряването на защитата и сигурността на няколко реални сигнала, използвани в ежедневието на хората, от злонамерена намеса, неоторизиран достъп, фалшифициране и сериозни атаки е възможно днес благодарение на създаването на математически базирани софтуерни решения [1].

Техническото обезпечаване и събирането на повече информация води до необходимост от използване на все повече устройства от медицинския персонал, но с бума на мобилните технологии в последните години това препятствие е значително по-лесно за преодоляване [6].

Добрата защита на една информационна система от база здравни данни трябва да бъде и добре управлявана от администраторите на здравни заведения. Специалисти по

проектиране на програмното обезпечаване са задължителни длъжности в изграждането на административната база на лечебните институции.

Осигуряването защитата на информацията започва още с проектирането и изграждането на бъдещата информационна система за защита на кардиологичните данни. Това става с конфигурирането на оборудването и програмното обезпечаване. Важен е анализът на информационните потоци и контрола на взаимната съвместимост. Когато този етап завърши се преминава към разработването на мерките за сигурност [4].

Сигурността на данните трябва да бъде гарантирана при предаване на записана медицинска информация и лични данни. Използването на технология за криптиране е един от най-ефективните начини за поддържане на сигурността на биомедицинските сигнали. Поради тази причина, въпросите, свързани с удостоверяването и поверителността, са заложени на карта в телемедицината, като се гарантира, че само оторизирани потребители имат достъп до медицинските и личните данни на пациентите. В същото време качеството на оригиналните сигнали трябва да бъде запазено до необходимата степен, за да не се нарушат диагностичните свойства на данните [1].

**1.1.Криптографски приложения**

Използваните методи и процеси в защитната архитектура на моделите за сигурност са: *Криптографията, Автентикацията, Упълномощаването, Проверки, Инфраструктура на публичния ключ, Цифрови сертификати.*

Криптографията е наука за шифриране и дешифриране на данни. Обикновено данните съществуват в своя суров вид и могат да бъдат четени от всеки. Такива данни не са защитени, тъй като хакерите могат да пробият защитата и да ги прочетат. Ако маскирате данните по някакъв начин, който ги прави да изглеждат безсмислени, вие сте ги криптирали успешно [5].

Така нареченият шифрован текст остава неразбираем за хората, които не знаят по какъв начин данните са криптирани. Т.е. декриптирането, превръщането на данните в първоначалния им изглед е механизъм познат само на избрани потребители и би бил труден да бъде проследен от хакери. Криптирането се осъществява посредством математически алгоритъм (шифър), който криптира и декриптира данните.

Конвенционалната криптография използва понятието криптиране със симетричен ключ (symmetric key encryption). При такова криптиране се използва само един ключ както за криптиране, така и за декриптиране на данните. Пример за конвенционална криптография е „Цезаровото писмо”, което използва метода „отместване с три”. При този

метод всяка буква се замества с буквата на трето място в азбуката след заместваната буква [7].

За да декриптирате текста, трябва да използвате същия метод, само че наопаки – отмествате с три букви назад. Съществуват много стандарти за криптиране. Такъв е стандартът за криптиране на данни DES ( Data Encryption Standard), който използва многократно по-сложен механизъм. Ако използвате симетрично криптиране, човекът, който ще чете информацията трябва да разполага с ключа за декриптиране. Докато пазите ключовете на сигурно място, обменът на информация между вас е сравнително сигурен [*5*].

Съществува и криптиране с публичен ключ, което изисква два ключа, наречено асиметрично криптиране. Единият /публичен/ ключ служи за криптиране, а другият /часният/ - за декриптиране на данните. При този метод веднъж изпратената информация вече не може да се прочете от криптиралия я с публичен ключ, а само от получателя с неговия частен ключ, докато при криптирането със симетричен ключ е необходима размяна на един ключ. Анализирайки заплахите и риска задачите относно защитата на данните в информационните системи става все по-сложна. Тя трябва да обхване освен физическото опазване и специализирания софтуер. Криптирането е един от начините за осигуряването на цялостност при предаването на данните.

Смисълът на една шифрова (криптографска) система е преобразуването на някакъв таен текст, така че неговото съдържание да бъде разбираемо само за посветени в тайната хора и неразбираемо за всички останали [7].

Основната цел на криптирания текст е защитата му, невъзможността да бъде разчетен от трето лице, освен от този, който го изпраща и този, който го получава. Криптографските преобразувания се осъществяват по точно определен алгоритъм, като той може да се реализира апаратно/хардуерно/ или изпълнен на универсален компютър, но винаги програмно.

Най-важната разлика между тези два типа е в начинът на съхраняване на ключовете. При апаратното криптиране ключовете се пазят в специално устройство и до тях няма програмен достъп [7].

Под понятието „програмно криптиране” ще разбираме такова криптиране, при което криптиращата последователност се получава, чрез програмни средства, изпълнявани на универсален компютър, а ключовете на криптографската система се пазят върху стандартните му запомнящи устройства [*7*].

Апаратното криптиране има няколко характеристики, сред които се нареждат сигурното съхранение на ключа, слабата адаптивност, висока цена и променливи параметри на апаратурата. При програмното особеностите са обратни – ниска цена и проблемно съхранение на ключовете. Разликите обуславят и появата на смесени реализации между програмно и апаратно криптиране. Двата основни елемента на процедурите при криптографията са алгоритъмът и ключът. Крипртираният текст трябва да е устойчив на атаките. В този смисъл криптографските алгоритми са от изключително значение.

Криптографският алгоритъм е система от краен брой указания и правила, задаващи реда на изпълнение на елементарни действия над явния и криптирания текст и над ключа с цел ефективно криптографско преобразуване [7].

Последователността от битове, думи или байтове, които потребителят е избрал при използване на криптографската система определя криптографския ключ. Криптографските алгоритми са много и разнообразни според криптографските преобразования. Те могат да бъдат симетрични, поточни, блокови, на публичните ключове, комбинирани, за еднопосочни хеш функции, за електронни подписи, за автентикация на съобщенията, за криптографски протоколи и др.

Автентикацията е процес, при който се използва име на акаунт и парола за идентифициране на потребител [*5*].

Типовете на автентикация са различни. Могат да се използват пароли и потребитески имена или биометрични данни. Упълномощаването представлява най-общо оторизирането на потебителите за достъп и дава определени права на използване на системата.Проверките на потребителите изискват записването им в системата и тяхното проследяване.

Инфраструктура на публичния ключ е сбор от технологии и средства, чрез която се постига сигурна комуникация. Отговаря за проверка на поверителността и автентичността на информацията, обменяна между две точки. Инфраструктурата на публичния ключ използва следните три криптографски технологии за генериране на компонентите на сигурността: шифри на симетричните ключове, шифри на асиметричните ключове, еднопосочни хеш-функции [5].

Целта тук е след създаването на акаунта и паролата хеш-функцията да ги криптира и запише. При всяко влизане в системата хеш-функциите сравняват криптираната парола и чак тогава се осигурява достъп в системата за потребителя. Цифрови сертификати се

базират на уникален цифров подпис. Автенчтичността на потребителя се установява след неговия електронен подпис /отпечатък/.

Голяма част от данните не са криптирани или са зле защитени. Публикувано през юли 2014 г. проучване на „Хюлет Пакард" установява, че 90% от устройствата, свързани с интернет, събират лични данни, 70% от които се изпращат без никаква форма на криптиране [3].

Естествено некриптираните данни са изложени на риска да бъдат разбрани или прочетени от всеки, за който са достъпни. Особено опасно е когато здравна институция или финансова компания не криптира данните за платежните документи на клиентите си, което за хакерите е благодатна почва за източване на лична информация, а чрез нея и средства. Такъв е случаят с компанията „Хоум депо", от която хакери извлекли номерата на кредитни карти на 55 милиона клиенти. Google, например, обръща внимание на това и все повече криптира кореспонденцията между потребителите и сървърите си.

Съвременните компютърни операционни системи притежават безплатни вградени инструменти за криптиране на твърдия диск, само че те не са включени по подразбиране и много малка част от потребителите ги използват. Всъщност повечето клиенти дори не подозират за съществуването на тези протоколи за сигурност [3].

Емблематичен за предизвикателствата, пред които сме изправени, е големият пропуск в протоколите за криптиране, открит още в началото на 2014 г., известен с името „Хартблийд" [3].

Както стана ясно по-горе криптографските алгоритми се използват за кодиране и декодиране на изпращаната информация. Един от най-използваните протоколи за криптиране са Secure Sockets Layer/SSL/ и Transport Layer Security/TLS/.

Една от версиите на SSL, така наречения „отворен" SSL, отговаря за защитата на над две трети от трафика в интернет [3].

Безспорно една от защитите при електронното общуване е идентификацията. Хилядите измами с документи, фалшиви самоличности, пари, паспорти и визи са неоспоримо доказателство, че проблемите в тази област на защита са много сериозни и налице. Често банковата институция например не може да установи, че лицето, което тегли пари, прехвърля по сметки или извършва транзакции е нейн клиент, най-малкото защото по електронен път той няма как да бъде разпознат като такъв, ако не представи необходимата идентификация. С технологичния напредък все по-често започват да се използват образите, гласовете и отпечатъците, паролите и електронните сертификати.

Идентификацията често се извършва с криптографски подходи. При обмен на криптирани съобщения основният идентификатор е притежаването на необходимия ключ [7].

Паролите са най-често използваното средство за идентификация. Изборът на пароли често е съобразен с личното усещане на потребителя, което определя и сигурността. Доказано е, че потребителите избират пароли, които са близки до личността им символи или психологически усещания, което понякога крие риск от разкриваемостта им. Слабо място се оказва и съхраняването на паролата, тъй като уязвимите места в Интернет пространството постоянно се променят и нарастват. Друг е моментът, че въведени в дадена система те задължително са криптирани и могат да бъдат изисквани от потребителите при тяхното евентуално забравяне. Други възможности за идентификация са електронния подпис, който е автентичен и категорично доказва подписания документ от изпращача и автентификацията на файловете и съобщенията, която дава възможност получателят да е сигурен, че получва оригиналния документ и като цяло оригиналната информация.

За изработването на код за автентичност се използват така наречените хеш функции, които са клас от еднопосочни функции [7].

Това са функции, които на входа си получават низ с произволна дължина, от когото на изхода си изграждат низ с постонна такава. Хубаво е винаги криптирането да е допълнено от автентифициране, което прави добре защитена една криптографска система.

**1.2. Гарантиране на защитата на информационни системи в здравеопазването с криптиране.**

При внедряването на информационни системи в здравните администрации и услуги е необходимо да се гарантира надеждност, безопасност и сигурност.

Прилагането на криптографски алгоритми, независимо от конкретния метод на внедряване (публичен ключ, секретен ключ или хибридни алгоритми), е много важно за сигурността на предаваната информация. Използването на протоколи за обмен на ключове, цифрови подписи и вграждане на воден знак са ефективни инструменти за защита на данни, сигнали и изображения. Изборът на най-подходящия алгоритъм за криптиране играе съществена роля в процеса на проектиране на схемата за защита на предаваната информация [1].

**1.3. Математически метод в процеса на криптиране.**

Често използван математически метод за процеса на криптиране е криптографията с елиптични криви, подход за осигуряване на криптиране с публичен ключ, който се основава на алгебричната структура на елиптични криви върху крайни полета [1]. Използването на криптография в биомедицински приложения е метод, който гарантира поверителността на медицинските данни на лицата. Методът, който представя това изследване за прилагане на криптография за защита на видовете кардиологични данни обхваща данните: ЕКГ, фотоплетизмографски сигнал (ФПГ) и Холтер. Процедурата за криптиране се извършва след компресиране на изследваните данни и извършване на вейвлет трансформация (ВТ) върху получената последователност.

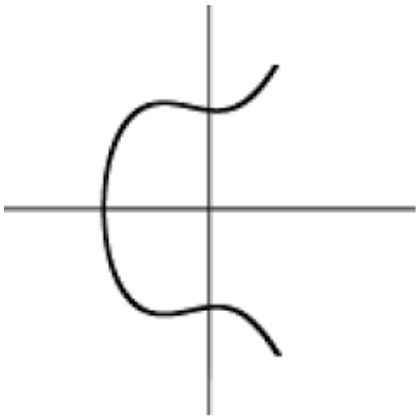
Алгоритъмът за криптиране е приложен въз основа на реални кардиологични данни от ЕКГ и FIG сигнали, получени чрез PPG устройство, позволяващо едновременно записване на два PPG сигнала и един ЕКГ сигнал. Паралелно е извършен Холтер запис, с помощта на устройство за Холтер мониторинг, поставено върху изследваното лице. Холтерът може непрекъснато да записва сърдечни данни до 72 часа [1].

Проективно пространство и елиптични криви Дефиниция:

Нека *F* е поле. Елиптична крива *E(F)* над *F* (зададена с уравнение на Вайершрас в обобщена форма) наричаме съвкупността от всички точки (*x, y)* на равнина *F2* , които удовлетворяват:

$$y^2 + a_1xy + a_3y = x^3 + a_2x^2 + a_4x + a_6, \qquad a_i \in \mathbb{F},$$

и една специална точка O, наричана безкрайна точка [10].



**Фиг. 1. Elliptic Curves Calculator /приложение/**

Предложената процедура за криптиране има за цел да осигури добра защита на трите вида кардио сигнали при създаване на архив от използваните ЕКГ, ФПГ и Холтер записи, получени при изследване на кардио записи от пациенти с различни сърдечно-съдови

заболявания и здрава контролна група. Създаденият алгоритъм е реализиран софтуерно в среда за програмиране на Microsoft Visual C++ като стандартно софтуерно приложение [1].

Извършени са математически анализи на проведените изследвания и са определени характеристики за оценка.

Това изследване анализира ефективността на отделните стъпки при прилагането на приложената процедура за защита на кардиологични данни (използвайки параметри за оценка на ефективността на използваните в процедурата алгоритми) и сравнява стойностите на параметрите на изходния сигнал с тези на входния сигнал за всичките три типа кардио данни.

**2. Методи за защита на кардиологични данни.**

Предимството на защитата на кардио сигналите е, че те са относително по-малко податливи на измами поради уникалния си характер. От друга страна, ЕКГ и ФПГ сензорите генерират постоянно голям брой отчети, които трябва да се обработват в реално време.

Електрокардиографията и фотоплетизмографията са съвременни, несложни инструменти за изучаване на здравословното състояние на субектите, предоставящи информация за състоянието на сърдечно-съдовата система, активността на автономната нервна система и други.

**2.1. Процедура за защита на кардио данни.**

Математически базираният метод за защита на кардио данни, предложен и изследван в тази статия, се състои от някои от следните стъпки: На първо място: *Прилагане на дискретна трансформация; Прилагане на оптимизирана компресия, базирана на ефективност на енергийното опаковане, на получената последователност; Вграждане на воден знак в редуцираните WT коефициенти; Процедура за криптиране с помощта на хибриден криптографски алгоритъм; Прилагане на обратна дискретна уейвлет трансформация на получената последователност; Определяне на изследваните параметри за оценка на използваните алгоритми.*

**2.2. Стъпки на математически базиран метод за защита на кардио данни.**

***Прилагане на дискретна трансформация;***

Дискретизацията/квантизацията често е ключова стъпка когато искаме да приложим **дискретни** (integer-valued) механизми за поверителност (напр. *geometric/discrete Laplace*, *discrete Gaussian*), или когато комбинираме

диференциална поверителност (DP) с криптография (HE/SMPC) или федеративно обучение.

Неправилна оценка води до липса на реална защита или ненужно голям шум, за това е необходимо измерване с точност чувствителността на определяне на шума. Не е уместно неограничено комбиниране на множество DP-операции без privacy accounting — записа на ε сумарно расте (composition). Използва се advanced composition или moments accountant. Запазването на клинична валидност и тестване дали важни клинични открития (напр. детекция на аритмия) оцеляват след защита е задължителна стъпка. Нужно е документиране [11].

***Прилагане на оптимизирана компресия, базирана на ефективност на енергийното опаковане, на получената последователност;***

Разработването на метода за компресия и защита на кардиологични сигнали (напр. ЕКГ), включва: оптимизирана енергийна трансформация (напр. чрез въллетно, Фурие или дискретно косинусово преобразуване); компресията се управлява според ефективността на опсковане на енергията (energy encapsulation efficiency, EEE) — тоест колко добре основната енергия на сигнала се концентрира в малък брой коефициенти и върху компресираните (дискретни) коефициенти се прилага математически метод за защита — например дискретен механизъм на диференциална поверителност (geometric или discrete Gaussian).

Така се постига двойна цел:

1.Намаляване на излишната информация чрез компресия с висока енергийна ефективност;

2.Осигуряване на поверителност чрез дискретен шум, добавен в пространството на компресираните коефициенти, където чувствителността е по-ниска.

***Вграждане на воден знак в редуцираните WT коефициенти - процедура за Дизайн-принципи/изисквания:***

**- Невидимост (imperceptibility)**: вграденото изменение да не разрушава клинично значимите характеристики (R-пикове, HRV и т.н.). Оценка чрез PRD / PSNR + клинични метрики.

**- Робустност**: водният знак трябва да оцелява на типични трансформации (компресия, шум, филтриране, частично премахване).

- **Криптографска сигурност**: използване на ключ (seed) за избора на коефициенти и/или генерация на битовата последователност.

**- Съвместимост с редукцията/DP**: вграждането трябва да работи при вече намален набор коефициенти; ако след това при прилагане на DP-шум (дискретен).

***Процедура за криптиране с помощта на хибриден криптографски алгоритъм;***

Хибридният подход комбинира асиметрична криптография (за защитено прехвърляне/обмен на ключ) и симетрична автентифицирана шифрация (за самите данни). Често се формулира като KEM (Key Encapsulation Mechanism) + DEM (Data Encapsulation Mechanism). Асиметричната криптография е удобна за сигурно споделяне на ключове, но бавна за големи блокове данни. Симетричните AEAD алгоритми (напр. AES-GCM) са бързи и дават интегритет/автентичност. Хибридът дава най-доброто от двата свята.

**Процедура**

| |
|---|
| **A. Генериране /подготовка ключове (еднократно/по нужда): Получателят генерира дълготраен асиметричен ключ.** |
| **B. Шифрриране - KEM + DEM** |
| **C. Дешифриране: Получателят прочита header, извлича** EncapsulatedKey(epk или RSA_encrypted_key). |

**Таблица.1**
**Процедура за криптиране с помощта на хибриден криптографски алгоритъм**

За постигането на компресирани WT коефициенти е необходимо да се шифрират **след** вграждането на воден знак и след евентуална дискретизация/DP (ако DP е част от pipeline трябва да бъде включен, определена поредността внимателно — обикновено: извличане фичъри → вграждане watermark → компресия/редукция → (ако е централно) DP → шифроване за съхранение/транзит).

**Заключение:**

Усъвършенставането на дигиталната здравна инфраструктура поствя на преден план съвременните средства за защита, както на личните, така и на изследователските данни в здравната индустрия, също и на ефективните взаимодействия между здравеопазването и пациентите. Предложеният софтуерен алгоритъм е изпълнен върху реални електрокардиографски, фотоплетизмографски и Холтер кардио данни. Осигуряването на защитата на няколко реални сигнала от злонамерена намеса, неоторизиран достъп, фалшифициране и сериозни атаки е възможно благодарение на създаването на математически базирани софтуерни решения. Техническото обезпечаване и събирането на огромна база от данни създава трайна необходимост от използване на все повече устройства от медицинския персонал, което налага дбрата защита на една информационна система от здрани данни да бъде и добре управлявана от администраторите на здравни заведения.

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# ARC (Autonomous Robot Control): A Low-Code, Skill-Based Software Platform for Rapid Robot Development

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***Abstract- Robotic systems increasingly rely on rapid software development tools that reduce integration time and lower the entry barrier for developers and researchers. This paper presents an overview and experimental evaluation of Synthiam's ARC (Autonomous Robot Control), a low-code software environment that enables the design, integration, and control of service and mobile robots through reusable software modules called Robot Skills. Unlike traditional robotics frameworks that require complex code development, ARC allows intuitive visual configuration and scripting using multiple languages. The system was implemented and tested on a mobile robotic platform equipped with camera and microphone interfaces. Two ARC Robot Skills—Camera Device and Speech Recognition—were integrated to demonstrate perception and human–robot interaction (HRI) capabilities. The results show that ARC significantly simplifies system integration while maintaining sufficient flexibility for academic and prototyping applications. The findings highlight the platform's strengths, limitations, and future potential for educational and research use in low-code robotics environments.***

## 1. INTRODUCTION

The field of robotics has seen rapid diversification in hardware, sensors, and control architectures. However, integration and software development remain time-consuming and technically demanding tasks that often slow down innovation. Researchers and educators increasingly seek low-code solutions that enable fast prototyping and easy experimentation without deep programming expertise.

Synthiam's ARC (Autonomous Robot Control) environment offers a graphical interface and a modular structure for building complete robotic systems [7]. Users can assemble behaviors and functions by combining Robot Skills, which represent self-contained components such as motor drivers, vision systems, or speech processors. This approach accelerates robot development cycles and enhances accessibility for non-expert users.

The present study analyzes the architecture and practical use of ARC, with emphasis on its skill-based design, scripting capabilities, and system modularity. A simple case study—using Camera Device and Speech Recognition skills on a mobile robot platform—demonstrates its potential for human–robot interaction and educational robotics [2].

## 2. BACKGROUND AND RELATED WORK

Low-code and no-code paradigms have gained prominence in industrial automation, mechatronics, and educational robotics. Tools like Blockly, Node-RED, and graphical ROS extensions provide simplified access to robot behaviors and data flows [5]. These frameworks reduce the need for manual coding while preserving logical structure and modularity.

ARC differentiates itself through a skill-based ecosystem and multi-language scripting environment. Each skill functions as a self-contained unit that can be added, configured, and interconnected through the main ARC interface. Users can select from a public Skill Store that includes hundreds of modules for sensors,

actuators, and AI services such as speech, vision, or cloud integration.

Previous studies and educational projects have demonstrated that visual programming accelerates learning and fosters creativity in robotics [1]. However, these tools often lack flexibility or hardware compatibility. ARC addresses this challenge by allowing both graphical and text-based scripting (Python, JavaScript, EZ-Script), enabling advanced customization while keeping a low-code entry level.

## 3. ARC Overview

ARC operates on Windows-based computers, connecting to robot controllers (e.g., EZB interfaces, Arduino boards, or networked devices) via USB, Wi-Fi, or serial communication. The software acts as the central runtime environment that manages communication, perception, and behavior execution.

The architecture consists of hardware, middleware, and application layers, where each skill communicates with others through shared variables and ControlCommand() calls. Robot Skills are reusable modules that provide functions such as camera input or speech recognition. Scripts may invoke skills using Blockly, Python, or JavaScript, allowing orchestration of complex behaviors with minimal code. ARC's EZB abstraction layer ensures compatibility with heterogeneous controllers, which is crucial for educational and research applications.

### *3.1 System Architecture*

ARC operates on Windows-based computers, connecting to robot controllers (e.g., EZB interfaces, Arduino boards, or networked devices) via USB, Wi-Fi, or serial communication. The software acts as the central runtime environment that manages communication, perception, and behavior execution.

ARC's architecture can be represented as a layered model:

1. **Hardware layer:** sensors, actuators, and controllers.
2. **Middleware layer:** ARC runtime handling I/O, network communication, and data synchronization.
3. **Application layer:** Robot Skills and user scripts defining robot behavior.

Each skill communicates with others through shared variables and *ControlCommand()* calls, allowing flexible orchestration between modules.

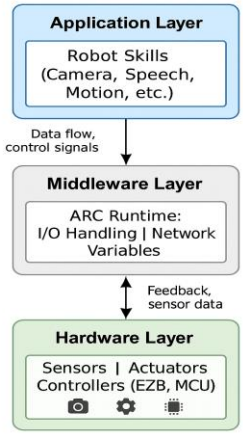


Fig. 1 ARC's layered model and data flow between hardware, middleware, and application layers.

### *3.2 Robot Skills and Skill Store*

Robot Skills are reusable software components that provide a specific function—camera input, speech recognition, motion control, etc. Users can install new skills directly from the online *Skill Store*. This modularity allows rapid expansion of functionality without recompilation or code changes.

Each skill exposes configuration parameters, start/stop controls, and scripting interfaces. For example, the *Camera Device* skill connects to standard USB or IP cameras, enabling image streaming, object tracking, and visual feedback. The *Speech Recognition* skill integrates local or cloud-based voice recognition services, allowing natural voice commands.

### *3.3 Scripting and Behavior Orchestration*

ARC supports multiple scripting environments:

- **Blockly:** visual block programming for beginners and educational use.
- **EZ-Script:** a simplified text scripting language unique to ARC.
- **Python and JavaScript:** for advanced customization and integration with AI services or external libraries.

Scripts can trigger *ControlCommand()* calls that activate or configure other skills. For instance, a Python script can capture a voice command through the *Speech Recognition* skill and instruct the *Camera Device* to start tracking a target.

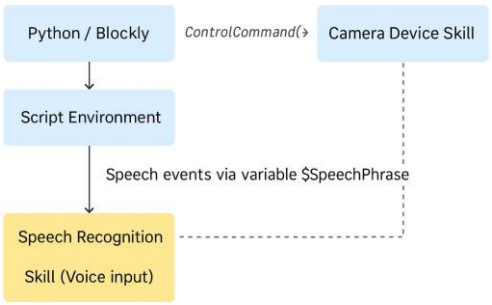


Fig. 2 Example how user scripts interact with skills using ControlCommand().

*3.4 Hardware Compatibility (EZB Abstraction)*

ARC introduces the EZB (EZ-Bridge) abstraction layer, which serves as a standardized interface between the software runtime and a wide range of microcontrollers, embedded boards, and robotic control units. This abstraction layer enables seamless communication by defining a universal command protocol that translates high-level software instructions into low-level device actions. The EZB protocol encapsulates functions such as digital and analog I/O handling, PWM signal generation, serial communication, and sensor data acquisition.

One of the key advantages of the EZB architecture is its hardware independence. The ARC Runtime communicates with compatible devices—such as Arduino, Raspberry Pi, ESP32, or custom microcontroller units—through the EZB API without requiring modification of the user's high-level robot configuration. In practice, this means that a developer can substitute one controller for another while maintaining the same skill configuration and scripting environment within ARC.

The abstraction layer operates over several transport interfaces, including USB, Wi-Fi, Bluetooth, and TCP/IP, ensuring that both wired and wireless robot controllers can be integrated into a single ARC project. This flexibility allows distributed control architectures, where different subsystems (e.g., motion control, vision, voice recognition) may be managed by separate boards connected under a single ARC runtime.

From an educational and research standpoint, the EZB abstraction provides a consistent experimental framework for multi-platform robotics development. Students or researchers can focus on system behavior, sensor fusion, and algorithmic logic instead of hardware-specific programming. This interoperability also simplifies maintenance, encourages hardware experimentation, and supports hybrid robot configurations that mix commercial and custom components.

In essence, the EZB interface functions as the communication backbone of ARC's modular ecosystem—bridging the gap between hardware diversity and unified software control.

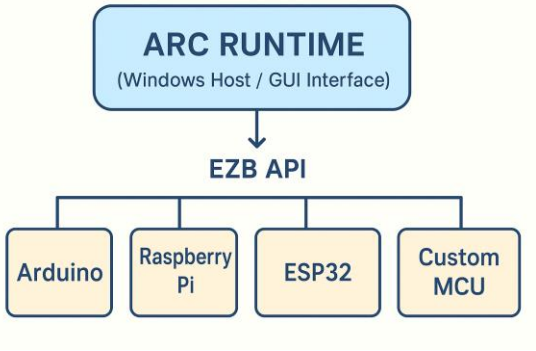


Fig. 3 Different hardware controllers communication through the common EZB interface

## 4. CASE STUDY: RAPID INTEGRATION ON A MOBILE SERVICE ROBOT

The test platform is a four-wheel mobile robot powered by a Li-ion battery pack and controlled via Raspberry Pi 4B. The Pi interfaces with ARC through a Windows control computer. Sensors include a USB camera, microphone, and speaker. Two key skills were integrated—Camera Device and Speech Recognition—to demonstrate visual and auditory interaction [3].

The setup required installing both skills, configuring the camera for continuous video capture, and setting up speech commands ('Start', 'Stop', 'Follow', 'Return'). A Python script connected speech recognition outputs to camera control via **ControlCommand**() calls. In experiments, the robot responded accurately to voice commands, achieving 91% recognition accuracy and 0.4 s latency with 32% CPU utilization on the host PC.

### *4.1 Robot Platform Description*

The test platform is a four-wheel mobile robot equipped with a Li-ion battery pack, DC motor drivers, and a Raspberry Pi 4B as the onboard computer. The Pi runs ARC through a Windows environment (via emulation or remote desktop connection to a control PC). Sensors include a standard USB camera, onboard microphone, and speaker module for interactive tasks.

Tabl. 1 Mobile robot's hardware summary used for testing ARC.

| Component | Description |
|---|---|
| Base | Four-wheel mobile platform |
| Drive motors | 4 × DC motors with encoders |
| Controller | Raspberry Pi 4B connected via Wi-Fi |
| Power supply | Li-ion battery pack, 11.1 V, 4 Ah |
| Sensors | USB camera, microphone |
| Actuators | Speaker, motor drivers |
| Operating environment | Indoor laboratory |

### *4.2 ARC Integration*

Two key skills were integrated:

- **Camera Device Skill:** provides real-time visual feedback for navigation and object detection.
- **Speech Recognition Skill:** allows voice-based command input for basic interaction.

These skills were selected for their fundamental role in human–robot interaction and perception. They represent a minimal but powerful configuration for testing ARC's usability and performance in real-world conditions [4].

### *4.3 Implementation*

The setup process involved:

1. Installing both skills from the ARC Skill Store.
2. Configuring the *Camera Device* for continuous frame acquisition at 30 fps.
3. Setting up *Speech Recognition* with a basic command list (e.g., "Start," "Stop," "Follow," "Return").
4. Writing a short Python script to link recognized words to control functions. For example:

```
if $SpeechPhrase == "start":
    ControlCommand("Camera Device", "TrackObject")
elif $SpeechPhrase == "stop":
    ControlCommand("Camera Device", "StopTracking")
```

Figure 4. represents the Functional flow of the voice-controlled visual tracking process in ARC. The user's spoken command is acquired by the Speech Recognition Skill and converted into a text variable ($SpeechPhrase), which is subsequently interpreted by a Python script. The script transmits a ControlCommand() instruction to the Camera Device Skill, initiating visual tracking operations. The Camera Device Skill performs target tracking and provides real-time feedback to the graphical user interface (GUI), thereby establishing a closed interaction loop between human input and robot perception.

```
[User Voice]
     ↓
[Speech Recognition Skill] → $SpeechPhrase Variable
     ↓
[Python Script] → ControlCommand("Camera Device", "TrackObject")
     ↓
[Camera Device Skill] → Visual Tracking → Feedback to GUI
```

Fig. 4 workflow of voice command - recognition - action - feedback.

*4.4 Experiment and Results*

The experiment was conducted in an indoor laboratory environment. The robot was instructed tracked its surroundings. Key evaluation metrics included:

- Time to first working prototype: verbally and visually ~2 hours.
- Average CPU utilization: 32% on host PC.
- Speech recognition accuracy (quiet environment): 91%.
- Latency between speech input and action response: 0.4 s.

4.4 Experiment and Results

The experimental evaluation was conducted to assess the feasibility and performance of the ARC platform in integrating multimodal interaction skills—specifically, speech recognition and vision-based tracking—on a mobile robotic system [6]. The setup aimed to demonstrate the platform's capability to provide real-time responsiveness and reliable communication between high-level software modules and low-level hardware interfaces through the EZB abstraction.

The experiment was performed in a controlled indoor laboratory environment with moderate ambient lighting and limited background noise to ensure stable sensory input conditions. The robot was positioned on a flat surface and connected wirelessly to the ARC Runtime running on a Windows host computer. Two ARC skills were utilized: the **Speech Recognition Skill**, configured for keyword-based command recognition, and the **Camera Device Skill**, responsible for real-time video acquisition and object tracking. Both skills operated concurrently under ARC's runtime environment, with inter-module communication managed by scripting through the **ControlCommand()** function.

The evaluation procedure consisted of issuing a predefined set of voice commands—*Start*, *Stop*, *Follow*, and *Return*—and observing the robot's reaction through its camera feedback displayed in the ARC graphical interface. Each command initiated a distinct action within the *Camera Device Skill* via Python scripting, corresponding to motion activation, object tracking initiation, or system halt. The accuracy and latency of the response were recorded to quantify the system's functional performance.

Performance data indicated that the average recognition accuracy of spoken commands reached 91% under normal acoustic conditions, with a maximum observed latency of 0.4 [Fig. 4,5] seconds between voice command recognition and corresponding visual response. The total CPU utilization of the host system during continuous operation remained below 35%, confirming that the ARC runtime efficiently manages multiple concurrent processes without overloading computational resources.

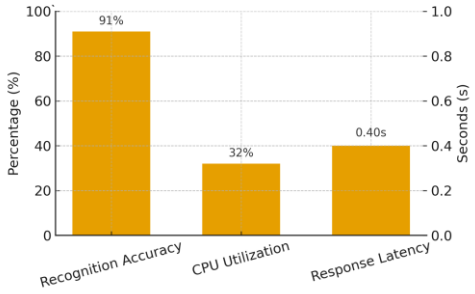


Fig. 5 Core System Metrics

The total time required for initial system setup and configuration—including skill installation, parameter tuning, and script debugging—was approximately 2 hours, highlighting the platform's potential for rapid deployment in experimental and educational scenarios.

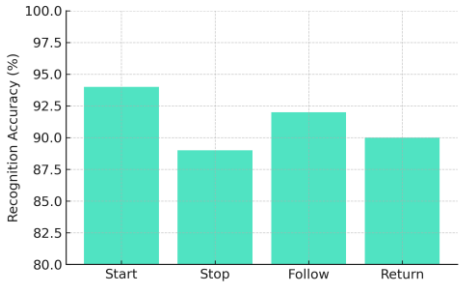


Fig. 5 Average recognition accuracy of spoken commands

Qualitative analysis revealed that the integration of the **Speech Recognition Skill** and **Camera Device Skill** enabled seamless multimodal interaction, offering intuitive control of visual tracking through natural language input. The graphical user interface provided clear visual feedback, facilitating user interpretation of system behavior and supporting iterative refinement of skill configurations.

In summary, the experimental outcomes validate the operational reliability and usability of ARC for real-time multimodal robot control. The results demonstrate that ARC's modular skill framework and scripting flexibility provide a practical foundation for developing interactive service robots without extensive coding effort. Future experiments will extend this evaluation toward dynamic environments, multi-skill coordination, and quantitative benchmarking against conventional ROS-based implementations.

Table 2. Experimental Performance Summary

| Metric | Value | Comment |
|---|---|---|
| Setup time to first prototype | ≈2 hours | Including skill installation |
| CPU utilization | 32 % | Host PC during operation |
| Speech recognition accuracy | 91 % | Quiet indoor lab |
| Command–action latency | 0.4 s | Average measured delay |
| Success rate of commands | 95 % | For defined vocabulary |

## 5. DISCUSSION

ARC's modularity enables rapid prototyping and intuitive integration. The system's main advantages include ease of configuration, skill reusability, and scripting flexibility. Limitations include dependence on Windows OS, inconsistent quality among community skills, and limited low-level hardware access. Despite these, ARC provides a practical tool for researchers and educators seeking rapid development environments.

**Advantages identified:**

- Intuitive graphical interface.
- Reusable skills with minimal configuration.
- Multi-language scripting flexibility.
- Reliable communication with diverse hardware.

**Limitations observed:**

- Platform dependency on Windows systems.
- Limited access to low-level hardware functions compared with open-source frameworks.
- Community skills vary in quality and documentation.
- Real-time performance constrained by CPU during continuous image processing.

Nevertheless, ARC offers an excellent platform for education, prototyping, and research requiring rapid proof-of-concept development.

## 6.RELATED PLATFORMS

Several platforms attempt to simplify robot programming: ROS, Webots, and Microsoft Robotics Developer Studio. However, these solutions generally require substantial coding and configuration. ARC's unique strength lies in combining visual design with scripting and direct access to community-developed skills. This balance of simplicity and flexibility positions ARC as a bridge between educational and research-grade robotics environments.

## 7. CONCLUSION

ARC provides a robust and accessible approach to robot development through its low-code, skill-based architecture. In the presented experiment, essential cognitive functions such as vision and speech were realized using pre-existing skills without custom driver development. The platform enables researchers and educators to focus on task design rather than software infrastructure.

Future work will expand the evaluation to multi-skill integration (e.g., navigation, mapping, and cloud connectivity) and performance benchmarking against ROS-based systems. Further development of open APIs and cross-platform support could make ARC a standard tool for rapid robotics innovation.

## 8. ETHICAL, SAFETY, AND OPERATIONAL CONSIDERATIONS

When employing voice and vision interfaces, user privacy and data handling must be considered. ARC's speech recognition modules may use third-party cloud services, necessitating compliance with privacy regulations. Safety measures, such as emergency stop functions and restricted motion zones, were implemented to prevent unintended actions during experiments.

## 9. ACKNOWLEDGMENTS

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# Using Green Hydrogen Energy Storage for Robot Charging Station

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***Abstract*—This article describes a solar-powered robot charging station that uses green hydrogen as a long-duration energy storage medium. Surplus photovoltaic energy is converted into hydrogen by a PEM electrolyser, stored in metal hydride canisters, and later converted back to electricity through a 300 W fuel cell to support nighttime robot charging. The system stores 1.2 Nm³ of hydrogen and delivers approximately 1.54 kWh of usable electrical energy, with a full refill requiring about 9.33 kWh of input. The resulting round-trip efficiency of ~16.5% reflects the real-world performance of small PEM systems. Despite the modest efficiency, the architecture provides reliable off-grid operation, scalable storage capacity, and flexible autonomous charging for diverse robot fleets.**

***Keywords—fuel cells, charge station, service robots***

## I. Introduction

Green hydrogen is produced by splitting water using renewable electricity [1]. When the solar resource is plentiful during the day but robot operations extend into evening and night, a hydrogen loop offers an elegant way to shift energy in time: solar electricity is converted to hydrogen by an electrolyser; hydrogen is stored in safe, compact metal-hydride canisters, and a fuel cell regenerates electricity for a low-voltage DC bus that feeds robot chargers after sundown. Unlike a battery bank, the power a station can deliver and the energy it can store are mainly independent. Power comes from the electrolyser and fuel cell ratings, while energy scales with the number of canisters. This separation is attractive when robots have sporadic but energy-intensive charging needs, or when the site is remote and unattended for long periods [2]. The goal of this article is to describe the general structure of such a station and to quantify the energy available to robots and the chain efficiency from electricity into hydrogen and back .

## II. Solar Charger Structure

The charger is best understood as three cooperating subsystems connected by a common DC bus. A photovoltaic (PV) array supplies a DC bus through maximum power point tracking (MPPT). The bus may include a modest buffer battery to absorb transients and support the bus during brief cloud passages. When the electrolyser must be fed with AC, a sine-wave inverter converts it from the DC bus; otherwise, a DC-input electrolyser can be used (Fig. 1). The robot side presents one or more isolated DC/DC chargers set to the fleet's nominal pack voltages (e.g., 24 V, 36 V, 48 V), with interlocks and contactors to ensure safe connection before energizing a port. Hydrogen generation and storage - during the day, surplus PV power is routed to a PEM electrolyser that splits deionized water into H2 and O2. Hydrogen is stored in metal hydride canisters that absorb gas into a solid lattice at comparatively low pressures and ambient temperatures. For the use case here, two MHS 800 canisters are installed in parallel so that the station can build a meaningful night reserve while staying compact and

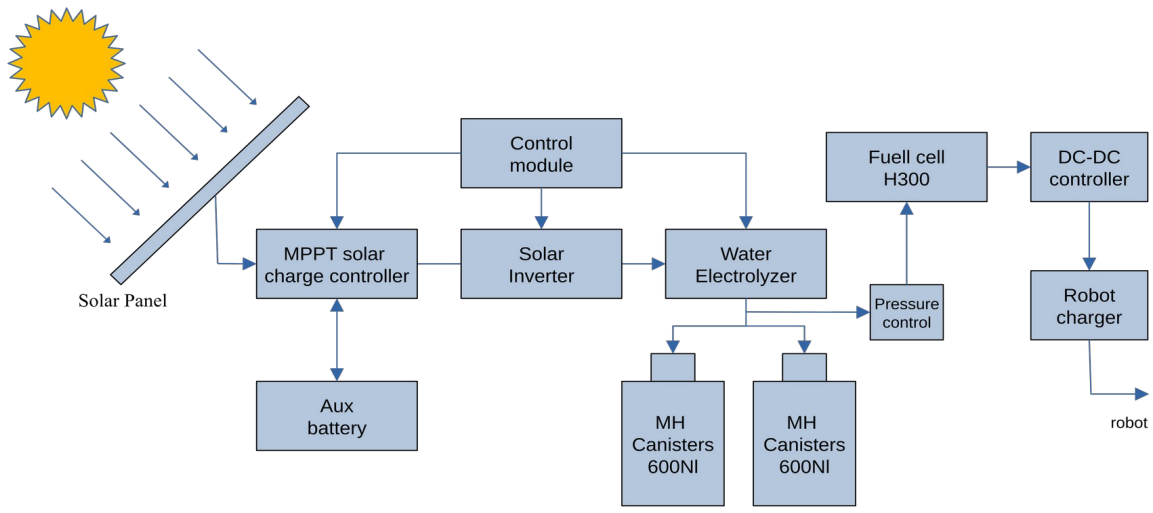


Fig.1 Charge station diagram

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serviceable. Electricity regeneration for night charging - when the sun fades or the load exceeds the PV output, a PEM fuel cell feeds the DC bus. The fuel cell runs steadily in its efficient region while the small buffer battery handles sudden plug-in spikes and short surges from fast chargers [3]. Supervision software coordinates when to start/stop the electrolyser, how to hold the bus setpoint, and when to request more or less fuel cell power.

## III. Energy calculation

This section uses manufacturer data to quantify the hydrogen produced, the electrical energy recovered for charging, and the implied round-trip efficiency. The hydrogen system's specific components are:

• H300 PEM fuel cell, rated 300 W with a hydrogen consumption of 3.9 l/min at full output and a listed system efficiency of 40 % at the rated voltage (Fig. 2) [4].


Fig. 2. H300 fuell cell

• On Fig 3 is shown HG72 PEM electrolyser with maximum hydrogen flow 1.2 l/min and installed power 560 W (max) [5].


Fig. 3. HG72 PEM electrolyse

• The required piping, valves, and pressure control systems to ensure safe operation in optimal conditions of the component (fig.4).

Fig. 4. Pressure regulator

• Two MHS 800 metal-hydride canisters, each storing 600 Nl when filled from HG-series generators; nominal discharge 4 Nl/min per canister (Fig. 5) [6].

Fig. 5. MHS800 metal-hydride canisters

*Hydrogen inventory from two canisters*

The total hydrogen inventory is

$$V_{H_2} = 2 \times 600\, Nl = 1200\, L = 1.2\, Nm^3$$

This inventory meets the fuel cell flow requirement because two canisters in parallel have a nominal combined outflow of ~8 L/min, which exceeds the H300's 3.9 L/min at full output.

*Fuel cell runtime and electrical energy recovered.*

Assuming the H300 operates at its rated 300 W, the runtime based on hydrogen volume is:

$$t_{run} = \frac{V_{H_2}}{V_{H_2,FC}} = \frac{1200\, l}{3.9\, l/min} \approx 308\, min \approx 5.13\, h$$

The electrical energy available at the DC bus from that run is then:

$$E_{out} = 0.300\, kW \times 5.13\, h \approx 1.54\, kWh$$

This value comes entirely from the two datasheet quantities: fuel cell power and hydrogen flow at full output.

*Electrolyser refill time and electrical input.*

The time to produce 1200l of hydrogen at the HG72's maximum flow is:

$$t_{fill} = \frac{1200\, l}{1.2\, l/min} = 1000\, min \approx 16.7\, h$$

If the electrolyser draws its installed power while producing at this rate, the electrical input required for two canister fills is:

$$E_{input} = 0.560\, kW \times 16.7\, h \approx 9.33\, kWh$$

That also implies an energy intensity of ∼7.8 kWh per 1 cubic meter of hydrogen at the HG72's maximum production rate.

*Electric-to-electric roundtrip efficiency.*

Using only the two measured endpoints (electrical input to the electrolyser and electrical output from the fuel cell), the station's electric round-trip efficiency for one charge-discharge cycle is:

$$\eta_{rt} = \frac{E_{out}}{E_{input}} \approx 1.54/9.33 \approx 16.5\,\%$$

Because this figure is derived purely from the two manufacturers' flow/power numbers, it is a practical indicator of what robots can expect at the DC bus from a given amount of PV electricity stored as hydrogen.

In Table I are summarized the main technical parameters of hydrogen charging station

TABLE I. CHARGE STATION PARAMETERS

| ***Parameter*** | ***Value*** |
|---|---|
| Electrolyser max. consumption | 560W |
| Electrolyser production rate | 1.2l/min |
| Total hydrogen storage | 1200 Nl |
| Max. working pressure | 16 bar |
| Fuel cell consumption | 3.9l/min |
| Fuel cell output power | 300W |
| Total energy stored | 1.54kWh |
| Overall efficiency | 16.5% |

## IV. DISCUSSION

The general architecture deliberately decouples duty cycles. During the day, PV serves the chargers first; any surplus is used to run the electrolyser until the two canisters are full. At night, the fuel cell sustains the bus for an estimated ∼5.1 h of continuous 300 W output, or longer at lower average power. If a field team prefers to treat energy in the language of robot batteries rather than hydrogen volumes, the ∼1.54 kWh figure is the most actionable. For instance, three Athena2 [7] robot batteries of ∼0.5 kWh each could be charged back-to-back (subject to charger efficiency and charge profiles), or a single large robot 1 kWh pack could be taken from a low to a high state of charge with margin for overheads. The efficiency computed above (∼16.5 %), accounts for all intermediate conversions without requiring assumptions about the higher/lower heating values of the fuel. It is also a realistic planning number because it uses the electrolysers' installed power at their maximum flow and the fuel cell's power at its rated hydrogen consumption. In practice, careful dispatch can raise the apparent round-trip slightly: for example, running the electrolyser at part-load when PV is abundant but temperatures are mild, trimming DC/DC losses by matching charger voltages closely to pack voltages, or allowing the fuel cell to operate a little below its peak output to avoid throttling losses. Conversely, cold canisters and aggressive charging may reduce effective hours; scheduling a gentle prewarm of the hydrides before the night window can improve gas delivery without materially changing the energy balance. None of these operational choices alter the core calculation; they help the station deliver that energy when it is most useful.

The structure scales predictably. Adding more MHS 800 canisters increases the night runtime in direct proportion. If autonomy rather than peak power is the limitation, this is the most economical change. If the station must charge several robots simultaneously, a second H300 operating into the same DC bus increases sustained power while leaving the energy inventory unchanged. If refill time is the constraint, additional HG72 units can be operated in parallel; their flows sum, and the required PV energy per fill scales accordingly. The control philosophy remains the same: the bus is served first; surplus energy is stored as hydrogen; and the fuel cell regenerates electricity when the bus needs it.

## V. CONCLUSION

A solar-hydrogen robot charger built around a small PEM stack is structurally simple yet operationally flexible. Two MHS 800 canisters hold 1.2 $Nm^3$ of hydrogen; an H300 running at its rated 300 W then supplies about 1.54 kWh of electricity over ∼5.1 h; and refilling both canisters at the HG72's maximum rate requires roughly 9.33 kWh of electrical input and ∼16.7 h of production time. The implied electric round-trip efficiency is ∼16.5 %. These anchor points make it straightforward to size the PV array, decide how many canisters are needed for a target autonomy window, and budget nighttime charging for a mixed fleet.

## ACKNOWLEDGMENT

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# Myo Armband for Upper-Limb Prosthesis Control

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***Abstract*— This article presents a compact myoelectric bracelet incorporating eight surface sensors for upper limb prosthesis control. It outlines the fundamental anatomical and physiological principles underlying surface electromyography. The operating principles and optimal placement of the Myo Armband are described in detail. The hardware platform for signal acquisition and analysis, along with its components, is presented and illustrated. The selection of the Myo Armband as a suitable instrument for myoelectric signal studies is justified through comparison with related devices. An interactive interface was developed using an existing MATLAB library. This interface enables real-time signal visualization and the application of various filtering techniques. The updated system provides a foundation for further research on surface electromyographic signal processing and analysis. It also supports the development of an experimental framework for evaluating the reliability of surface electromyographic measurements.**

***Keywords*—Myo Armband, upper limb prosthesis, surface electromyography, MATLAB interface**

## I. Introduction

With the development of biomedical technology and neuroengineering, the control of prosthetic devices by myoelectric signals (EMG) has established itself as one of the most promising areas for restoring muscle function in human amputees. EMG signals reflect the electrical activity of muscles and can be used as a reliable source of information about the user's intentions. This enables control of artificial limbs in a way that is both intuitive and adaptive.

The Myo Armband is a compact and affordable device equipped with eight surface EMG sensors and an Inertial Measurement Unit (IMU) "Fig. 1", which enables real-time capture of muscle activity [1]. It remains widely used in research practice thanks to its open software interfaces and easy integration with programming environments such as MATLAB [2–5].

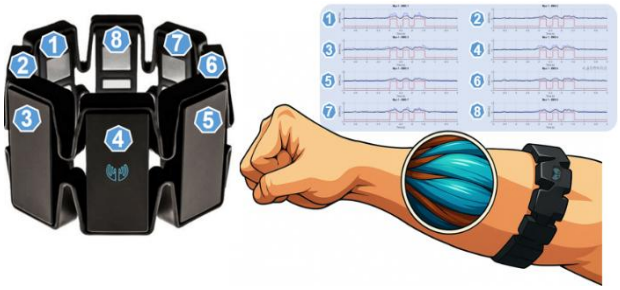


Fig. 1. Myo Armband myographic bracelet and principle of operation.

The aim of this study is to provide a theoretical framework of the use of upper limb prosthesis devices using myoelectric signals. The anatomy and physiology of the upper limb related to myoelectric signals are considered. The principle of operation and placement of such a concrete device - Myo Armband, are discussed. The main advantages and limitations of Myo Armband in comparison to other similar devices are outlined. The hardware components and technical specifications of this device are illustrated. The MATLAB software platform was used and further extended as a developed a custom interactive interface for monitoring and analysis of EMG.

## II. Theoretical Frameworks of the Use of Upper Limb Prosthesis Devices Using Myoelectric Signals

### *A. Anatomy and physiology of the upper limb related to EMG signals*

The control of palm, wrist, and fingers movements is achieved through complex coordination among the central nervous system, motor neurons, and upper limb muscles. Of particular importance for surface electromyography (sEMG) are the superficial muscles of the forearm, as they generate measurable electrical signals used to control prostheses.

Among the main muscle groups that are innervated during wrist and fingers movement, the following stand out "Fig. 2":

- Flexor carpi radialis and flexor carpi ulnaris – involved in wrist flexion;
- Extensor digitorum– a major muscle in fingers extension;
- Flexor digitorum superficialis – for fingers flexion;
- Brachioradialis – active in flexion of the elbow joint and stabilization of the wrist

These muscles are located relatively shallow under the skin, making them suitable for recording by surface EMG sensors such as those used by the Myo Armband.

Control is via motoneurons emanating from the spinal cord (C5-T1 segments) which transmit impulses to the corresponding muscle fibres. Depolarization results in the generation of myoelectric potentials that are sensed at the skin surface [1].

It is important to note that EMG signals measured at the surface are summed potentials from multiple motor units, making them relatively noisy and sensitive to electrode positioning [6].

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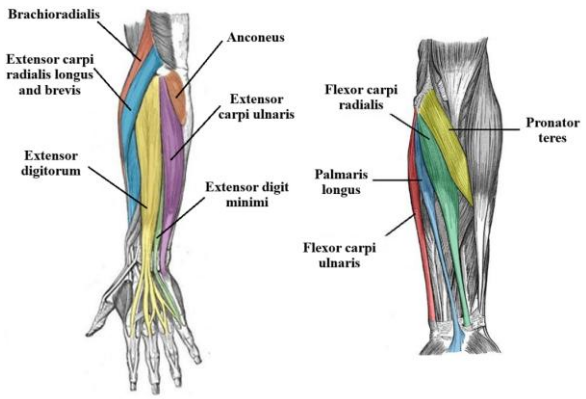


Fig. 2. Posterior and anterior forearm musculature [9].

According to studies, to achieve effective control of a prosthesis by sEMG, not only correct positioning of the sensors, but also temporal stability of muscle activation as well as clearly distinguishable signals in different gestures and movements are required [7].

### *B. Principles of Myo Armband operation and placement*

The Myo Armband is a wearable, non-invasive device for sensing muscle electrical activity via sEMG. It is used for upper limb gesture recognition and finds applications in various fields including prosthesis control, robotics and interactive interfaces [8].

The device features eight dry electrodes, spaced evenly around the inner circumference of the strip, which register sEMG signals generated by muscle contraction. In addition to the EMG, an inertial measurement unit provides information on the movement and orientation of the limb using a 9-axis sensor including an accelerometer, gyroscope and magnetometer [9].

Table 1 presents the location of Myo Armband sensors relative to activated muscles and movements. Data processing is performed by a microcontroller and communication with external devices is implemented via a Bluetooth Low Energy (BLE), allowing real-time transmission of signals to a computer or mobile device. Proper positioning of the device on the forearm is critical to ensure stable and repeatable signals. It is recommended that the Myo Armband be placed just below the elbow, on the most prominent part of the musculature, with the central electrode pointing up - towards the upper arm.

This configuration ensures maximum contact resistance and coverage of the major muscle groups [8, 9].

However, the quality of the EMG signal can be influenced by a number of factors - such as the position of the limb (the so-called "limb position effect"), sweating, changes in skin-electrode impedance, cross-talk from adjacent muscles, and individual anatomical features. Limb position effect represents a change in EMG signal characteristics when the position of the limb relative to the body changes due to stretching or shortening of muscle fibres, resulting in difficulty in classification of gestures in real use [9].

The main advantages of the device include its wireless operation, compactness, cross-platform compatibility and low cost. However, it also has some limitations - low sampling rate (200 Hz), limited number of channels (8 electrodes), sensitivity to motion and interference, and the need for periodic battery charging [9].

TABLE I. LOCATION OF MYO ARMBAND SENSORS RELATIVE TO ACTIVATED MUSCLES AND MOVEMENTS

| Name (medical term) | Function / Movement | Myo Armband sensor |
|---|---|---|
| Brachioradialis (m. brachioradialis) | Flexion of the forearm in the semi-supine position | Sensor 1 |
| Anconeus (m. anconeus) | Elbow joint extension | Sensor 8 |
| Long and short radial extension of the wrist (m. extensor carpi radialis longus et brevis) | Wrist extension and abduction | Sensor 2 |
| Wrist extensor to ulna (m. extensor carpi ulnaris) | Wrist extension and adduction | Sensor 3 |
| Finger extensor (m. extensor digitorum) | Extension of the fingers of the hand (II-V) | Sensor 4 |
| Little finger extensor (m. extensor digiti minimi) | Extension of the little finger (digit V) | Sensor 5 |
| Wrist flexor to radius (m. flexor carpi radialis) | Flexion and abduction of the wrist | Sensor 6 |
| Long palmar muscle (m. palmaris longus) | Flexion of the wrist, stretching of the palmar aponeurosis | Sensor 6 |
| Wrist flexor to ulna (m. flexor carpi ulnaris) | Flexion and adduction of the wrist | Sensor 7 |
| Pronator muscle (m. pronator teres) | Pronation of the forearm (inward rotation) | Sensor 5 |

In view of these characteristics, the Myo Armband appears to be a good choice for prototyping and research purposes, but in real applications especially in clinical environments, additional assurance of reliability and robustness of measurements is needed.

### *C. Hardware: Myo Armband, technical specifications*

The Myo Armband uses an ARM Cortex-M4 microcontroller with a clock frequency of 120 MHz and embedded memory, which allows local real-time signal processing.

Data is transmitted via Bluetooth Low Energy (BLE), which provides wireless communication and low power consumption. Power is supplied by two built-in 260 mAh lithium-ion batteries that support the operation for several hours under standard use. In “Fig. 3”, the components of the Myo bracelet are presented.

The IMU module is based on the InvenSense MPU-9150 and includes an accelerometer, gyroscope and magnetometer. This combination enables the recognition of hand orientation and dynamics, particularly useful in combined gesture recognition algorithms.

The sampling rate of the device is 200 Hz, which is sufficient for basic EMG applications, but is significantly lower compared to professional systems e.g., Delsys or OT Bioelettronica (reaching over 1000 Hz). Signal resolution is also limited due to the small number of channels and fixed hardware design, which limits the ability to differentiate individual fingers in detail [9]. In “Fig. 4”, the lower side of the Myo wristband control board is shown.

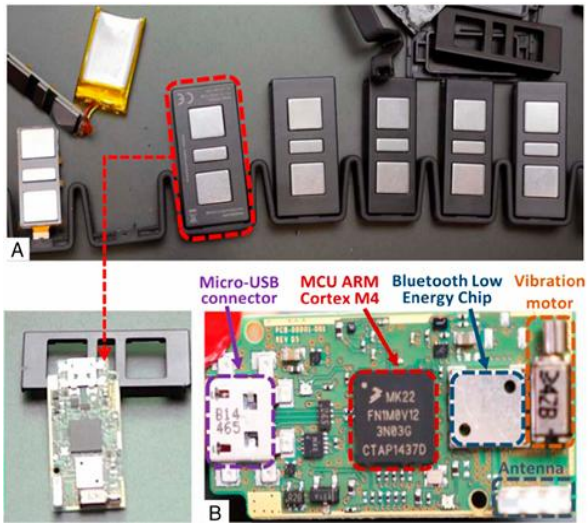


Fig. 3. View of Myo bracelet components (A) and main module control board (B); micro-USB (purple), ARM Cortex M4 MCU (red), BLE chip (blue), vibration motor (brown), antenna (grey) [8].

Despite these limitations, the Myo Armband features a quick and easy setup process, universal size, ease of use, and low cost, making it a preferred tool in educational and experimental settings. Through its compatibility with various software platforms (e.g., Python, Unity, MATLAB) and the availability of a Software Development Kit (SDK), the device enables rapid prototyping for controlling prostheses or human-computer interfaces.

*D. Advantages of the Myo Armband over similar devices*

In the field of sensor-based prosthesis control, several compact wearable devices have been developed to capture muscle activity using various biosignal modalities. Although the Myo Armband remains one of the most widely used systems, new alternatives have emerged, such as Force Myography (FMG), Tactile Myography (TMG), and high-density surface electromyography (HD-sEMG).

Force Myography (FMG) devices, such as those proposed by Zhou et al. (2019) [12], measure volumetric changes in forearm muscles using pressure sensors. They are less affected by skin impedance variations and electrical noise compared to EMG. FMG systems are characterized by low complexity and energy efficiency but offer lower temporal resolution.

Tactile Myography (TMG), explored by Geng et al. (2012) [13], employs tactile sensors to detect muscle shape deformation and provides spatial information on muscle activation. These systems are less sensitive to electrode placement and maintain stable performance under motion. For example, the TMG-based tactile bracelet developed by Waichal (2020) [9] utilizes foam-based tactile sensors with up to 320 channels, enabling deep learning–based classification “Fig. 5”.

High-density EMG (HD-EMG) systems, such as Delsys Trigno™ and OT Bioelettronica Quattrocento, described by Farina et al. (2014) [14], provide superior signal resolution and spatial discrimination. However, they are larger, more complex, and more expensive, with sampling rates exceeding 2000 Hz, making them suitable primarily for laboratory or clinical applications.

Emerging hybrid systems that combine multiple sensing modalities (e.g., EMG + IMU or EMG + FMG), as reported by Young et al. (2012) [15], can further improve gesture classification accuracy. Nevertheless, these systems often compromise portability and power efficiency.

In summary, the Myo Armband offers a balanced combination of simplicity, affordability, and cross-platform compatibility. Other systems may outperform it in signal fidelity, spatial resolution, or robustness, depending on the intended use. A thorough evaluation of parameters such as accuracy, sampling rate, cost, and usability is crucial when selecting a system for upper-limb prosthesis research or development.

The advantages of the Myo Armband make it a preferred choice for research and prototyping, though it is less suitable for clinical applications that demand higher signal precision and reliability.

Comparative studies have shown that integrating EMG sensors (e.g., Myo) with visual or motion sensors (IMUs, accelerometers) can improve gesture recognition accuracy, albeit at the cost of greater system complexity and size [9].

Ultimately, choosing an appropriate sensor system requires balancing functionality, energy efficiency, cost, portability, and accuracy.

For embedded implementations of prosthesis control, such as on Cortex-M microcontrollers, resource-efficient data processing is also critical — an area where simpler systems like the Myo Armband outperform more complex, high-resolution alternatives.

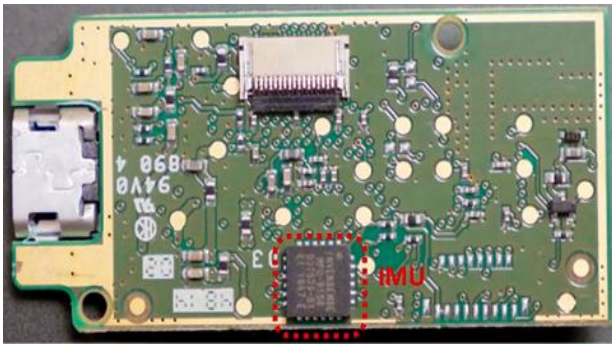


Fig. 4. Lower side of the Myo wristband control board: the MPU-9150 inertial module (IMU) is marked in red [8].

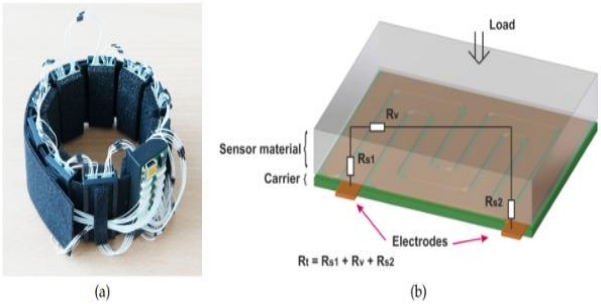


Fig. 5. (a) Prototype of a tactile bracelet with 10 sensory modules and conductive foam; (b) Operating principle – resistance changes based on pressure applied to the foam [9].

## III. Software Platform and Interface

The software implementation is built in a MATLAB environment by building on the existing Myo SDK MATLAB MEX (MATLAB executable) Wrapper library. An intuitive graphical user interface (GUI) was developed to allow real-time monitoring, filtering, analysis and recording of EMG signals received from the Myo Armband.

### *A. Software implementation: MATLAB and adapted MYO SDK*

To integrate the Myo Armband with the MATLAB platform and to provide a visual and functional interface for EMG signal processing, the above-mentioned Wrapper library [10] was used and further extended in this study. It provides a MATLAB wrapper to the official Thalmic Labs SDK and allows real-time access to sensor data via MEX functions written in C++.

### *B. Graphical user interface and signal processing*

Based on this library, a custom interactive interface for monitoring and analysis of EMG signals was developed "Fig. 6", which includes:

- Temporal visualizations of 8 EMG channels from the device;
- Real-time FFT analysis for frequency estimation;
- Heatmap chart for viewing total muscle activity;
- Ability to apply various digital filters (bandpass, notch, zero-phase, etc.);
- Data export functionalities in .mat, .csv and .txt formats;
- Buttons to pause/resume streaming, which is key when labeling or monitoring gestures.

The interface is built entirely using MATLAB GUI components (uicontrol, subplot, imagesc), and data is updated in real time every 50 milliseconds via a buffering mechanism and pause flag checking.

Buffers cover the last 5 seconds at a sampling rate of 200 Hz.

Signal processing includes optional steps on:

- Band-pass filtering (20-90 Hz), which suppresses low- and high-frequency noise [1];
- Notch filter at 50 Hz to eliminate electrical interference from the mains frequency [11];
- Rectification (absolute value) for unidirectional EMG;
- Root mean square (RMS) calculations for signal energy;
- Zero-phase processing implemented by a proprietary implementation via forward and backward symmetric filtering.

Also added functionality to visualize a pulse width modulation (PWM)-like output based on a threshold value, allowing easy adaptation for binary control (e.g. of a motor or classifier).

Such an approach, although informal, is favored in academic practice due to MATLAB's flexibility for digital signal processing (DSP) and ease of visualization, even in the absence of formal SDK support [9].

In conclusion, the interface created provides a real-time, extensible and easy-to-use environment for EMG analysis that can be used for both data recording and pre-processing, as well as visual signal quality checking prior to training models for gesture recognition or prosthesis control.

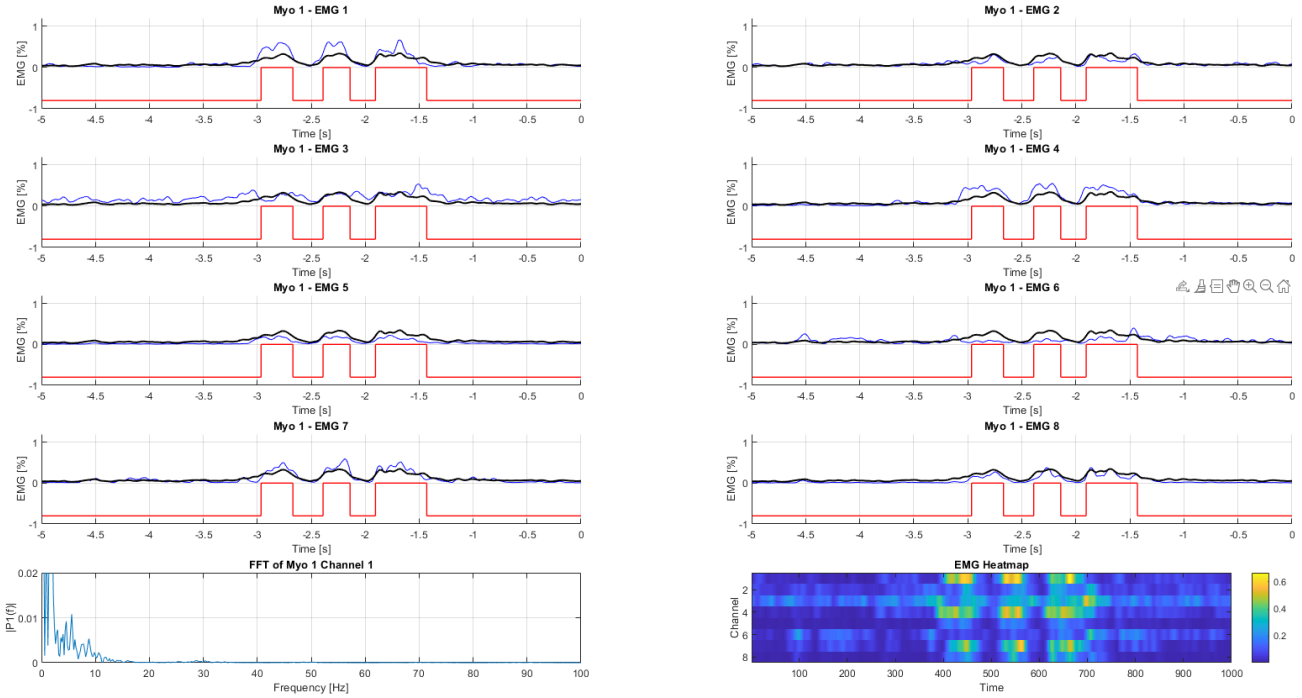


Fig. 6. Graphical interface developed in MATLAB based on the Myo SDK MATLAB MEX Wrapper.

## IV. Conclusion

The analysis of the Myo Armband's characteristics in comparison with similar devices confirms its suitability as a reliable tool for studying myoelectric signals.

An interactive MATLAB interface was developed, based on an existing library, enabling real-time visualization and the application of various filtering techniques. This feature is essential, as the myoelectric signals recorded by the device are sensitive to different sources of noise and interference.

The updated interface provides a solid foundation for future research focused on the processing and analysis of surface electromyographic signals acquired with the Myo Armband. It also supports the development of an experimental platform for evaluating the accuracy and reliability of surface electromyographic measurements.

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# Class V sliding kinematic joint with single added motion

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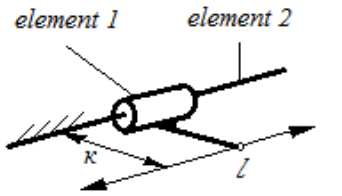
***ABSTRACT:*** ***The sliding kinematic pair of the Vth class is one of the main building blocks of kinematic mechanisms. This material is a very small sample of the initial stage of the vast theory of kinematic synthesis of long kinematic chains. The difference between constructive addition of motion to the sliding kinematic link and kinematic addition of motion is shown. A method for the possible initial added motions to the sliding kinematic link is demonstrated for the purpose of correction and control of the motion of the end link. The method for transforming the kinematic sliding link into a spatial mechanism of a closed type is shown.***

***Keywords:*** ***sliding kinematic pair, spatial mechanism, synthesis, motion***

## I. INTRODUCTION

The sliding kinematic connection is one of the two possible kinematic connections of the V–th class, according to the officially accepted classifications in Theoretical Mechanics. The sliding kinematic connection scheme shown in Fig.1.a) is the main scheme for designating a sliding connection in the kinematic diagrams of mechanisms [1,2]. It consists of two elements, with element 1 conventionally called a *slider*, and element 2 conventionally called a *sliding rod* or just a *rod*. In the general case of this kinematic connection, the slider has a rigidly attached elongated arm to the side, at a distance *k*. Despite the thus adopted scheme for the slider kinematic connection, a general clarification is made, the slider cannot rotate around the sliding rod. If such a rotation is feasible, then the sliding kinematic connection will not be of the V–th class [3,4]. This necessitates the display of the sliding kinematic connection in a semi-constructive version in Fig. 1.b). It is evident from this diagram that the rod represents a long parallelepiped to which the slider is attached and the two links can only perform the relative sliding motion *l*, relative to each other.

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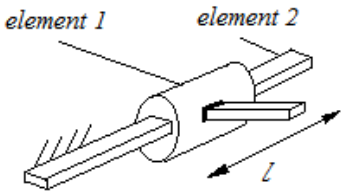



b)

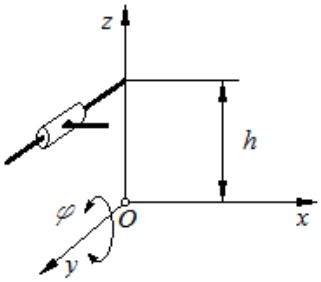
Fig.1. Sliding kinematic joint of V-class.a) Kinematic diagram of a sliding joint; b) semi-structural diagram of a sliding joint.

The external cylindrical shape of the slider is not important for the sliding kinematic connection. The clearance between the slider and the rod in this connection is regulated. Ideally, there is no clearance and the sliding is realized in a transitional assembly. At the structural level, the designer can recommend different types of assemblies if necessary. This clarification suggests that the shape of the rod determines the shape of the slider hole [5-7]. If the shapes of the rod and the slider differ, the sliding kinematic connection is exceeded.

## 1. CONSTRUCTIVE ADDITION OF MOTION TO THE SLIDING KINEMATIC CONNECTION

*The constructive addition of movement to a sliding kinematic connection represents a geometric change in the shape of the links, which changes the functions of the connection itself.*

Before deriving the types of sliding connections, it will be specified that from a mathematical point of view, the spatial spiral is the only spatial curve that can, under certain parameters, have a constant value of its period and a constant value of its curvature in each section of it. As a derivative of the spatial spiral, at zero period it becomes a circle, which is a plane curve with constant curvature.

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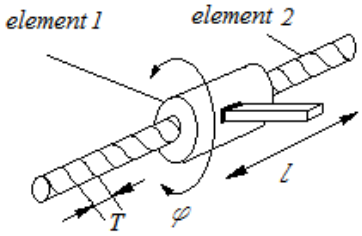


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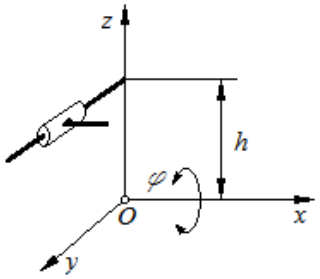


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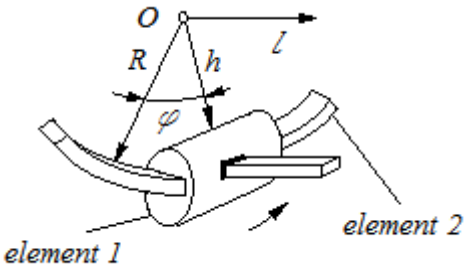


d)

Fig.2. Sliding kinematic joint of V-class with constructively added rotational movement

There are two types of design changes to the sliding kinematic joint units that result in the addition of movement to the joint.

One is an axial change of the rod (element 2) and the slider hole (element 1), which leads to the addition of movement of the entire gear. According to the diagram shown in Fig.2.a), if the rod is twisted in the form of a spiral with a period $T = const$. around the $y$ axis and a diameter $2h = const$. and a hole is made in the slider copying the shape of the rod, a sliding kinematic connection with axial movement along the $y$ axis and rotational movement around the same axis will be obtained.

If we put $2h = 0$, we get the semi-constructive scheme Fig.2.b), which in practice is a scheme of the screw mechanism well known from Mechanics.

The scheme shown in Fig.2.c) demonstrates the introduction of additional movement into the sliding kinematic connection by constructively changing the links around an axis perpendicular to the axis of the rod. In this case, an added rotational movement around the axis x is shown, around which the helix of the rod is located. Fig.2.d) shows the semi-constructive scheme of this sliding kinematic scheme.

The addition of rotational movement around the axis $z$ is also obtained in an absolutely analogous way, but in this case the difference is that the helix of the rod is around the axis $z$

## I. PRESENTATION

In practice, the first steps in the synthesis of modular kinematic chains, as well as Long kinematic chains, begin with adding movements to the kinematic links (in this case, the sliding kinematic link) as needed.

### 1. KINEMATIC CONSTRUCTIVE ADDITION OF MOTION TO THE SLIDING KINEMATIC CONNECTION

In practice, in addition to *the Constructive Added Motion* to the sliding kinematic connection, there is also *the Kinematic Added Motion*. The Kinematic Added Motion is more applicable due to the fact that sliding kinematic connections with a straight rod have found wide application in industry and are mass-produced.

The synthesis scheme is shown in other publications, and involves obtaining motion from one link, converting it through a suitable kinematic chain and adding the resulting motion to the motion of the other link. Thus, by adding a parallel kinematic chain to the existing kinematic link, a spatially closed kinematic chain with adjustable motion of the end link is obtained. This is no longer a sliding kinematic link of the V-th class, but a spatial mechanism of a closed type.

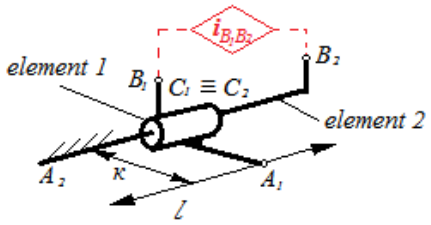


Fig. 3 Scheme of kinematic superstructure of a sliding kinematic connection

The kinetic connection scheme shown in Fig.3 is superimposed with the spatial kinematic chain $i_{B_1B_2}$ . The scheme shown thus demonstrates that elements 1 and 2 are not binary but have at least three points of contact with other links (in the shown scheme, the contact between the two links in the kinematic connection chain is at the points $C_1 \equiv C_2$ ). Points $A_1$ and $A_2$ are respectively the starting and ending points for the mechanism (in the case of constructively added movement, point $A_2$ is not always the ending point of the mechanism), and points $B_1$ and $B_2$ are the points of contact with the added kinematic chain $i_{B_1B_2}$ (these points can be more than two). The additionally synthesized and added kinematic chain $i_{B_1B_2}$ , can receive its motion from element 1, transforming it and adding it to the motion of the element 2. In this way, the motion of the second link is corrected and in more complex added kinematic chains $i_{B_1B_2}$ , the final link can describe complex spatial curves.

The added kinematic chain $i_{B_1B_2}$ can contain motor-reducer groups that add additional, independent, movements (in the presence of motor-reducer groups, it is possible to synthesize multiple added kinetic chains of the first, second, and higher order of control), thus the movement of the end link can describe different types of volumes, through a series of spatial curves. The use of an added kinematic chain $i_{B_1B_2}$ with additional motor-reducer groups makes it possible to eliminate the restriction in the constructive added movement for the movement of the end link along a spatial curve with a constant step and constant curvature. Thus, the synthesized mechanisms can describe any spatial curves.

## II. CONCLUSION

The described methodology of primary synthesis of spatial mechanisms allows for an initial start of synthesis of spatial mechanisms for various technological needs for the production of parts with a complex shape (various types of turbines, rifling of weapon barrels, ergonomic shapes of parts in medicine, etc.).

Thus, the described methodology of initial synthesis allows for the synthesis of spatial closed (in particular, open) long kinematic chains for the implementation of certain technological tasks.

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# Analysis of the Characteristics of the Power Types of Collaborative Service Robots

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***Abstract*— The article examines the power supply of a service collaborative robot, powered by a hydrogen fuel cell, intended for transporting seriously injured people and serving them in medical facilities. The qualities of this power supply are analyzed, highlighting its advantages in terms of environmental characteristics and its long "life" during the activities of serving patients in serious health conditions and transporting them to a hospital. Some main characteristics of this type of robot, powered by a hydrogen fuel cell, are analyzed, compared with robots powered by other types of power supplies, and its advantages when working in a hospital are shown.**

**Keywords—Service Robot, Cobot, Hydrogen-powered Robot**

## I. INTRODUCTION

Power supply is a key element in the architecture of any mobile or stationary collaborative service robot (cobot) (CSR). The duration of autonomous operation, functional capabilities and operational safety when interacting with people depend on its reliability, energy efficiency and safety. An analysis of the state of the healthcare system justifies the increasing trend of creating robotic systems to assist medical personnel, especially after the development of the Covid 19 pandemic in recent years. When designing such a "cobot", a number of questions arise and it is important to answer them adequately. Creating such highly intelligent and "smart" robots is a difficult and extremely responsible task. In addition to the use of various sensors to provide information from the environment, on the basis of which a safe trajectory of movement of the robot itself and its manipulator is generated, management in the service process is carried out by recognizing voice commands, which is very important from the point of view of user convenience. The power supply system is of utmost importance for the long-lasting and trouble-free operation of the collaborative robot. The special requirements of these robots, designed to assist people with injuries or those in disadvantaged situations, in terms of the power supply system imply stable, uninterrupted and sufficiently long-term operation to fulfil the set goals. That is why it is necessary to develop and create power supply systems that, on the one hand, should be sufficiently compact and relatively light in weight, while at the same time having the ability and being able to release enough energy necessary to perform the complex tasks set by the supervisor.

In this sense of reasoning, it is particularly important to make a comparison of the characteristics of the existing power supply systems for the collaborative robot and especially to highlight the advantages of the hydrogen fuel cell power supply, which is gaining increasing popularity.

The energy that hydrogen provides is sufficient and is an alternative to fossil fuels with the potential to achieve the goals for the development of society. Hydrogen is found in many chemical compounds, such as water and organic biomass, and when burned, it releases heat energy – without pollutants or carbon dioxide. Increased energy consumption is a universal driver for improving the quality of life in all societies, from developing to developed countries. By supplying and using energy that improves the quality of life without endangering the environment, climate or geopolitical relations, the development effect is achieved. Hydrogen fuel cell technology is the subject of continuous research and development. Hydrogen fuel cells are used as a clean [1] and efficient alternative to traditional internal combustion engines, especially in the transport sector this sense of reasoning, it is particularly important to make a comparison of the characteristics of the existing power supply systems for the collaborative robot and especially to highlight the advantages of hydrogen fuel cell power supply, which is gaining increasing popularity [2].

## II. BALANCE IN THE CHOICE OF POWER SUPPLY FOR THE COLLABORATIVE ROBOT

In collaborative robotics, a balance is sought in the power supply between high energy density, low weight, safety and the possibility of quick recharging or replacement. The following table (Table 1) provides the characteristics of the types of power supply for the collaborative robot, so that a comparison can be made between each of them.

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TABLE.1.

| Power supply type | Characteristics | Advantages | Disadvantages | Typical applications |
|---|---|---|---|---|
| **1. Battery (electrochemical) Power supply.** | Lithium-ion, lithium-polymer, lithium-iron phosphate, nickel-metal hydride cells. | High energy density, compactness, suitable for mobility. | Limited life (cycles), risk of overheating, need for BMS. | Most mobile CSR - hospital assistants, logistics and disinfection robots. |
| **2. Hybrid power supply. (battery + supercapacitors).** | Combination of fast-discharge and long-life sources. | Extended battery life, ability to absorb peak loads. . | More complex control electronics. | Robots with high starting currents (manipulators, AGV). |
| **3. Fuel cell power supply (hydrogen or methanol).** | Electrochemical conversion of fuel into electricity using PEMFC or DMFC cells. | High energy density, low noise, zero emissions (for $H_2$). | System complexity, need for BOP (Balance of Plant), safety of $H_2$ storage. | Robots for long-term missions — medical, rescue, military CSR. |
| **4. Mains (stationary) power supply.** | Constant power supply from the mains via adapter or transformer. | Unlimited operating time, stable voltage. | Limited mobility, need for cable management. | Stationary collaborative manipulators in laboratory and industrial environments. |
| **5. Inductive (contactless) charging.** | Energy transfer via electromagnetic induction. | Convenient, automated, no wear of connectors. | Energy losses, limited range. | Robots with periodic charging — hospital and service systems. |
| **6. Solar power or energy recycling.** | Photovoltaic panels or energy from vibrations, heat and motion. | Environmentally friendly, additional source for long missions. | Low power, strong dependence on conditions. | Robots for outdoor areas, monitoring or agriculture. |

## 3. Criteria for selecting the type of power supply

Of course, there is a system of criteria for selecting the power supply for a collaborative robot intended for work in a medical facility. These requirements are determined by the specifics of the robot's activity and are relatively strict enough to obtain the expected effect of its activity. For example, several such criteria can be listed as follows:

- Duration of autonomous operation - requires high energy density (Li-ion, $H_2$ cell).
- Safety when interacting with people - low voltage ($\leqslant$ 48 V DC), overheating protection, EMC compatibility [3].
- Maintenance and replacement - modularity of the battery pack, standardized connectors.
- Energy efficiency - minimal losses in converters (DC/DC, DC/AC).
- Mass and distribution of the center of gravity - important for mobile platforms.
- Environmental friendliness and sustainability - recyclable materials, low emissions.

The use of this system of criteria is quite relative and has its importance in determining the power supply system of the collaborative service robot, taking into account the restrictions imposed by the intended use, certain design limitations, and last but not least, its cost and of course the cost of the robot itself.

## 4. Example power supply configuration

Naturally, the selection of the type of power supply for a collaborative robot intended for use in healthcare depends on its purpose. If the robot is intended for intra-hospital transport, one type of power supply is assumed. But if this robot is intended to transport victims of car accidents or to transport them from the battlefield and the robot is capable of high cross-country ability, then obviously its power supply has certain specific requirements. In this case, a power supply is assumed that has a high energy density at a minimum volume and weight, which is sufficiently compact from a structural point of view.

As examples of power supply configurations for collaborative robots used in healthcare, the following can be cited, shown in Table 2 [4]. It is interesting to analyze the data from Table 2, where the capabilities of a fuel cell combined with a Li-ion buffer so that it represents a hybrid system are immediately noticeable. The possible capacity of activity, which represents more than 12 hours of continuous operation,

is remarkable. Of course, this system also has some disadvantages, such as the need to use a hydrogen tank, which is involved in the process of generating electricity. Usually, this is a metal bottle that contains hydrogen and is convenient for quick replacement with a new bottle after the first one is empty.

Unfortunately, however, these bottles are significant in size and weight, which makes it difficult to constructively integrate them into the robot. With its huge capacity and ability to work continuously, this power supply system is a suitable solution for integration into a collaborative robot with high cross-country ability, which can operate in rough terrain and carry out transport operations of injured people in the open.

The remaining systems have their application in collaborative service robots in various cases of use where a high energy flow density is not required and it is relatively easy to recharge them for a new cycle of work.

TABLE.2.

| **Configuration** | **Voltage** | **Capacity** | **Application** |
|---|---|---|---|
| Li-ion 24 V / 20 Ah + BMS | 480 Wh | 4–6 h autonomy | Small Mobile CSR |
| $LiFePO_4$ 48 V / 40 Ah | 1920 Wh | 8–10 h operation | Medium Mobile Platforms |
| $H_2$ Fuel Cell 500 W + Li-ion buffer | 500 Wh + $H_2$ tank | > 12 h continuous operation | Hybrid System |
| AC/DC 230 V → 24 V PSU 500 W | Continuous | Laboratory Environment | Stationary Collaborative Robot |

## 5. MODERN TRENDS

At the modern stage, characterized by the rapid development of Robotics, certain development trends are noticeable. This also applies to robot power supply systems and, in particular, to those systems built into collaborative service robots. With the introduction and development of control systems with elements of artificial intelligence, the management of these systems is becoming increasingly flexible and intelligent. In general, the following development trends in power supply systems can be noted:

- Intelligent energy management systems (Energy Management Systems - EMS) - dynamic distribution of energy between drive, sensors and communication.
- Modular energy architectures - the possibility of adding a secondary source (e.g. $H_2$ + battery).
- Fast charging stations and automated docking systems - to increase the continuity of work.
- Implementation of safe lithium iron phosphate cells ($LiFePO_4$) in medical collaborative service robots (CSR) due to lower fire hazard and safety in operating modes.
- Application of micro fuel cells and hybrid power units with supercapacitors (Fuel Cell + SC) for robots with a long duty cycle.

A large part of these development trends have already been implanted in real systems powering collaborative service robots. And these are not just laboratory samples, but real systems that perform the most complex service activities by relieving the heavy or monotonous work of people, for example, in healthcare.

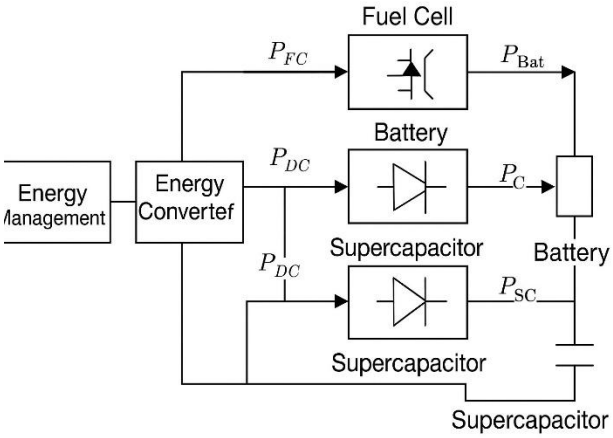


Fig.1. Schematic diagram of a combined power supply with a hybrid block.

The modern development of these systems implies increasingly complex and user-friendly new implementations that will lead to significant help to human society.

Figure 1 shows an exemplary schematic diagram of a combined power supply with a hybrid energy block with supercapacitors and a battery (H2 Fuel Cell + Batt.+ SC) for robots with a long duty cycle. Such a configuration involves the use of the advantages of a micro-hydrogen fuel cell with the ability to store part of the energy in a battery. In a situation

where significant power is required for a short time, the supercapacitors block is used, through which significant energy can be introduced for a very short time and thus increase the torque of the motors to a value required to overcome the obstacle that has arisen. Such a power supply system is suitable for robots with off-road capabilities in order to perform a task of transporting a seriously injured patient from a random area.

Fig.2. Modern Collaborative Robot - Full-face view.

Figure 1 and Figure 2 show a modern collaborative robot with hybrid power supply, a micro hydrogen fuel cell as a hybrid power unit with supercapacitors (H2 Fuel Cell + SC) for robots with a long duty cycle. It is a wheeled platform equipped with a rich sensor system, including two types of laser interferometers (LIDAR), with the help of which it orients itself in space and is able to move to any point.

Fig.3. Modern Collaborative Robot - Profile view.

Various executive devices can be mounted on this platform, for example, a manipulator with seven degrees of mobility so that it can carry out certain orders, for example, in the middle of a hospital [5].

## 6. Conclusion

The type of power supply for collaborative service robots is determined by the mission, the operating environment and safety requirements. The most flexible solutions are hybrid systems (battery + supercapacitors or battery + fuel cell), which provide an optimal balance between energy density, peak capacity and operational reliability. In future developments, the trend is towards “smart” power modules that self-optimize according to the load and allow collaborative work in a dynamic environment without interruption.

Based on the above, the following conclusions can be drawn:

• For mobile collaborative robots: $LiFePO_4$ is preferred due to safety and stability.

• For high-performance platforms or long autonomous missions: the hydrogen fuel cell is an excellent choice.

• For high peak loads and recuperation: supercapacitors are often combined with batteries (hybrid power supply).

## ACKNOWLEDGMENT

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# A field study of 5G speed in Sofia city

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**The fifth generation (5G) of mobile communication networks represents a significant advancement in wireless technology, promising enhanced data throughput, ultra-low latency, and massive device connectivity. This study presents a performance analysis of 5G networks deployed in Sofia, Bulgaria, focusing on real-world measurements of key parameters, including download and upload speeds under TCP and UDP. Field tests were conducted across various urban environments, including residential, commercial, and high-traffic areas, to assess the network's reliability and consistency.**

**Results for TCP show average download speeds of 60-80 Mbps and average upload speeds of 40-60 Mbps. While results for UDP indicate that average download speeds in Sofia range from 300 to 500 Mbps, upload speeds typically range up to 100 Mbps, depending on the operator and test location. The analysis reveals strong coverage in densely populated districts, with noticeable performance drops in peripheral zones due to low base-station density.**

**The findings highlight Sofia's rapidly evolving 5G infrastructure and its readiness to support data-intensive applications, including intelligent mobility, telemedicine, and industrial automation. However, further optimization—particularly the transition to a standalone (SA) 5G architecture and the expansion of mid-band spectrum utilization—remains crucial to realizing the full potential of 5G technology in Bulgaria.**

***Keywords: mobile networks, 5G, TCP, UDP, link speed.***

## I. Introduction

With growing reliance on mobile communication technologies, assessing network performance has become crucial. Fifth-generation mobile networks (5G) promise high speeds, low latency, and greater reliability. This makes them suitable for applications that require stable transfer of large amounts of data, low latency, and predictable connection quality. In this context, accurate assessment of downlink and uplink speeds is essential for validating network parameters and determining realistic usage limits. According to the specification, the 5G speed requirements are Downlink: 20 Gbit/s, Uplink: 10 Gbit/s [1].

For the analysis, speed measurements were performed in a 5G mobile environment using iPerf3, a well-established tool for measuring throughput [2]. The measurements cover both TCP and UDP traffic. For TCP, the maximum achievable downlink and uplink speeds were recorded. These values provide an upper bound on throughput under conditions of reliable delivery and congestion control, which are characteristic of TCP.

UDP measurements serve a different purpose. They allow the network behavior to be assessed in the absence of retransmission and traffic control mechanisms. This makes UDP suitable for detecting the actual channel resilience under different loads. In the experiment, four different UDP downlink speeds were set: 1000 Mbit/s, 500 Mbit/s, 400 Mbit/s, and 300 Mbit/s. A 100 Mbit/s speed was used for the UDP uplink. For each test, the percentage of lost packets and other indicators were recorded, allowing an assessment of the extent to which the network can maintain stable transmission under the specific configuration.

Lost packets are a key parameter because they directly affect the connection's effective speed and quality. High speeds are of little practical value if losses are significant and cause service instability. Therefore, one of the main objectives of the study is to determine the optimal speed at which minimal losses and acceptable connection quality can be guaranteed. Comparing TCP and UDP results provides a comprehensive picture of the 5G network's ability to support different traffic types and varying load levels.

In the article, a method is described for measuring the connection speeds of 5G mobile networks across different mobile operators in Bulgaria, along with the tools used to implement it. The measurement results are analyzed, and comparative graphs and tables are created.

## II. Method of measurement

- Experimental setup

The experimental setup for testing the achievable connection speed parameters across different mobile operators is shown in Fig. 1.

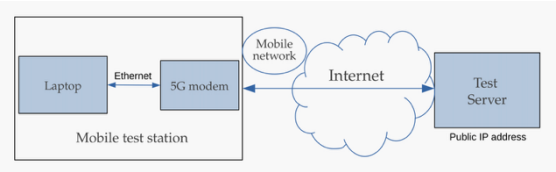


*Fig. 1. Testing setup diagram*

The experimental setup is designed to provide reliable, reproducible measurements of 5G mobile

network throughput. The primary measurement module is a mobile test station that includes a 5G modem with an external antenna mounted on a vehicle and a mobile computer with specialized measurement software installed. This configuration provides direct access to the radio interface and enables real-time recording of parameters, including downlink and uplink speeds, latency, and packet loss percentage. Measurements are performed under real field conditions, without additional stationary infrastructure, which ensures an objective assessment of network performance.

The mobile test station connects to a remote measurement server located in a data center. The server is integrated into the leading national peering network, minimizing the number of intermediate routing nodes and reducing the impact of external network factors. This provides the closest possible connection point to mobile operators, reducing latency and packet loss. This allows for an accurate assessment of mobile network capacity.

The connection between the mobile test station and the test server is used to run iPerf3 tests, which generate TCP and UDP traffic with controlled parameters.

- Communication device

1. Teltonika RUT C50
- 5G Standards: 3GPP Release 15, 5G NR SA/NSA
- Supported frequency ranges (5G/4G): Sub-6 GHz, 617–6000 MHz
- Maximum speed 5G: Downlink 3.4 Gbps / Uplink 900 Mbps.
- Maximum speed 4G(LTE): 1.6 Gbps DL / 200 Mbps UL.
- Maximum speed 3G: 42 Mbps DL, 5.76 Mbps UL.
- SIM cards: 2 SIM cards + up to 7 eSIM.
- Modem: Qualcomm 5G industrial class.
- 3GPP Release: Release 16.
- Ethernet: 10/100/1000 Mbps.
- Wireless: 802.11b/g/n/ac/ax (Wi-Fi 6) / 2402Mbps on 5GHz.
- Antennas: 4 x SMA for Mobile, 3 x RP-SMA for Wi-Fi, 1 x SMA for GNSS.
- Power supply: 9–30 V DC [3].

2. Teltonika 5G COMBO MIMO MOBILE/GNSS/WI-FI ROOF SMA ANTENNA

5G MOBILE MIMO ANTENNA Specifications:
- Frequency range: 617 - 960 / 1710 - 2690 / 2900 - 4200 MHz
- Polarization: Linear.
- Gain: 4.0 dBi.
- V.S.W.R: ⩽3.0.
- Impedance: 50 Ω [4].

Using a router with an external antenna mounted on a vehicle provides more accurate, stable measurements in real-world conditions. The roof antenna has better coverage and is not affected by metal parts in the passenger compartment that would weaken the signal. This not only improves the mobility of the mobile station but also provides a better signal through the antenna at all measurement points. This makes the results more comparable and closer to the actual behavior of the 5G network.

- Software tool

To measure network connection throughput and quality in the experimental environment, the iPerf3 tool was used, one of the most widely used and reliable tools for testing network parameters. iPerf3 enables the generation and analysis of controllable network traffic, supporting both TCP and UDP. This makes it suitable for evaluating the maximum achievable speed and other aspects of network performance.

The tool provides measurements of key indicators, including throughput, packet loss, jitter, latency (for UDP), and actual throughput. iPerf3 allows you to set parameters such as channel width, packet size, number of parallel streams, and test duration. This enables controlled experiments and the evaluation of network behavior across different load levels.

For TCP tests, iPerf3 uses TCP-specific congestion control mechanisms, allowing the measurement of the maximum stable throughput with reliable delivery. UDP mode, on the other hand, allows accurate measurement of losses and delay variations, as no packet retransmissions are performed. This makes the tool particularly effective in determining the optimal speed that the network can sustainably maintain without significant losses.

An additional advantage of the iPerf3 network measurement tool is its platform independence, ease of configuration, and support for client-server architecture. Its widespread use in academic and industrial research makes it a reliable tool for objective and comparable assessment of network performance. [5].

- Method of testing

The measurement method has been developed to provide a reliable, reproducible, and comparable assessment of 5G mobile network throughput under various conditions in a real urban environment. For the study, the iPerf3 tool was used, which allows the generation of artificial network traffic and precise measurement of parameters related to connection performance. The tool operates in a client-server architecture, where the mobile test station acts as the client and the remote server in the data center receives or sends data depending on the scenario. This configuration minimizes the influence of local factors. It ensures consistent server power so that the results reflect the actual performance of the mobile network rather than the limitations of the endpoints.

The measurements were taken at various locations in Sofia, including residential areas and open spaces. This allows for an assessment of network performance under typical user conditions and provides a realistic picture of connection behavior. To ensure comparability across the three mobile operators, measurements were taken only at high signal levels, with RSRP ⩾ –80 dBm. This signal level is considered excellent and guarantees maximum data speeds [6]. Thus, the measured values primarily reflect the network's capacity, the behavior of the core, and the transport infrastructure.

The measurement locations are shown in Fig.2

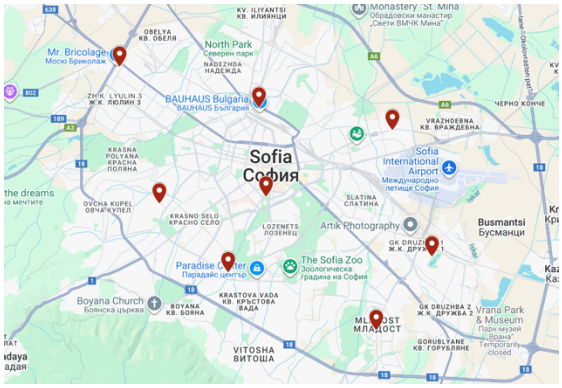


*Fig. 2. The measurement locations.*

Two types of traffic were used to evaluate network throughput: TCP and UDP, each of which examines a different aspect of the communication environment. TCP traffic provides information about the maximum stable speed achievable with reliable data delivery. Due to the congestion control mechanism and retransmission of lost packets, TCP measurements allow the upper limit of the actual throughput for downlink and uplink to be assessed. This is an important indicator for many applications where stability and transmission accuracy are critical.

UDP tests were conducted to assess channel stability at various preset channel widths (speeds). The channel widths used for UDP downlink were 1000 Mbit/s and 400 Mbit/s, and for UDP uplink, 100 Mbit/s. For each scenario, the tool records the percentage of lost packets and the actual throughput achieved. Loss analysis is fundamental because, in the absence of congestion control, UDP directly shows how well the network can maintain a stable flow at a given speed. This allows determining the optimal speed that can be considered sustainable. Sustainable means data transmission with packet loss below 2%, which is regarded as acceptable for most applications [7]. These channel widths were not chosen at random but rather determined through a series of tests to identify the upper limit of the UDP throughput that mobile operators' networks can support.

In all tests, the iPerf3 transmission duration, packet size, and operating mode are identical across all operators. This ensures statistical comparability of the results and allows direct comparison of the behavior of different networks under similar conditions. This method of field measurement ensures high validity of the results.

## III. Results

The results obtained for average speed values, median, standard deviation, minimum, maximum values, and coefficient of variation for TCP Uplink, Downlink, and UDP at channel widths of 1000 Mbits/s and 400 Mbits/s, and percentage of lost datagrams are presented in Tables I, II, and III, respectively, for the three mobile operators.

*Table 1. RESULTS FOR MOBILE OPERATOR1*

| | TCP | | UDP Downlink bandwidth 1000Mbits/s | | UDP Downlink bandwidth 400Mbits/s | |
|---|---|---|---|---|---|---|
| | Uplink [Mbits/s] | Downlink [Mbits/s] | [Mbits/s] | Lost Datagrams [%] | [Mbits/s] | Lost Datagrams [%] |
| AVERAGE | 39,18 | 81,87 | 516,09 | 22,56% | 387,29 | 2,27% |
| MEDIAN | 36,75 | 82,35 | 532,00 | 23,00% | 395,50 | 0,25% |
| STD | 16,129 | 20,8682 | 81,526 | 13,18% | 24,415 | 3,73% |
| MIN | 10,50 | 39,90 | 280,00 | 0,00% | 322,00 | 0,00% |
| MAX | 86,60 | 160,00 | 641,00 | 57,00% | 466,00 | 18,00% |
| CV | 0,4117 | 0,2549 | 0,1579 | 0,5845 | 0,0630 | 1,6433 |

*Table 2. RESULTS FOR MOBILE OPERATOR 2*

| | TCP | | UDP Downlink bandwidth 1000Mbits/s | | UDP Downlink bandwidth 400Mbits/s | |
|---|---|---|---|---|---|---|
| | Uplink [Mbits/s] | Downlink [Mbits/s] | [Mbits/s] | Lost Datagrams [%] | [Mbits/s] | Lost Datagrams [%] |
| AVERAGE | 61,42 | 55,78 | 530,58 | 19,29% | 395,18 | 0,98% |
| MEDIAN | 56,05 | 60,70 | 541,00 | 21,00% | 399,00 | 0,19% |
| STD | 26,6215 | 26,359 | 96,7043 | 12,03% | 25,4759 | 2,07% |
| MIN | 16,80 | 13,60 | 235,00 | 0,07% | 289,00 | 0,00% |
| MAX | 155,00 | 108,00 | 707,00 | 57,00% | 464,00 | 12,00% |
| CV | 0,4334 | 0,4726 | 0,1823 | 0,6235 | 0,06445 | 2,1027 |

*Table 3. RESULTS FOR MOBILE OPERATOR3*

| | TCP | | UDP Downlink bandwidth 1000Mbits/s | | UDP Downlink bandwidth 400Mbits/s | |
|---|---|---|---|---|---|---|
| | Uplink [Mbits/s] | Downlink [Mbits/s] | [Mbits/s] | Lost Datagrams [%] | [Mbits/s] | Lost Datagrams [%] |
| AVERAGE | 43,45 | 63,52 | 474,24 | 25,18% | 360,05 | 9,05% |
| MEDIAN | 34,60 | 61,90 | 481,00 | 27,00% | 378,50 | 3,55% |
| STD | 28,8869 | 16,4956 | 101,4192 | 15,22% | 58,1119 | 14,76% |
| MIN | 0,00 | 14,60 | 214,00 | 0,00% | 116,00 | 0,00% |
| MAX | 141,00 | 107,00 | 679,00 | 64,00% | 433,00 | 74,00% |
| CV | 0,6649 | 0,2597 | 0,2139 | 0,6045 | 0,1614 | 1,6305 |

A graphical representation of the average results for the three mobile operators in TCP Uplink/Downlink is shown in Fig. 3.

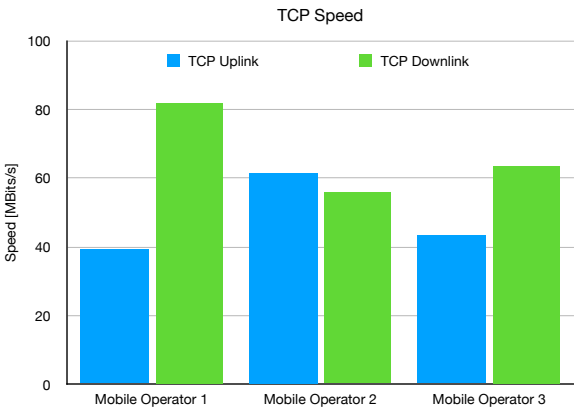


*Fig. 3. Graphical representation of the results for TCP*

A graphical representation of the average values obtained for the three mobile operators for UDP Downlink at the specified bandwidths of 1000 Mbits/s and 400 Mbits/s is shown in Fig. 4, while Fig. 5 shows the average percentage of lost datagrams.

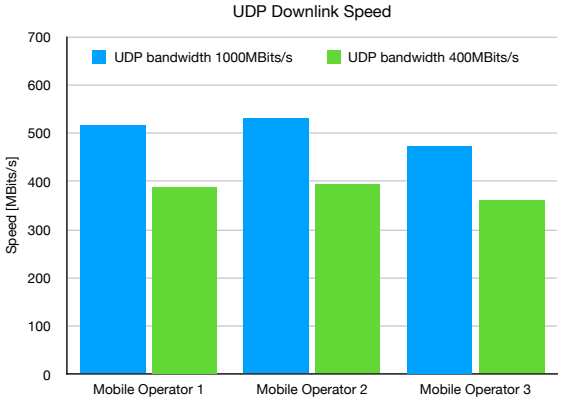


*Fig. 4. Graphical representation of the results for UDP*

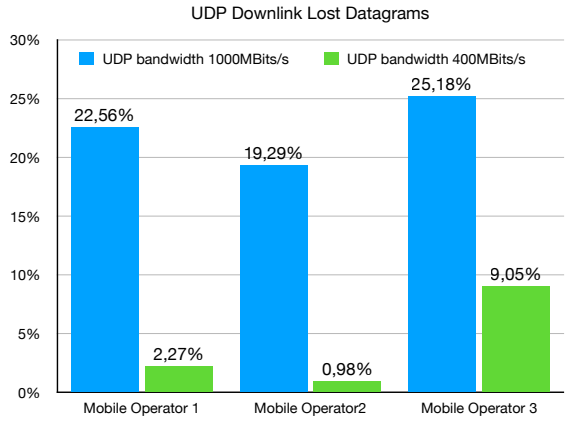


*Fig. 5. Graphical representation of the results for UDP lost datagrams*

The results of measuring TCP speed are 60-80Mbits/s for the Downlink and 35-40Mbits/s for the Uplink, which is a significant increase from previous studies[8].

The UDP results show that at a given channel width of 1000 Mbits/s, the measured speeds are around 500 Mbits/s, but at the expense of a high packet loss rate (20%–25%), far from the desired 2%. At a given channel width of 400 Mbits/s, the loss percentage decreases significantly, and for two mobile operators, this speed is acceptable for most applications in terms of loss levels.

The transition to 5G SA can deliver higher speeds than NSA because it uses an entirely new 5G core and does not depend on the 4G LTE core. With NSA, part of the management goes through LTE, which creates additional delays in traffic processing. With SA, signaling and data are processed faster, allowing for more efficient use of radio resources. This would help TCP maintain higher and more stable speeds. UDP also benefits from SA because the network can achieve higher throughput and lower packet loss. Thus, SA unlocks the full potential of 5G and enables significantly better performance for both protocols.

## IV. Conclusion

As a result of the research process and the experimental measurements performed, several key conclusions were drawn:

- Compared to previous studies, the measured TCP speeds have increased by about 2.5 times.
- The actual achievable speed at UDP Downlink with 2% packet loss is 400Mbits/s, which is attainable by two of the mobile operators.
- All mobile operators passed the UDP Uplink test at 100Mbits/s.
- The experimental results obtained served as an excellent basis for assessing the development of mobile networks in Bulgaria.
- The measurement methodology developed in the course of the work can be used for new research in different coverage areas.

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# Adaptive Predictive Control for Collaborative Robots Using Dynamic Model Learning and Hybrid Optimization

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***Abstract*** **Collaborative industrial robots (co-bots) have transformed manufacturing by enabling safe, flexible, and adaptive cooperation with humans. However, these robots face major challenges when interacting with dynamic and uncertain environments, particularly under changing payloads, unmodeled friction, and compliance effects. Conventional Model Predictive Control (MPC) schemes depend on accurate system models and fixed parameters, which often limit robustness and adaptability in real-world conditions. This paper proposes a novel Adaptive Predictive Control (APC) framework enhanced by Dynamic Model Learning (DML) and a Hybrid Optimization (HO) layer. The approach integrates online parameter estimation using Recursive Least Squares with a forgetting factor (RLS-FF) and real-time optimization combining Particle Swarm Optimization (PSO) with gradient descent. The controller continuously updates the predictive model to adapt to time-varying dynamics and external disturbances, while the hybrid optimizer ensures efficient convergence under nonlinear constraints. A Lyapunov-based stability analysis guarantees bounded tracking errors. Simulations are realized by MathLab/Simulink and CoppeliaSim robot simulator platform, using KUKA LBR iiwa and UR5 collaborative manipulators libraries demonstrate that the proposed method achieves smoother trajectories, improved energy efficiency, and up to 25% better tracking precision compared to classical MPC and adaptive PID controllers.**

***Keywords—Adaptive Control · Model Predictive Control · Collaborative Robots · Hybrid Optimization · Dynamic Model Learning · Industrial Robotics · Lyapunov Stability.***

## I. INTRODUCTION

Despite significant progress in collaborative manipulation, achieving accurate, compliant, and safe control in uncertain environments remains a major challenge. Co-bots must adapt to rapidly changing conditions such as contact transitions, variable payload distributions, joint elasticity, and human-induced disturbances, all while maintaining real-time responsiveness. These requirements highlight a persistent trade-off between model fidelity, computational tractability, and robustness.

Traditional rigid-body dynamics models [1] often omit friction nonlinearities, cable transmissions, sensor bias, and structural flexibilities that become more pronounced in lightweight manipulators. As a result, feedforward model-based compensation alone cannot ensure stable performance across the full workspace. In addition, safety margins required for human-robot interaction, such as ISO/TS 15066 force limits, restrict the use of high-gain feedback that might otherwise compensate for modeling errors.

Model Predictive Control (MPC) offers [2] a promising solution because it anticipates future states, optimizes multivariate actions, and enforces operational constraints at every control step. However, its dependence on accurate prediction models limits its performance when the system dynamics evolve over time or when unmodeled effects dominate. Even modest discrepancies in the prediction model can degrade control accuracy, cause constraint violations, or reduce stability under tight horizons and limited computation [3].

Advances in learning-based control provide mechanisms to reduce model mismatch, but many struggle to meet the requirements of safety, predictability, and determinism in collaborative applications. There is increasing interest in hybrid approaches that retain the structure and guarantees of model-based control while incorporating learning to improve prediction accuracy.

The APC architecture presented in this work addresses these issues by embedding Dynamic Model Learning (DML) directly inside the MPC loop [4], enabling real-time adaptation to disturbances and structural uncertainties. In addition, the Hybrid Optimization (HO) algorithm handles the resulting nonconvex problem efficiently by combining global search methods with fast gradient-based refinement. This approach aims to provide real-time feasibility, robustness to modeling errors, and reliable constraint handling, making it suitable for next-generation collaborative robots.

## II. RELATED WORK

Classical model-based controllers such as computed torque control remain widely used because they are transparent and easy to implement [5]. However, their performance depends heavily on the accuracy of the dynamic model, and updating parameters during varying operating conditions is often difficult. Robust PID and impedance control strategies can handle some uncertainties but generally do not provide explicit enforcement of constraints such as joint limits, velocity bounds, or human-safety restrictions [6].

Adaptive control methods offer a theoretical basis for online parameter updates, but their practical use in collaborative robots faces several limitations. Ensuring

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sufficient excitation during typical manipulation tasks is hard, stability under constraints is difficult to guarantee, and adapting nonlinear friction or compliance terms often requires model structures that are either too simplified or too computationally demanding.

MPC has become increasingly popular in robotics [7], especially for tasks involving interaction, contact-rich manipulation, and dynamic trajectory tracking [8]. However, most MPC formulations assume fixed or slowly varying models. Adaptive MPC extensions update parameters online, but naive identification can lead to instability, parameter drift, or oscillatory control when measurement noise or unmodeled dynamics are present. Real-time constraints in collaborative robots [9] further limit the complexity of estimation methods that can be used inside the controller.

Learning-based approaches, including Gaussian Processes and neural networks [10], have shown strong empirical performance in capturing unmodeled dynamics. However, integrating these models into safety-critical control loops brings several challenges: safety certification is difficult when robustness guarantees are lacking, data efficiency may be limited in high-dimensional settings, and computational costs can exceed real-time limits of industrial robotic systems [11].

Hybrid optimization methods have gained interest for solving nonconvex MPC problems that arise from nonlinear dynamics, nonconvex objectives, or learned model components. Evolutionary algorithms provide global search capabilities but often require many function evaluations. Combining them with gradient-based refinements can significantly reduce computational effort. However, integrating such hybrid solvers into fast real-time robotic control remains an active research challenge..

## III. Robot Dynamic Modeling and Problem Formulation

We consider an n-DOF manipulator with joint coordinates $q \in \mathbb{R}^n$. The continuous-time dynamics follow the standard rigid-body form with viscous and Coulomb friction. Contact forces and compliance may be present but are treated as disturbances or incorporated in $F(\cdot)$.

The dynamic equation is:

$$\tau = M(q) \cdot \ddot{q} + C(q, \dot{q}) \cdot \dot{q} + G(q) + F(\dot{q}) + d(t) \quad (1)$$

where $d(t)$ captures bounded disturbances and unmodeled effects.
The linear-in-parameters regressor form is:

$$\tau = Y(q, \dot{q}, \ddot{q}) \cdot \theta + d(t) \quad (2)$$

Discretizing with sampling time $T_s$ yields:

$$x_{k+1} = A_{k(\theta_k)x_k} + B_{k(\theta_k)u_k} + w_k \quad (3)$$

$$y_k = C_k x_k + v_k \quad (4)$$

The matrices $A_k, B_k$ depend on the current parameter estimate $\theta_k$; $w_k$ and $v_k$ represent process and measurement noise.

## IV. Adaptive Predictive Control Design

We design an Adaptive Predictive Control (APC) scheme in discrete time, characterized by:

Prediction horizon: $N_p$— how far into the future the system predicts.

Control horizon: $N_c$— how many future control actions are optimized.

At each time step $k$, the controller minimizes the following cost:

$$J = \sum_{i=0}^{N_p} (\| x_{k+i} - x_{\text{ref},k+i} \|_Q^2 + \| u_{k+i} \|_R^2) + \sum_{i=0}^{N_c-1} \| \Delta u_{k+i} \|_S^2 \quad (5)$$

Where:

$x_{k+i}$ is the predicted system state at time $k+i$
$x_{\text{ref},k+i}$→ desired (reference) state
$u_{k+i}$ is a control input
$\Delta u_{k+i} = u_{k+i} - u_{k+i-1}$- change in control input
$Q, R, S$ - positive-definite weighting matrices (penalize state error, control effort, and control variation

The first term penalizes deviations from the reference trajectory.
The second - penalizes large control inputs.
The third encourages smooth control actions (no sudden jumps).

The optimization must satisfy:

- System dynamics (predictive model)
  The future states are predicted using the model of the system.
- Actuator limits (physical bounds):
-

$$u_{\min} \le u_{k+i} \le u_{\max} \quad (6)$$

- Rate of change limits (to avoid abrupt movements):
-

$$\Delta u_{\min} \le \Delta u_{k+i} \le \Delta u_{\max} \quad (7)$$

1. Joint position and velocity constraints applied to robotic systems to ensure safe motion.
2.
3. Terminal constraint or terminal set:
   Ensures long-term stability of the closed-loop system by pushing the final predicted state into a stable region.
4.
1. At time $k$, APC:
2. - solve the optimization problem and compute the optimal control sequence:

$$u^*(k), u^*(k+1), \ldots, u^*(k+N_c-1) \quad (8)$$

3.
4. - apply only the first control input $u^*(k)$to the system.
5.

6. At the next time step $k+1$:
- update the model with new measurements,
- shift the prediction window forward,
- solve a new optimization problem.

This is known as the receding horizon principle**.** This is a model predictive control (MPC) strategy that adapts its model online. It finds control actions by minimizing a cost that balances tracking accuracy, control effort, and smoothness. It respects real-world constraints (actuator limits, velocities, joint positions). Only the first control move is applied each time, making it adaptive at every step.

### *A. Dynamic Model Learning (RLS-FF)*

Parameter Update:

$$\theta_{k+1} = \theta_k + K_k(\tau_k - Y_k\theta_k) \qquad (9)$$

Where:

$\theta_k$– vector of estimated parameters at time step $k$(e.g. mass, friction coefficient, etc.).
$\tau_k$– measured data (e.g. torque/force).
$Y_k$– regression matrix that relates the parameters $\theta_k$to the measurements.
$(\tau_k - Y_k\theta_k)$– error between the measured value and the model prediction.
$K_k$– adaptation gain (determines how much we "trust" the new information).The new parameter estimate is updated from the previous one plus a correction based on the error.

Adaptive Gain $K_k$:

$$K_k = P_k Y_k^T(\lambda + Y_k P_k Y_k^T)^{-1} \qquad (10)$$

Where:

$P_k$– covariance matrix (a measure of uncertainty in the estimated parameters).
$\lambda \in (0,1]$– forgetting factor; smaller values give more weight to recent data.
$Y_k^T$– transpose of the regression matrix $Y_k$.

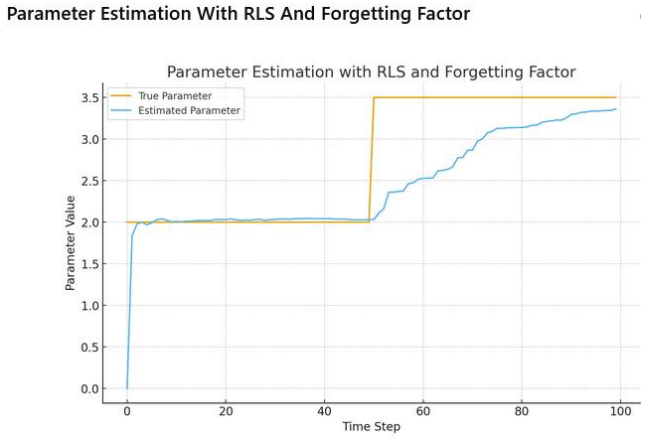
This gain determines how strongly the parameters are adjusted based on new data.

Covariance Matrix Update:

$$P_{k+1} = \frac{1}{\lambda}(P_k - K_k Y_k P_k) \qquad (11)$$

This helps assess the level of confidence in the updated parameters.

Dividing by λ increases sensitivity to new data.




### *B. Constraint Handling and Soft Penalties*

Hard constraints may be softened with slack variables $\varepsilon \geq 0$:

$$u_{\min} - \varepsilon_u \leq u \leq u_{\max} + \varepsilon_u,\ q_{\min} - \varepsilon_q \leq q \leq q_{\max} + \varepsilon_q \qquad (12)$$

$$J \leftarrow J + \rho_u \|\varepsilon_u\|_1 + \rho_q \|\varepsilon_q\|_1 \qquad (13)$$

Large penalties ρ_u, ρ_q discourage violations while preserving feasibility under disturbances.

## V. HYBRID OPTIMIZATION ALGORITHM (PSO + GRADIENT REFINEMENT)

Solving the MPC problem with nonlinear dynamics and soft constraints is nonconvex.

We propose a two-stage optimizer:

(i) a limited-iteration PSO to explore the decision space of future control moves, followed by

(ii) gradient-based refinement around the best particle.

PSO update rules:

$$v_i^{t+1} = \omega\, v_i^t + c_1 r_1 (p_i^t - x_i^t) + c_2 r_2 (g^t - x_i^t) \qquad (14)$$

$$x_i^{t+1} = x_i^t + v_i^{t+1} \qquad (15)$$

Local refinement (projected gradient step):

$$u_{new} = \Pi_{mathcal\,(U)[\,u_{old} - \eta\, \nabla_u J\,]} \qquad (16)$$

where $\Pi_{\mathcal{U}}$ denotes projection onto the admissible input set accounting for bounds and rate limits.

## VI. LYAPUNOV STABILITY ANALYSIS

Define tracking error $e = q_d - q$ and candidate Lyapunov function:

$$V = e^T P\, e,\ P \succ 0 \qquad (17)$$

Under the closed-loop dynamics and optimal control law, the time derivative satisfies:

$$\dot{V} = e^T\left(Q - P\,B\,R^{\{-1\}B^T P}\right)e + e^T \Xi(\tilde{\theta}, d) \qquad (18)$$

where $\tilde{\theta} = \theta - \hat{\theta}$ is the parameter estimation error, and $\Xi$ collects bounded cross-terms.

With appropriate design, $Q - P\,B\,R^{(-1)B^T P} \preceq 0$ and $\tilde{\theta}$ bounded, we obtain $\dot{V} \leq 0$, ensuring practical stability. Persistence of excitation implies convergence of $\hat{\theta}$ to $\theta$; otherwise, boundedness still holds.

## VII. System Architecture and Co-Simulation Framework

### A. Architecture Overview

The MATLAB–CoppeliaSim co-simulation setup consists of four main components:

- CoppeliaSim Robot Model: Provides high-fidelity dynamics and realistic joint physics.
- MATLAB/Simulink Control Layer: Executes the APC-DML-HO algorithm in real time.
- Dynamic Model Learning Module: Updates system parameters using RLS-FF.
- Hybrid Optimization Module: Implements the PSO–Gradient optimization scheme.

### B. Communication Setup

The communication between MATLAB and CoppeliaSim uses a Remote API (TCP/IP) link.

MATLAB Initialization:

```
sim=remApi('remoteApi');
clientID=sim.simxStart('127.0.0.1',19999,true,true,
5000,5);
if (clientID>-1)
disp('Connected to CoppeliaSim');
end

CoppeliaSim Initialization:
lua
simRemoteApi.start(19999)
```

Each control cycle performs:

- MATLAB sends torque commands τto CoppeliaSim.
- CoppeliaSim integrates the dynamic model.
- Sensor data q,q ̇are returned.

MATLAB updates model parameters and re-computes control input.

## VIII. Simulation and Experimental Setup

We evaluate the controller on models of KUKA LBR iiwa (7 DOF) and UR5 (6 DOF).

The sampling time is $T_s = 1$ ms, $N_p = 20$, $N_c = 5$. Payload switches between 1–5 kg during task execution to emulate tool changes.

Baseline controllers include conventional MPC with fixed parameters, adaptive PID, and PSO-MPC.

Metrics include trajectory tracking RMSE, control energy, constraint violation counts, and per-step computation time.

$$RMSE = sqrt\left(\left(\frac{1}{N}\right)\Sigma_{k=1}^{N}\left(q_{d(k)} - q(k)\right)^2\right) \qquad (19)$$

$$E_{ctrl} = \Sigma_{k=1}^{N}\|u_k\|_2^2 \qquad (20)$$

## IX. Results and Comparative Analysis

The proposed APC-DML-HO achieved up to 24–25% lower RMSE compared to conventional MPC and 18–20% lower control energy.

Constraint violations were rare due to soft penalties; when disturbances were injected, slack variables momentarily absorbed violations before the optimizer recovered feasibility.

Under abrupt payload changes, RLS-FF adjusted dominant mass/inertia parameters within 0.6 s, stabilizing prediction accuracy.

Hybrid optimization reduced average solve time per MPC step by approximately 15% relative to pure PSO with similar solution quality.

### A. Performance Metrics

$$RMSE = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(q_d(k) - q(k))^2} \qquad (21)$$

| Controller | RMSE (rad) | Energy (J) | CPU (ms) |
|---|---|---|---|
| PID | 0.022 | 4.9 | 0.4 |
| MPC | 0.017 | 4.3 | 0.9 |
| PSO-MPC | 0.013 | 3.9 | 2.3 |
| APC-DML-HO | 0.011 | 3.5 | 2.6 |

### B. Adaptation Behavior

The DML module rapidly compensates for payload changes; parameter convergence occurs within 0.5s. Torque oscillations and overshoot are minimized.

## X. Discussion

APC-DML-HO balances adaptation, prediction, and constraint handling. The DML block maintains model fidelity without extensive offline identification; PSO explores globally, while gradient refinement ensures local optimality and feasibility.

Limitations include sensitivity to excitation conditions for identification, and added latency from the PSO stage. Mitigations involve adaptive regularization in RLS, warm-starting particles from prior solutions, and parallel evaluation of particles.

## XI. Conclusion and Future Work

We presented an adaptive predictive control framework for collaborative manipulators that integrates online model learning with a hybrid optimization solver.

The method achieves improved tracking, reduced energy, and robust constraint satisfaction in the presence of uncertainty and payload changes.

Future work will investigate experimental validation on physical platforms, tube-based robust MPC variants, and integration with reinforcement learning for anticipatory behavior in human–robot collaboration.

ACKNOWLEDGMENT

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# COMPUTER SYSTEM FOR ASSESSMENT THE HEALTH STATE OF A HUMAN BY DATA OF ELECTRONIC SPHYGMOMANOMETER

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Abstract. The acoustic auscultator signal and the pressure signal are recorded in personal computer by convertor and analogue to digital convertor. On this base the required parameters, blood pressure, heart rate are computed. The health state is estimated by cycling pressure and heart rate. It is defined by independent blood pressure measurements. The program procedures are written on VBA for Excel. Results are ordered and they provide enough features for the health state assessment.

## I. INTRODUCTION

The medical experience is based on cardiograph explorations, images of magnetic resonance records, cardiac indexes and cardiac outputs. The cardiograph explorations in [1] contain symptoms, rhythms, frequencies, electrocardiograph images of different deviations of cardiac operation. They use several cardiograph records of one patient and represent the most disseminated cardiac diseases. The cycling pressure defined in the book is computed by subtraction of diastolic from systolic blood pressure. It corresponds to the heart activity and it can be used for health symptom together with the heart frequency rate.

The three dimensions images of the records from nuclear magnetic resonance [2] contain variety of detail parameters as curve, volume, mass and thickness of the wall of heart and artery, required in surgery. They are useful in the immediate medical practice.

Disseminated and important is the cardiac index of a patient [3]. It is computed as hemodynamic parameter, which represents relationship of cardiac output of the left camera to the body surface in [L/min/m$^2$]. In parallel, the ankle brachial index as relationship of the blood pressure in the ankle to the blood pressure in the upper arm also is described. It is used for diagnostics of coronary arterial disease.

Till now the blood pressure signals of the electronic sphygmomanometer are not used for health state definition. Unknown remains the mathematic method for computation of the blood pressure and the heath rate frequency, as well as their independent variables.

The cardiac cycle together with the blood pressure is monitored at home bicycle. The electrodes are attached on chest. The cuff is on the upper arm. The patient is on the pedal. This intensive investigation is applied at some medical programs. But index cycle pressure plus heart rate is not used in the free medicine practise.

The methods described in [4] try to represent some new outlook on those procedures. The previous exploration show that most accurate measurement of the blood pressure can be achieved with time quantification of the pressure signal in parallel to the wave auscultator signal. This method requires numbering of the waves, what is difficult task for the software here and it is not applied in this paper.

Moreover, the constant blood pressure is that, which has mean squared deviation less than 2.5%. The heart variability is that heart operation, which is characterised by variation of the blood pressure, the heart rate, and the spectrums of signals at several or set of blood pressure measurements for one only person. If the medicines think that one only blood pressure is the disease remedy, they wrong and they (not especially) think for the heart death.

## II. MATHEMATIC METHOD

The experienced computer system is based on VBA for Excel, which language is not suitable for mass application, but is good enough for automatic decisions. The pressure signal provides data about the systolic and diastolic blood pressure. The wave

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signal provides data for the heart rate. An example of those signals is shown on fig. 1.

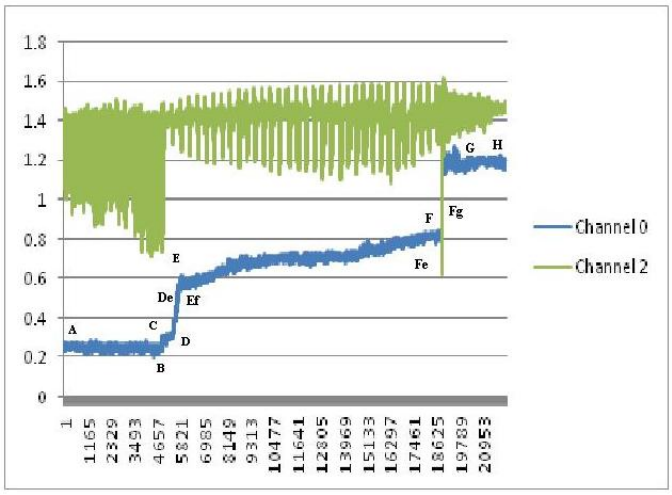


Fig. 1. The pressure signal defined by points and the wave signal of electronic sphygmomanometer.

The points of the pressure signal are automatically computed by the software and the higher level of point G or point H corresponds to the level of $L_s$ given in the formulas. The measurement constant is chosen from $L_s$. The table 1 shows the points and the time limits of the corresponding file. They are computed automatically by software.

Table 1. The key points of the pressure signal.

| Number | TimeExtrem | DataExtrem |
|---|---|---|
| 0 | 0.002 | 0.261230469 |
| 1 | 9.81400013 | 0.258789063 |
| 2 | 9.815999985 | 0.300292969 |
| 3 | 10.93799973 | 0.297851563 |
| 4 | 11.00399971 | 0.346679688 |
| 5 | 11.46199989 | 0.576171875 |
| 6 | 11.52600002 | 0.537109375 |
| 7 | 35.7140007 | 0.830078125 |
| 8 | 35.73400116 | 0.825195313 |
| 9 | 37.73199844 | 0.99609375 |
| 10 | 37.79399872 | 1.166992188 |
| 11 | 44.19800186 | 1.188620103 |
| | 6.004 | |
| | 12.004 | |
| | 38.732 | |

The formulas for systolic blood pressure are:

$$X_{s1} = C *( L_s - ((x_d + x_e)/2))/(L_s - x_{max}) \quad (1)$$

$$X_{s2} = C *( L_s - ((x_e - x_d)/(t_e - t_d))/(L_s - x_{max}) \quad (2)$$

$$X_{s3} = C *( L_s - (\Sigma x_{de})/N))/(L_s - x_{max}) \quad (3)$$

$$X_s = X_{s1} + X_{s2} / 2 \quad (4)$$

where points D and E define the systolic interval of the pressure signal, and the $x_{max}$ is pressure at point $x_B$ , C is the measurement constant at point B and point C in mmHg and $L_s$ in V is the level after the cuff becomes out of air pressure.

The software takes the best of those results and gives it to the final systolic solution.

The corresponding diastolic blood pressure has next formulas:

$$X_{d1} = C *( L_s - ((x_{ef} + x_{fe})/2))/(L_s - x_{max}) \quad (5)$$

$$X_{d2} = C *( L_s - x_f)/(L_s - x_{max}) \quad (6)$$

$$X_{d3} = C *( L_s - ((x_{ef} + x_{fe} + x_f )/3))/(L_s - x_{max}) \quad (7)$$

$$X_{d4} = C *( L_s - ((\Sigma x_{ef})/N))/(L_s - x_{max}) \quad (8)$$

where points $x_{ef}$ , $x_{fe}$ , $x_f$ , and $x_{ef}$ define the diastolic interval of the pressure signal, C is the measurement constant at point B and point C in mmHg and $L_s$ in V is the level after the cuff becomes out of air pressure. The computer also takes the best of those results and gives it as final diastolic blood pressure.

The formula for the heart rate is:

$$P = 60 * (N_w / (t_e - t_s)) \quad (9)$$

where $N_w$ is the number of upper waves of the wave signal for the corresponding period $(t_e - t_s)$, defined by point Fg after point F and point C, which lies after point B.

It is seen that systolic and diastolic blood pressure are mathematic results, not direct results of the sensors. Thus the difference between computer and the electronic sphygmomanometer can exists. But computer computes in some manner the required data, which are close to the real ones. Some of them can look as too abnormal, but sphygmomanometer also can surprise with some abnormality.

The authors in [1] define the heart activity by cycle pressure:

$C_P = X_{sys} - X_{dias}$ (10)

It can be a parameter of the heart activity together with the heart rate:

$H_A = P + CP$ (11)

They are results of the heart operation. Naturally, their sum is a parameter of the heart condition. The normal sum is 40 + 60 = 100. But with some interval 30 around it the limits are expanded enough. Thus normal heart activity lies between 70 and 130. From one to other blood pressure measurements it can vary, and this circumstance is accepted as normal. When heart activities is over or lower of those values for many consecutive measurements it is a symptom for abnormalities. This parameter can give some useful information at our way of live.

## III. RESULTS OF THE SOFTWARE

The software takes the data about pressure signal and wave signal. It computes middle lines of the waves, upper waves and lower waves. The pressure value of beginning point (p. A) defines the variations of the pressure signal. The first transition at p. B is small. The second transition at p. $D_e$ is higher. And the third transition at p. $F_g$ define the end of measurement with transition, which is similar to that of point $D_e$ or it is some higher. For different signals it vary in small degrees and it can stop the software. These are the main points of the automatic computation the points of pressure signal. Moreover, the pressure signal is defined between upper, lower, left and right limits. Computer can computes them automatically. The results of the software are shown in table 2.

In the table 2 normal variability for the pressure, heart rate and the index are seen. Thus the health state is normal and acceptable.

The computer system reads the signals of measurements but the Excel is activated by hand. The programmer pastes the program to the file of Excel and computes the blood pressure and heart rate.

Table 2. The blood pressures, heart rates and diagnostic indexes.

| File No | Systolic BP, mmHg | Diastolic BP, mmHg | Heart rate, p/min | Cycle Pressure mmHg | Index (CP+P) |
|---|---|---|---|---|---|
| 1 | 128 | 83 | 73 | 45 | 118 |
| 2 | 116 | 85 | 42 | 31 | 73 |
| 3 | 121 | 84 | 61 | 37 | 98 |
| 4 | 120 | 83 | 54 | 37 | 91 |
| 5 | 119 | 79 | 59 | 40 | 99 |
| 6 | 129 | 82 | 60 | 47 | 107 |
| 7 | 136 | 83 | 60 | 53 | 113 |
| 8 | 135 | 84 | 60 | 51 | 111 |
| 9 | 136 | 82 | 59 | 54 | 113 |
| 10 | 133 | 82 | 59 | 51 | 110 |
| 11 | 136 | 87 | 60 | 49 | 109 |
| 12 | 111 | 78 | 60 | 33 | 93 |
| 13 | 129 | 81 | 74 | 48 | 122 |
| 14 | 123 | 81 | 61 | 42 | 103 |
| 15 | 126 | 79 | 51 | 47 | 98 |
| 16 | 131 | 80 | 61 | 51 | 112 |
| 17 | 125 | 80 | 44 | 45 | 89 |
| 18 | 116 | 79 | 52 | 37 | 89 |
| 19 | 125 | 81 | 45 | 44 | 89 |
| 20 | 114 | 81 | 40 | 33 | 73 |
| 21 | 111 | 79 | 65 | 32 | 97 |
| 22 | 114 | 81 | 52 | 33 | 85 |
| 23 | 127 | 81 | 69 | 46 | 115 |
| 24 | 117 | 79 | 60 | 38 | 98 |
| 25 | 121 | 79 | 59 | 42 | 101 |
| 26 | 153 | 80 | 92 | 73 | 165 |
| 27 | 127 | 79 | 48 | 48 | 96 |
| 28 | 109 | 82 | 47 | 27 | 74 |
| 29 | 103 | 80 | 60 | 23 | 83 |
| 30 | 130 | 82 | 79 | 48 | 127 |
| 31 | 121 | 78 | 66 | 43 | 109 |
| 32 | 117 | 79 | 47 | 38 | 85 |
| 33 | 136 | 83 | 60 | 53 | 113 |
| 34 | 122 | 81 | 60 | 41 | 101 |

| File No | Systolic BP, mmHg | Diastolic BP, mmHg | Heart rate, p/min | Cycle Pressure mmHg | Index (CP+P) |
|---|---|---|---|---|---|
| 35 | 133 | 81 | 61 | 52 | 113 |
| 36 | 117 | 77 | 56 | 40 | 96 |
| 37 | 130 | 83 | 87 | 47 | 134 |
| 38 | 118 | 81 | 64 | 37 | 101 |
| 39 | 116 | 78 | 75 | 38 | 113 |
| 40 | 111 | 85 | 53 | 26 | 79 |
| 41 | 138 | 84 | 62 | 54 | 116 |
| 42 | 132 | 76 | 71 | 56 | 127 |
| 43 | 130 | 80 | 41 | 50 | 91 |
| 44 | 129 | 79 | 49 | 50 | 99 |
| 45 | 127 | 81 | 77 | 46 | 123 |
| 46 | 124 | 81 | 54 | 43 | 97 |
| 47 | 137 | 85 | 61 | 52 | 113 |

Some time the blood pressures are not computed. The reason is in the thresholds, which must be modelled in the corresponding instructions.

Thus many files can be assessed for health state. They are shown in the table 2. The difference between computed and measured blood pressure data is around 10% and rarely is over 20%. It never exceeds 30%.

This approach to health state assessment can be useful for active human life. It can be applied to handmade assessment of own health state with electronic sphygmomanometer.

## IV. CONCLUSIONS

The intensive cardiac bicycle test is based on monitor the cardiac cycle and the blood pressure. It is not applied in medical practise as a stationary test. The electronic sphygmomanometer provides data about blood pressure and the heart rate. These data are used in the explorations of the current paper. They are enough for preliminary medicine diagnostics, based on the corresponding index Cycle blood pressure plus Heart rate. The software of the computer system automatically computes the required parameters and generates data about cycle blood pressure and heart rate. The diagnostics is for the doctors, but the tables show a normal heart activity.

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# Подход за оценка на въздействието на сервизен робот със социално поведение в здравеопазването

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***Абстракт*—Статията представя нов подход за оценка на въздействието на сервизен робот със социално поведение в здравеопазването. Подходът е предложен на базата на обзор на статии, свързани с концепцията за кибер-физичната медицинска сестра. Аргументирана е необходимостта от моделиране на *социалния контекст* на взаимодействието пациент – сервизен робот за по-адекватно оценка на въздействието на робота върху човека.**

***Ключови думи*—Сервизен робот, социално поведение, социален контекст, здравеопазване.**

## I. Въведение

Сервизните роботи в здравеопазването изпълняват част от физическите задачи на медицинските сестри по отношение на индивидуалния пациент за по-ефективна съвместна грижа за пациента и по-малко натоварващо ежедневие на персонала. [1,2,3,4]. Когато сервизният робот изпълнява и социални функции – диалог и адаптиране към динамиката на взаимодействието – оценката на въздействието на робота върху човека се усложнява с необходимостта да бъдат взети пред вид не само индивидуалните медицински характеристики на пациента – *възраст* и *тежест на състоянието* – но и индивидуалните личностови характеристики.

Предложен е нов подход за моделиране на поведението на пациента в зависимост от следните фактори, имащи отношение към неговата личност – пол, характер и социален контекст на взаимодействието с робота. Подходът е предложен на базата на обзор на *статии*, свързани с концепцията за кибер-физичната медицинска сестра, представени в секция II на статията. Секция III представя новото в предложения подход за оценка на въздействието на сервизния робот със социално поведение, както и някои насоки за бъдещи изследвания.

## II. Концепция за кибер-физичната медицинска сестра

Концепцията за кибер-физичната медицинска сестра е представена в [5,6,7]. В [5] е формулирана концепция за кибер-физична медицинска сестра, която представлява хуманоиден сервизен робот със следните 4 характеристики: приятен, търпелив, учтив и физически силен. Последната характеристика се отнася до необходимостта медицинската сестра да обслужва пациенти с ограничена подвижност, докато първите 3 – до умението тя да проявява емпатия към емоционалното състояние на пациента. Това се реализира чрез т. нар. социален сензор от високо ниво, който открива прояви като *привързаност* и използва този механизъм на взаимодействие с други хора за терапевтични цели [5].

В [6] е предложено социалният сензор да открива също прояви на *доверие* към робота. В емпирично проучване е показано, че роботите предизвикват от неутрални до позитивни оценки относно фактори като *доверие* или *общителност* като не е установена статистически значима разлика от реакциите към човек. Следователно няма негативни фактори относно използването на сервизни роботи със социално поведение в здравеопазването, които да заместват медицински сестри.

В [7] са добавени нови характеристики на кибер-физичната медицинска сестра – *прецизност* и *предвидимост*. Проучено е влиянието на фактора антропоморфизъм върху доверието, което може да се изгради между пациента и киберфизичната медицинска сестра. Участниците в проучването оценяват 3 неутрални лица - на андроид, робот със стилизирани черти на лицето и човек - от гледна точка на 3 положителни и 3 отрицателни социални черти – доверие, общителност и емоционална стабилност, както и агресия, странност и заплашителност. Участниците приписват положителни социални качества на неутрални лица, включително и на роботи, което говори за допустимостта да бъдат използвани сервизни роботи със социално поведение в здравеопазването. Нещо повече, тези лица не предизвикват асоциации с отрицателни социални характеристики. Това е в сила както за жените, така и за мъжете участници в проучването.

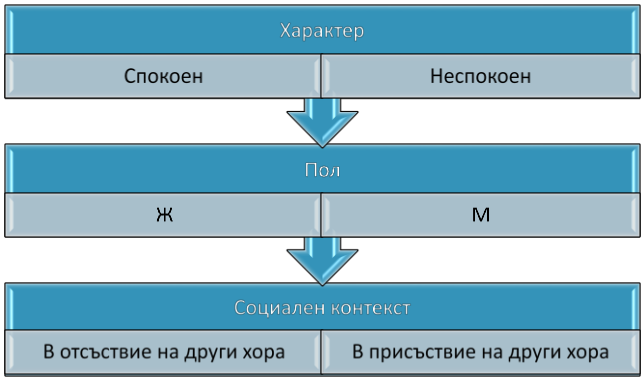
Установено е индивидуално предпочитание към различните типове роботи – с андроидни или стилизирани черти. Препоръчва се предварително апробиране на взаимодействието на пациента с отделния тип робот.

В [8] е представен подход за реализиране на различните когнитивни функции на кибер-физичната

медицинска сестра NurseBot чрез модули за обработка на текст и глас за разпознаване на емоционално състояние и съответна гласова реакция към пациента.

## III. Фактори за оценка на въздействието на СРСПЗ

Предложеният подход за моделиране на поведението на пациента е в зависимост от следните фактори, имащи отношение към неговата личност – характер, пол и социален контекст на взаимодействието с робота (фиг. 1).




**Фигура 1. Моделиране на поведението на пациента в зависимост от 3 определящи фактора – характер, пол и социален контекст.**

Особено важна характеристика на поведението на пациента е дали проявява признаци на неспокойство или е спокоен. Тази особеност може да е моментна – поради болка и дискомфорт, или устойчива характеристика на неговия характер. Първото ниво на диагностика оценява моментното състояние за овладяване на болката и стреса. Следващото ниво е оценка на характера на пациента когато болката е овладяна. В зависимост от това, дали характерът е спокоен или неспокоен, стратегиите на поведение на сестрата или сервизния робот са различни.

Поведението на сътрудничество се проявява най-адекватно когато пациентът е в спокойно състояние. В процеса на наблюдение на движенията и действията на пациента е възможно еднозначно да бъде определено състоянието му и да бъде взето решение относно необходимостта от интервенция – медицинска или психологическа. При тази преценка се взема пред вид и полът на пациента.

Установено е, че емоционалната реакция на негативни стимули е по-интензивна при жените, отколкото при мъжете [4]. Затова е важно полът на пациента да бъде отчетен на това междинно ниво на анализ.

Следващото ниво е преценката дали поведението на пациента се променя в зависимост от това, дали е сам или в присъствие на други хора. Нещо повече, установено е че отношението към робота зависи от вътрешни психологични особености като това, дали човек е социално-ориентиран или е индиферентен към присъствието на други хора в процеса на взаимодействие с хуманоиден робот [5].

а)

б)

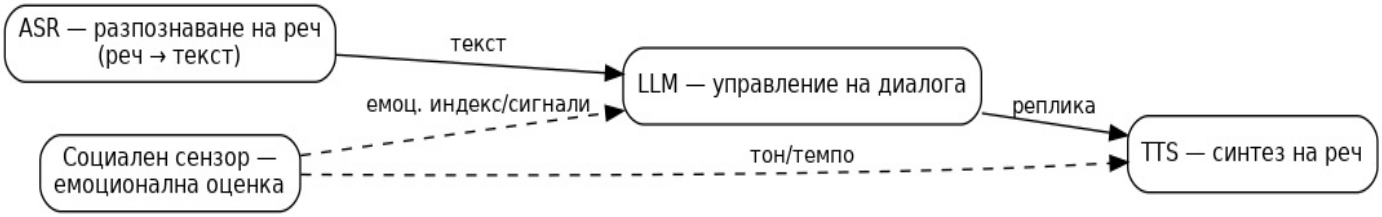
**Фигура 2. Моделиране на поведението на пациента в зависимост от 3 определящи фактора – характер, пол и социален контекст а) в отсъствие на човек; б) в присъствие на човек (генерирано с помощта на SORA AI [6]).**

Възможна хипотеза за бъдещо проучване е очакването, че отношението към сервизния робот със социално поведение е различно в зависимост от това, дали пациентът проявява отношението в присъствие на персонала/други хора, или не. Очакването е, че оценката на робота от социално ориентираните пациенти няма да се мени в зависимост от контекста, докато индиферентният пациент ще оценява робота

по различен начин в присъствието на други хора, отколкото в тяхното отсъствие. Следователно, стратегията на поведение към индивидуалния пациент трябва да бъде съответно адаптирана в зависимост от личностните особености на пациента.

## IV. Архитектура на диалоговата част на робота

Системата е изградена от четири основни комуникационни компонента: ASR (система за разпознаване на реч), LLM (голям езиков модел за управление на диалога) и TTS (синтезатор на реч), допълнени от мултимодален социален сензор за емоционална оценка. Във физическия слой роботът събира аудио-визуални и тактилни данни, чрез микрофони, камери, чувствителен на допир екран и други сензори.




**Фигура 3. Архитектура на диалоговата система.**

Звуковият вход се обработва предварително за да се повиши качеството на разпознаване чрез шумопотискане, VAD и честотна обработка, след което ASR превръща речта на пациента в текст. Текстът, се допълва от сигнали от социалния сензор, които се подават към голям езиков модел (LLM). Архитектурата на диалоговата система е представена на фиг.3.

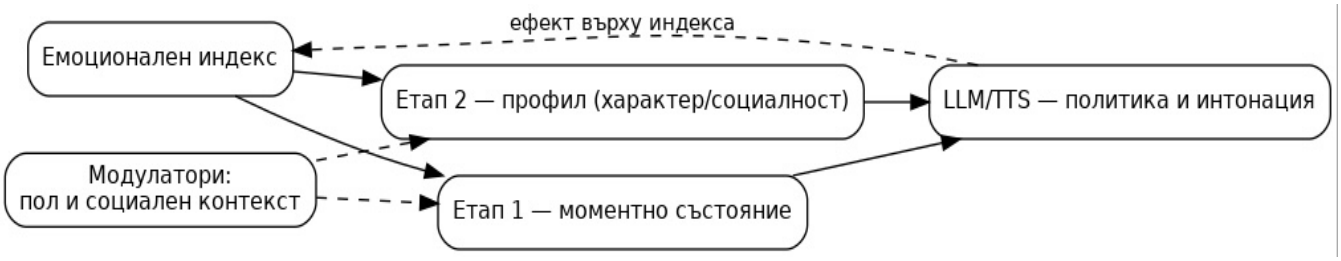
Този модел поддържа състояние на диалог, извличайки в реално време намерения, и интерпретирайки контекста, а също и вземайки решения за следващ ход - например: информация, въпрос, обяснение, емпатична реакция, пауза или повикване към персонал за помощ. Накрая TTS синтезира отговора, като контролира темпото, интонацията и паузите, за да постигне подходящ емоционален тон и емпатично поведение.

Сърцевина на системата е социалният сензор от високо ниво, чиято роля е да разпознава прояви като привързаност, доверие/недоверие и емоционална стабилност/напрегнатост, за да управлява терапевтичното взаимодействие.

Този сензор обединява три канала: (1) гласова просодия (тембър, височина, вариация, интензитет, микропаузи), (2) визуални индикатори (мимики, движение на очи, поза, двигателно напрежение) и (3) езикови маркери в самия текст (семантични и прагматични сигнали за тревожност, болка, обезпокоеност, доверие). Сензорът поддържа единен емоционален индекс с краткосрочна динамика (моментно състояние) и дългосрочни трендове (индивидуални особености), който се връщат към LLM за избор на стратегия и към TTS за настройка на интонация/темпо в отговорите на робота. Методиката за оценка следва двустепенна логика. Първо, системата определя моментното състояние: наличие на болка/дискомфорт, тревожност, раздразнение - на базата на остри промени в емоционалния индекс.

Целта на това ниво е бързо овладяване на стреса чрез промяна на темпо и тон, въвеждане на кратки инструкции, пауза или извикване на персонал. След като острите симптоми се овладеят, се извършва оценка на характера - дали пациентът е по-скоро спокоен или неспокоен тип, социално ориентиран или индиферентен към присъствието на други хора. Тази оценка се използва за дългосрочна персонализация на диалога (например по-структурирани и кратки реплики при неспокоен тип; по-разгърната, дружелюбна комуникация при спокоен/общителен тип).

В методиката се включва и факторът пол: установено е, че емоционалната реактивност към негативни стимули е средно по-интензивна при жените, което налага по-деликатно въвеждане на информация и по-плавни преходи между теми, както и по-внимателно управление на темпото/интонацията. Тази особеност се отчита на междинно ниво при преценка за необходимостта от интервенция (медицинска или психологическа) и при настройка на праговете в емоционалния индекс.




**Фигура 4. Алгоритъм за модулация на емоционалния индекс.**

Съществен е и социалният контекст на взаимодействието. При социално ориентирани пациенти нагласите към робота са по-стабилни независимо дали разговорът е насаме или в присъствие на персонал/близки; при индиферентни пациенти е възможна контекстно зависима оценка – различно отношение, когато присъстват други хора. Оттук следва хипотезата: стратегията на робота да се адаптира спрямо контекста – например да редуцира излишната социалност при индиферентен пациент в групова ситуация или да поддържа непроменена емпатична линия при социално ориентиран пациент независимо от присъствието на други.

За управлението на съдържанието на диалога се използва тематичен модул - подбор на неутрални и успокояващи теми, поднесени като кратки, лесни за потвърждение въпроси/твърдения. Примерни блокове: ежедневен режим („Да измеря ли пулса или предпочиташ малко музика?“), кратки неутрални въпроси: („Кога през деня се чувстваш най-добре?“), насочени към контрол и предвидимост („Сега ще ти обясня стъпка по стъпка какво предстои“). LLM наблюдава ефекта на темата върху емоционалния индекс и динамично продължава, сменя или прекъсва темата.

Така темите стават инструмент за измерване и едновременно интервенция - „микро-експерименти“ за тестване на реакциите в реално време. Подходът е съвместим с извода, че поведението на пациента и отношението му към робота зависи от личностните и контекстните фактори и следователно би изисквало адаптивни стратегии. Интонационният контрол в TTS се използва като основна управляваща променлива за регулация на състоянието: при покачване на тревожност/болка - по-бавен темп, по-ниска амплитуда, удължени паузи; при стабилизиране – постепенно връщане към неутрален речеви профил. Тези промени се инициират автоматично от социалния сензор и се валидират от LLM според контекста (напр. прекъсване на обясненията и преминаване към успокояваща формула „Ще говоря по-бавничко; Кажи ми, ако имаш нужда от почивка“). Алгоритъмът на взаимодействие между отделните компоненти е илюстриран на фиг.4

Валидацията на системата комбинира субективни и обективни мерки. Субективно се използват въпросници за комфорт, доверие и яснота; обективно – динамика на емоционалния индекс, показатели от просодия/мимика, честота на ескалациите и времето до стабилизиране на състоянието след интервенция. За да се осигури безопасност, LLM работи заедно с правила за граници, зададени в неговия промпт (напр. избягване на чувствителни теми без човешки надзор) и със специфични, предварително валидирани скриптове за критични ситуации.

## V. Заключение

Статията представя нов подход за оценка на въздействието на сервизен робот със социално поведение в здравеопазването върху пациентите. Описани са основните характеристики на социалното поведение на сервизния робот, както и факторите, влияещи на оценката на пациента за робота. Представен е модел на адаптация на диалога на робота към особеностите на пациента и социалния контекст. Предвидено е апробиране на модела в емпирични условия.

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# An Approach to Developing an Optimal Model of the Mobile Platform of a Collaborative Robot

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***Abstract*— The article presents a methodology for selecting a drive system for a mobile platform of a collaborative mobile robot, taking into account the requirements for it. Optimization of the drive system and its functional capabilities, in accordance with the overall set of criteria, will ensure excellent stability, maneuverability, and energy efficiency of the cobot. The possible mechanisms for driving the platform are examined and an analysis is made of the situations in which they can be implemented, depending on the application of the collaborative mobile robot. Keywords—Service Robot, mobile platform, Cobot.**

## INTRODUCTION

The rapid advancement of collaborative robots (cobots) has created new opportunities for their integration into dynamic and unstructured environments, where mobility, adaptability and human–robot interaction are becoming critical requirements. Unlike traditional industrial robots, which operate in strictly controlled settings, mobile cobots must navigate complex terrains, share workspaces with humans, and perform a diverse range of tasks with high precision and safety. These emerging conditions demand the development of optimized mobile platforms [1], [3], [7] capable of supporting advanced perception, navigation and interaction functionalities.

Achieving such optimization requires a systematic approach that integrates mechanical design, sensor configuration, motion control, energy management, and environmental constraints into a unified model. The mobile platform becomes the foundation upon which the robot's cognitive and operational capabilities are built. Therefore, defining an optimal model is essential not only for improving mobility performance, but also for enabling intelligent behaviour, reliable operation, and effective collaboration with human operators.

This report presents an approach for developing an optimal model of the mobile platform of a collaborative robot. The methodology includes the analysis of various mobility mechanisms, the evaluation of sensory and energy subsystems, and the formulation of a structured framework for design optimization. The aim is to achieve a balanced solution that maximizes maneuverability, stability, energy efficiency, and environmental adaptability, while meeting the specific functional requirements of collaborative applications.

Through this approach, the study contributes to the broader effort of enhancing the autonomy, safety and functional versatility of next-generation mobile cobots, enabling their deployment across industrial, service, medical, and field environments.

## I. FUNCTIONAL CAPABILITIES OF THE MOBILE PLATFORM

### Mobility and navigation

Drive: The platform is equipped with four wheels (or alternatively with omnidirectional wheels/track modules), ensuring movement in all directions.

Navigation: Uses Lidar, IMU, ultrasonic/infrared sensors, and cameras for mapping the environment (SLAM) and autonomous movement.

Automatic obstacle avoidance: Analyzes the environment in real time and changes the trajectory to avoid collisions. Precise positioning: GPS or visual localization to determine the position indoors or outdoors.

## II. METHODOLOGY

The proposed approach for developing an optimal model (Fig.1) of the mobile platform of a collaborative robot [2], [4] follows a structured methodology that integrates mechanical design, sensory system optimization, mobility analysis, and energy management.

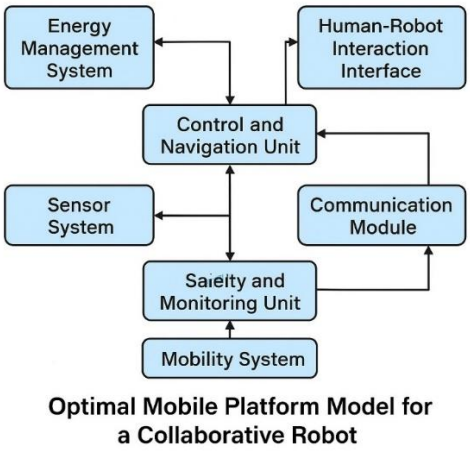


***Fig.1 The mobile system.***

The methodology is organized into several key stages, each addressing critical aspects of performance, safety, and operational efficiency.

ACKNOWLEDGE THE FINANCIAL SUPPORT OF THE PROJECT WITH FINANCING AGREEMENT NO. PVU-44 OF 05.12.2024 UNDER PROJECT NO. BG-RRP-2.017-0011 "ECOLOGICAL COLLABORATIVE ROBOTS POWERED BY GREEN HYDROGEN" UNDER THE RECOVERY AND RESILIENCE MECHANISM FOR THE IMPLEMENTATION OF AN INVESTMENT UNDER C2I2 "INCREASING THE INNOVATION CAPACITY OF THE BULGARIAN ACADEMY OF SCIENCES (BAS) IN THE FIELD OF GREEN AND DIGITAL TECHNOLOGIES" FROM THE RECOVERY AND RESILIENCE PLAN, BULGARIA.

*1. Requirements Definition*

The process begins with identifying the functional, operational, and environmental requirements of the collaborative robot. These include:

- ✓ intended tasks and interaction scenarios,
- ✓ required load capacity and workspace,
- ✓ expected terrain conditions and mobility constraints,
- ✓ safety standards for human–robot interaction,
- ✓ endurance, autonomy, and energy efficiency criteria.

A detailed requirements matrix is formulated to guide subsequent design decisions.

*2. Selection and Evaluation of Mobility Mechanisms*

Several mobility configurations are analysed to determine the most suitable mechanism for the application. These may include:

- ✓ Mecanum wheels for omnidirectional motion,
- ✓ differential drive systems for simplified control,
- ✓ Ackermann steering for higher-speed maneuvering,
- ✓ tracked or triangular chain-track modules for off-road capability.

Each mobility type is assessed using performance indicators such as maneuverability, obstacle negotiation, stability, traction, and energy consumption. Simulation models or empirical tests support the comparative evaluation.

*3. Modeling of Mechanical Structure*

A geometric and dynamic model of the mobile platform is developed, incorporating:

- ✓ chassis geometry and center of mass estimation,
- ✓ suspension or stabilization systems (if applicable),
- ✓ kinematic and dynamic equations of motion,
- ✓ load distribution and structural rigidity considerations.

This model enables verification of stability margins, turning behaviour, and motion smoothness under different operating conditions.

*4. Sensor System Integration*

The next step focuses on designing and integrating the sensory subsystem responsible for perception and navigation. The methodology includes:

- ✓ selection of appropriate sensors (IMU, LiDAR, encoders, camera modules, ultrasonic sensors, etc.),
- ✓ definition of sensor placement for optimal field of view and minimal interference,
- ✓ calibration procedures for accurate data acquisition,
- ✓ fusion of sensory information to support localization, mapping, and obstacle avoidance.

Sensor performance is evaluated through controlled tests or simulation data.

*5. Energy Subsystem Design and Optimization*

To ensure continuous operation, the energy subsystem is modelled and optimized. The process includes:

- ✓ evaluation of power consumption of motors, electronics, and sensors,
- ✓ selection of power sources (Li-ion battery pack, supercapacitors, hybrid fuel cell systems),
- ✓ development of an energy management strategy to balance peak loads, regenerative braking, and continuous supply,
- ✓ estimation of autonomy based on operating profiles.

This stage integrates numerical analyses to optimize energy density and operational duration.

*6. System-Level Integration and Functional Architecture*

A unified functional architecture is created to connect mobility, perception, control, and energy modules. This includes:

- ✓ development of a block diagram representing data and control flows,
- ✓ definition of communication protocols and subsystem interfaces,
- ✓ integration of motion control algorithms with sensory inputs,
- ✓ implementation of safety mechanisms for human–robot interaction.

The full system model ensures seamless cooperation between hardware and software components.

*7. Simulation, Verification, and Optimization*

- ✓ The integrated model is tested through:
- ✓ physics-based simulations,
- ✓ kinematic/dynamic testing,
- ✓ sensor simulation scenarios,
- ✓ energy profile validation.

Optimization algorithms (multi-criteria optimization, Pareto analysis, or heuristic methods) are applied to refine the design based on predefined criteria such as maneuverability, stability, energy efficiency, and operational robustness.

*8. Prototype Development and Experimental Validation*

A prototype of the mobile platform is constructed to validate the theoretical model. Experimental tests include:

- ✓ motion and navigation trials,
- ✓ sensor accuracy and robustness evaluation,
- ✓ energy consumption and autonomy measurements,
- ✓ performance assessment under realistic collaborative scenarios.

Collected data is compared to simulation results to refine the final model.

## III. The Approach For Optimizing The Robot Structure

The intelligent mobile system integrates perception, control, and motor capabilities to enable autonomous and adaptive operation of a mobile platform. The sensor subsystem collects environmental data, which is processed by AI control (Fig.2), perception, and localization modules to recognize objects and spatial structures [6].

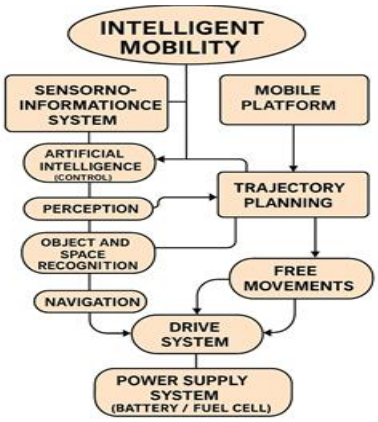


***Fig.2 The intelligent mobile system.***

The system enables autonomous, safe, and adaptive mobility—it can orient itself, plan, avoid obstacles, and perform tasks such as docking and navigation without human intervention.

The approach to optimizing the robot structure includes the following steps (Fig.3) :

1. Defining the objective function: This can be a combination of parameters such as the scope of the workspace, the length of the manipulator, the constraints of the motors, etc. The

goal is to create an objective function that needs to be optimized.
2. Defining the constraints: This includes the constraints on the dimensions of the robot, the workspace, the maximum and minimum lengths of each part of the manipulator, and other constraints that may affect the design of the robot.
3. Using optimization methods: In order to find the optimal values of the parameters of the robot structure, various optimization methods can be used, such as genetic algorithms, simulated cooling, gradient methods, etc.
4. Design and analysis of the results: Once the optimal parameter values are obtained, a detailed design of the robot structure can be carried out, and then the results of simulations or experiments can be analyzed.

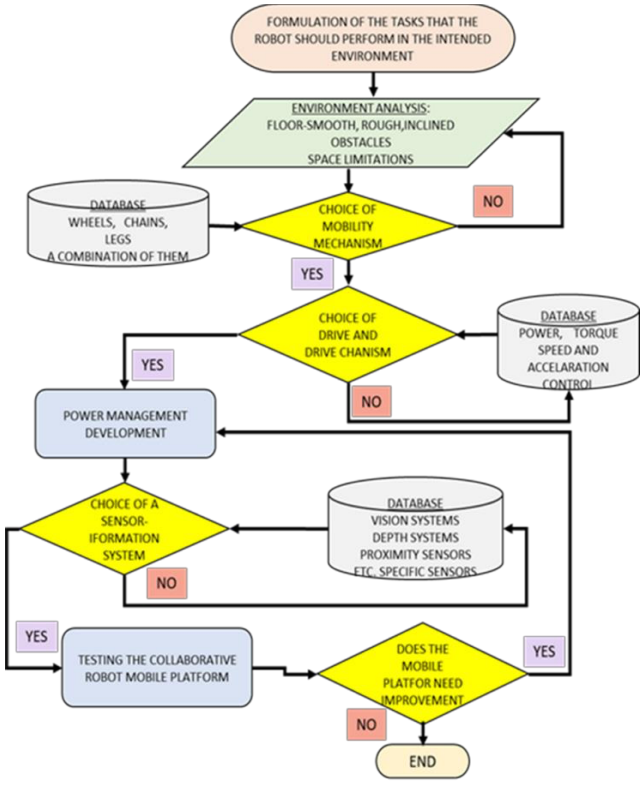


***Fig.3 Block diagram of an approach for developing an optimal model of a mobile platform for a cobot.***

This approach can help create robots with better performance and efficiency in various applications, such as healthcare, education, etc. Using this method and upgrading it by using parametric identification and calibration of a robot manipulation system leads to the synthesis of a model operator by studying the service coefficient.

## III. DIFFERENTIAL WHEELED MOBILITY

Differential wheeled locomotion is among the most widely adopted mobility solutions in service, industrial, and medical robotics due to its high mechanical efficiency, simplicity, and straightforward control structure. Wheeled platforms are especially suitable for structured indoor environments where low rolling resistance and high locomotion speed offer substantial operational advantages.

A. Advantages of Wheeled Locomotion

*1) High Energy Efficiency*

Wheels exhibit minimal rolling resistance, resulting in reduced energy consumption, lower heat generation in actuators, and extended operational autonomy. This makes wheeled platforms well-suited for applications requiring long-duration missions or continuous mobility.

*2) High Maximum Speed*

Compared to tracked and legged systems, wheeled robots can achieve significantly higher translational velocities. This characteristic is valuable in logistics, fast indoor delivery, and surveillance applications that require rapid and efficient point-to-point movement.

***Fig.4 3D image of a differential wheel variant Mobility.***

*3) Mechanical Simplicity*

Wheeled platforms feature a simple mechanical architecture with few moving components. They lack high-stress joints and complex suspension mechanisms, typically requiring only motors, gearboxes, and wheel assemblies. As a result, they are easy to manufacture, maintain, and scale.

*4) Simplified Control and Kinematics*

Differential drive robots provide mathematically tractable kinematics. Two-wheel differential platforms, four-wheel variants, and robots employing Ackermann steering all enable predictable motion control with low computational requirements.

*5) High Performance on Flat Surfaces*

Wheeled systems operate optimally on smooth, hard terrain such as laboratory floors, concrete, tile, and industrial surfaces. This makes them ideal for most indoor service and medical environments.

*6) Low Maintenance Requirements*

Typical maintenance tasks—such as tire replacement, bearing lubrication, and gearbox servicing—are minimal compared to those of tracked or legged systems, reinforcing wheels as a cost-effective mobility choice.

B. Limitations of Wheeled Locomotion

*1) Limited Obstacle-Crossing Capability*

Wheeled robots encounter challenges when negotiating steps, curbs, rubble, or highly uneven terrain, restricting their applicability in disaster-response and off-road environments.

*2) Reduced Off-Road Performance*

Due to their small contact area, wheels provide less traction and are more prone to slippage on deformable surfaces such as soil, sand, and mud.

*3) Performance Issues on Wet or Slippery Terrain*

Slick or wet surfaces significantly reduce wheel traction. Specialized tire patterns or compliant rubber materials are required to mitigate this effect.

*4) Limited Payload Capacity*

Load distribution across discrete wheel contact points restricts the maximum payload capacity of small to mid-sized wheeled robots, when compared to tracked platforms.

*5) Poor Mobility on Soft Terrain*

Soft substrates such as grass, snow, mud, and sand may cause wheel sinkage and reduced stability, negatively affecting mobility and control accuracy.

C. Application Domains of Differential Wheeled Robots

*1) Laboratory and Educational Robotics*

Low cost, intuitive control, and inherent safety make wheeled platforms highly suitable for research, prototyping, and STEM education.

*2) Industrial Logistics and Warehousing*

Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs) commonly employ wheels to enable reliable operation in large industrial facilities with smooth floors.

*3) Medical and Service Robotics*

Wheeled platforms are frequently used for autonomous delivery of medical supplies, logistics support in clinical environments, and service tasks in hospitals and laboratories.

*4) Inspection and Security*

Wheeled systems support long-duration patrols, infrastructure surveillance, and indoor/outdoor monitoring tasks where low energy consumption is advantageous.

*5) Domestic and Office Robotics*

Robotic vacuum cleaners, indoor delivery robots, and office service robots predominantly rely on wheels due to low noise, simplicity, and smooth indoor terrain.

*6) Agricultural Robotics*

Although less suitable for highly uneven terrain, wheeled robots can be deployed for precision farming, crop monitoring, and spraying on firm ground or moderately irregular surfaces.

D. Summary

Differential wheeled mobility provides a highly efficient and mechanically simple solution for structured environments. While limited in obstacle negotiation and off-road performance, wheeled platforms remain the dominant choice for logistics, industrial automation, medical service robotics, and indoor autonomous systems due to their cost-effectiveness, high speed, and low maintenance requirements.

***Fig. 4 3D image of a 3D Omni/Mecanum***

Two other alternative options for driving the mobile platform of a collaborative service robot are Omni wheels (Fig.4) [5], [8], and triangular chain modules. The Mecanum drive provides holonomic motion in the plane, enabling independent control of the longitudinal and lateral velocities, as well as of the yaw rate around the vertical axis. As a result, the platform can perform omnidirectional motions and achieve precise docking in confined and structured environments such as the interior of a field medical unit or a hospital corridor.

Triangular chain-track modules (Fig.5), in turn, represent a more complex mechanical structure, in which each running unit consists of three sprockets connected by a continuous track. The triangular geometry and the placement of the modules with respect to the robot body allow the instantaneous centre of rotation to be shifted to the contact point between the track and the obstacle, thus enabling the platform to roll over curbs, rocks and stairs. This configuration offers superior terrain-traversal capability and stability on soft, rough or debris-covered surfaces, which is critical for search-and-rescue operations and field medical deployments in harsh outdoor conditions.

**Fig. 5 3D image of a mechanism for mobility with triangular sprockets for a cobot.**

The comparative analysis indicates that the Mecanum drive is more suitable when manoeuvrability and high-precision positioning in constrained indoor spaces are the primary design criteria, whereas the triangular chain-track solution is preferable when off-road mobility and robustness are dominant requirements. In the following sections, the Mecanum configuration is therefore adopted as the baseline mobility system for the medical service robot, while the chain-track variant is treated as an alternative option for extreme-terrain scenarios.

*Table 1.*

**Comparison of Mobility Systems for Mobile Robots**

| Criteria | Standard Wheels | Mecanum Wheels | Tracked (Chain-Track) Drive |
|---|---|---|---|
| Mobility DOF | 2 ($V_x, \omega$) | 3 ($V_x, V_y, \omega$) | 2 ($V_x, \omega$) |
| Energy Efficiency | ★★★★★ | ★★★★ | ★★★ |
| Speed | ★★★★★ | ★★★★★ | ★★★ |
| Maneuverability in Tight Spaces | ★★★ | ★★★★ | ★★★ |
| Sideways (Lateral) Motion | X | ✓ | ★★★★★ |
| Terrain Adaptability | ★★ | ★ | ★★★★★ |
| Obstacle Crossing | Poor | Poor | Excellent |
| Slip Resistance | Moderate | Low | Very good |
| Control Complexity | Low | Moderate | Moderate |
| Maintenance Cost | Low | Moderate | High |
| Production Cost | Indoor, industrial floors | Indoor, logistics | Off-road, rescue, military |

Where each type is most suitable

✓ Standard wheels - Logistics, Hospitals, Laboratories, Autonomous deliveries, Industrial AGV/AMR

✓ Mecanum wheels - narrow spaces, service robots, warehouses with limited aisles, robot manipulators that need to move sideways

✓ Track drive - military applications, rescue operations, uneven and rough terrain, inspection of external infrastructure.

Comparison of triangular chain modules, classic chain drive and extended chain drive

The triangular chain module design is implemented by a chain that moves around three gears forming a triangular geometry. The front gear is raised, serving as an element for overcoming obstacles. The central gear often acts as a drive wheel.

**Fig.6 3D image of a variant of a mobility mechanism with a chain for a cobot.**

**Fig. 7 3D image of a variant of a mobility mechanism with extended chain for a cobot.**

The advantages of this design are that it has the best ability to overcome obstacles - stairs, rocks, curbs, as well as the ability of the moment center of rotation (ICR) at the point of contact of the robot to "overcome" obstacles instead of crashing into them.

The triangular chain module design is ideal for rescue missions and very uneven terrain and is very stable on slopes. Torsion suspension can be included for improved dynamics.

Disadvantages of triangular track modules are more complex mechanics (three sprockets, longer chain), higher production and maintenance costs and a smaller contact area with the ground, which leads to less traction in mud/sand compared to long chains.

Applications: Search and rescue robots, robotic platforms for field/defense operations, work in collapsed buildings, reconnaissance and inspection

Classic track drives (fig.6 compact standard tracks) are characterized by a construction of two parallel tracks, each of which is supported by several rollers.

Their advantages are that they have good mobility on any terrain on uneven terrain, simpler and more affordable than triangular track modules. They are compact, which makes them with good maneuverability in confined spaces. A special quality is the balanced performance between speed, traction and stability.

The disadvantages of the classic track drive are the lower performance in overcoming obstacles compared to triangular tracks. It can "jump" when climbing sharp edges or curbs, which makes them less stable on very steep slopes.

They find applications in industrial service robots, telepresence or manipulation robots, small unmanned vehicles (UGVs), medical mobile platforms.

Extended (long-track) drives (fig.7 - long, multi-roller track system) are characterized by a structure covering almost the entire length of the chassis, multiple support rollers, which results in a very large contact area with the ground, as well as improved traction for soft or slippery terrain.

Advantages of the long-track drive are the best traction among the three systems (mud, snow, sand), high stability for transporting heavy payloads, low vibrations on rocky terrain due to the many support rollers. This makes them an excellent choice for heavy, field medical robotic systems.

Disadvantages include a large contact area, which results in lower top speed. Higher power requirements during cornering, and increased weight and energy consumption.

Used in heavy field medical robots, logistics and transport UGVs, snow/mud platforms, high stability applications.

*Comparison Table 2*

| Criterion | Triangular Tracks | Classic Tracks | Extended Tracks |
|---|---|---|---|
| Obstacle crossing | ⋆ ⋆ ⋆ ⋆ ⋆ | ⋆ ⋆ ⋆ | ⋆ ⋆ ⋆ ⋆ |
| Traction in mud/sand | ⋆ ⋆ ⋆ ⋆ | ⋆ ⋆ ⋆ | ⋆ ⋆ ⋆ ⋆ ⋆ |
| Slope stability | ⋆ ⋆ ⋆ ⋆ | ⋆ ⋆ ⋆ | ⋆ ⋆ ⋆ ⋆ ⋆ |
| Speed | ⋆ ⋆ ⋆ | ⋆ ⋆ ⋆ ⋆ | ⋆ ⋆ |
| Maneuverability | ⋆ ⋆ ⋆ | ⋆ ⋆ ⋆ ⋆ | ⋆ ⋆ |
| Manufacturing complexity | High | Medium | High |
| Maintenance | Medium | Low | High |
| Shock/mud resistance | Medium | High | Very High |
| Optimal terrain | Rubble, rescue | Indoors/medium terrain | Heavy off-road |

From the analysis (Table 2), the following conclusion can be drawn:

✓ To overcome high obstacles, it is desirable to use triangular modules.

✓ Classic tracks are the optimal option for balanced mobility, speed and compactness.

✓ For maximum traction and stability in difficult terrain, extended systems with long tracks are the best choice.

**Fig. 8 3D image of a variant of a mechanism for mobility with a combined chain, the first with triangular sprockets and the second with two wheels, for a cobot.**

Considering a mixed (hybrid) wheel-in-chain drive type – a platform with two short chain modules, each consisting of several support wheels around which a rubber chain is stretched (Fig.8). This combines the characteristics of wheel and chain drives.

The hybrid variant shown is characterized by the fact that the tracks remain at the front (for better traction and overcoming obstacles), and at the back: only one large wheel, which helps stability and maneuverability. This is a variant (Fig. 9) between a tracked and wheeled robot - often used in platforms for uneven terrain.

The kinematic and structural idea of this hybrid variant is that on the side there are two independent track modules (left and right), with each module consisting of several wheels

(rollers) that distribute the weight along the length of the track and can be driving or supporting.

**Fig. 9 3D image of a hybrid (mixed) version of a mobility mechanism for a cobot.**

Externally, the system behaves like a classic tracked robot (differential control: left/right track), but internally we have a wheeled chassis, which provides better load distribution, less local deformation of the track, more uniform overcoming of irregularities.

2. Advantages of mixed drive

✓ Lower ground pressure due to the large contact area of the track and the distribution of the weight over several support wheels, which leads to less sinking in soft terrain (mud, sand, snow) compared to wheel drive.

✓ Good cross-country ability and smooth movement, which is due to

the many support wheels smoothing out shocks, and hence less vibration of the platform and manipulator - important for medical and service tasks.

✓ Stability on slopes due to the length of the support base (the distance between the front and rear contact wheels) provides good longitudinal stability.

Low center of gravity → lower risk of overturning when moving on a slope.

✓ Mobility in difficult conditions is realized through the combination of "wheels + tracks" and is optimal for destroyed buildings, uneven terrain around field hospitals, mud and wet grass.

3. Disadvantages include:

✓ Higher complexity and cost - more wheels, bearings and axles → more maintenance components. The chain wears out and requires periodic tensioning and replacement.

✓ Higher energy consumption - the friction between the chain and the rollers is greater than that of a purely wheeled platform, which leads to higher energy consumption at the same speed.

✓ Lower maximum speed due to mass and friction, the maximum linear speed is usually lower than that of omni-wheels or standard wheels.

4. Such a mixed chain drive is very suitable for field medical and rescue robots - reaching victims through rubble, mud, snow. Logistic tasks in difficult terrain - transporting consumables, oxygen cylinders, hydrogen cylinders, etc. around a field hospital.

In conclusion, the mixed wheel plus chain drive in the shown configuration gives a more even load distribution on the support wheels and provides a stable and reliable mobile platform for a collaborative robot.

## III. LEGGED MOBILITY CONCEPT

Legged mobility represents a fundamentally different approach to ground locomotion compared to wheeled and tracked platforms. Instead of relying on continuous surface contact, legged systems generate motion through discrete footholds, enabling a robot to traverse complex, discontinuous, or highly unstructured environments. In the context of collaborative service robotics and field medical deployment, legged locomotion provides a significant strategic advantage by allowing the robot to operate effectively where conventional mobility mechanisms become ineffective.

A legged mobile platform (Fig.10) typically consists of multiple articulated limbs, each comprising several degrees of freedom (DoF) that enable lifting, swinging, placement, and load-bearing actions. The resulting kinematic structure allows the robot to dynamically adapt its posture and center of mass to maintain stability during locomotion. Depending on the gait pattern—tripod, quadrupedal crawl, trot, or dynamic bounding—the system may operate in statically stable or dynamically stable regimes. This versatility enables robust locomotion over rubble, debris, collapsed structures, steep inclines, and soft deformable terrain, all of which are common in disaster-response and field medical scenarios.

Compared to wheeled and tracked mobility, legged systems offer several critical advantages. First, individual foot placement allows precise selection of stable contact points, enabling traversal of obstacles that cannot be rolled over. Second, the ability to control body height, pitch, and roll allows the robot to maintain a stable operating platform for a mounted collaborative manipulator, even when the surrounding terrain is uneven. Third, legged locomotion reduces the need for large continuous contact areas, minimizing ground disturbance and allowing the robot to move through narrow passages, rubble voids, and staircases.

**Fig.10 3D image of a legged mobility concept**

However, these benefits come with significant engineering challenges. Legged platforms require sophisticated control architectures that integrate inverse kinematics, gait planning, whole-body control, and real-time balance stabilization. The energy consumption of legged systems is typically higher than that of wheeled or tracked robots due to the active lifting of limbs and the continuous torque demand of multi-joint actuators. Safety in human-robot interaction is also more complex, as the robot must ensure compliant behavior despite having many rapidly moving limbs.

In field medical contexts, the legged mobility concept is particularly promising. A quadrupedal collaborative robot

can access confined or obstructed areas to deliver medical supplies, perform teleoperated manipulation, support patient assessment, or carry diagnostic sensors. The platform's ability to adapt posture enables stable manipulation even on irregular terrain, while its mobility allows deployment in environments that are inaccessible to conventional mobile medical robots. As a result, legged mobility forms a strong foundation for next-generation collaborative systems capable of assisting medical personnel under extreme operational conditions.

## IV. COLLABORATIVE SERVICE ROBOT DESIGNED FOR PEDIATRIC HOSPITALS.

Based on an analysis of the activities of healthcare workers: doctors, nurses, laboratory technicians, physiotherapists, and orderlies, it is proposed to create a collaborative mobile robot that can perform some of the activities of hospital workers, thereby not only facilitating their work in processes that can be robotized, but also creating conditions for reducing the risk of infection among staff.

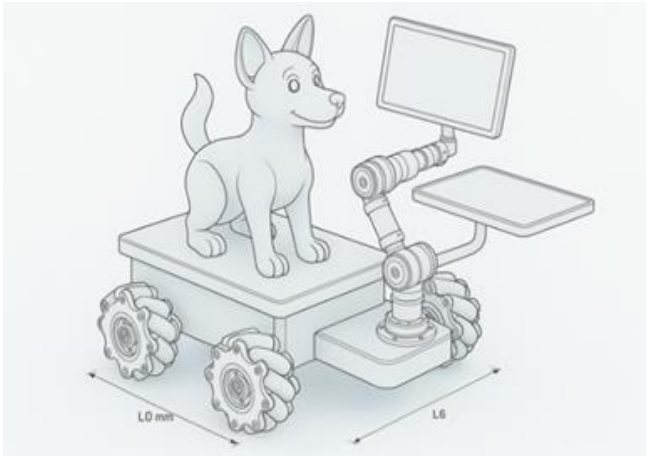

**Fig.11 Collaborative service robot designed for pediatric hospitals.**

A cobot model (Fig..11) has been proposed that can be implemented in pediatric clinics.
The model is a mobile platform with omni-wheels of a Collaborative Service Robot (Fig. 50). Its design resembles a children's toy and is expected to be well received by young patients. The mobile platform is built with four omnidirectional wheels, which provide high maneuverability in confined spaces, and the arm is a manipulator with a degree of redundancy allowing for increased manipulability. A tray is provided for picking up and handing over manipulated objects (medicines, cups, utensils, etc.) to ensure greater reliability and safe use of the cobot.

## 6. CONCLUSION

Any requirement for the robot's mobile platform ultimately boils down to imposing certain restrictions on the choice of drive system.
The optimal drive configuration will ensure excellent stability, manoeuvrability and energy efficiency.
The methodology presented is the basis for conducting research aimed at optimizing the selected drive system and its functional capabilities in accordance with the overall set of criteria.
The resulting assessment enables the collaborative robot to function reliably.
A well-chosen platform is a stable basis for its implementation in intelligent collaborative robotic systems.

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# Ecological Challenges of Modern AI-Driven Robotics

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***Abstract*: Robotics is increasingly driven by artificial intelligence (AI) through large language models (LLMs), vision–language models (VLMs), and large action models (LAMs), enabling unprecedented autonomy and adaptability. These capabilities, however, rely on hyperscale datacenters which rapidly increasing power density and cooling demands impose significant environmental costs. Rack-level power densities have risen from 2–4 kW in early datacenters to more than 100–140 kW in modern AI facilities, intensifying electricity and water consumption. This article reviews the ecological implications of AI-driven robotics, examines representative gigawatt-scale datacenter projects, and surveys emerging technological pathways aimed at mitigating energy and resource impacts.**

***Keywords: AI-driven robotics, hyperscale datacenters, energy consumption, water usage, sustainability, foundation models, robotic autonomy, environmental impact***

## I. Introduction

Robotics has historically been rooted in deterministic, rule-based control systems. Early industrial robots were programmed using explicit algorithms that defined motion trajectories, sensor feedback loops, and decision rules with limited capacity for adaptation. While these systems proved reliable in structured environments such as automotive assembly lines, they were inherently brittle in the face of uncertainty and environmental variability. Over the past decade, the integration of AI - particularly deep learning and foundation model, has transformed robotics into a data-driven discipline capable of learning, generalization, and multimodal reasoning.

Large language models enable robots to interpret and generate natural language instructions, vision–language models provide semantic understanding of visual scenes, and large action models learn mappings from perception to sequences of physical actions. Together, these systems allow robots to operate in domains such as healthcare, logistics, agriculture, and disaster response, where classical control approaches are insufficient. Yet the intelligence enabling these capabilities is rarely embedded entirely within robotic platforms. Instead, it resides predominantly in remote datacenters that perform both training and inference at scale.

This architectural decoupling between physical robots and computational intelligence has fundamental ecological implications. Hyperscale datacenters consume rapidly growing amounts of electricity and water, contributing to greenhouse gas emissions, grid instability, and resource competition. As robotics becomes increasingly dependent on cloud-based AI, its environmental footprint becomes inseparable from that of global datacenter infrastructure.

## II. From Algorithmic Robotics to Foundation Models

The earliest robotic systems relied on control theory, finite state machines, and kinematic modeling to execute predefined tasks. Techniques that used algorithmic control ensured precise motions but required carefully engineered environments. These systems lacked learning capabilities and were unable to generalize beyond their programmed conditions – Fig.1.

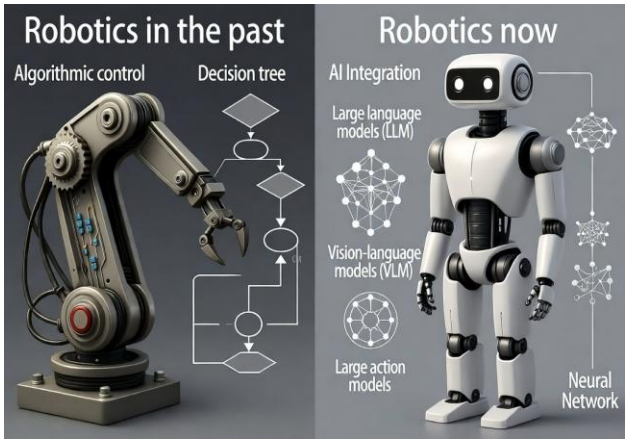


Fig. 1. Algorithmic vs AI enabled robotics control

The introduction of machine learning, and later deep learning, marked a turning point. Reinforcement learning enabled robots to optimize behavior through interaction with environments, while supervised learning improved perception tasks such as object recognition. More recently, foundation models have unified perception, reasoning, and action. LLMs allow robots to parse abstract instructions, VLMs integrate vision and language for contextual understanding, and LAMs generate coherent action sequences directly from sensory input. Systems such as RT-2 demonstrate how textual and visual representations can be mapped directly to robotic

ACKNOWLEDGE THE FINANCIAL SUPPORT OF THE PROJECT WITH FINANCING AGREEMENT NO. PVU-44 OF 05.12.2024 UNDER PROJECT NO. BG-RRP-2.017-0011 "ECOLOGICAL COLLABORATIVE ROBOTS POWERED BY GREEN HYDROGEN" UNDER THE RECOVERY AND RESILIENCE MECHANISM FOR THE IMPLEMENTATION OF AN INVESTMENT UNDER C2I2 "INCREASING THE INNOVATION CAPACITY OF THE BULGARIAN ACADEMY OF SCIENCES (BAS) IN THE FIELD OF GREEN AND DIGITAL TECHNOLOGIES" FROM THE RECOVERY AND RESILIENCE PLAN, BULGARIA.

actions, reducing the need for hand-engineered pipelines [16,17].

These advances, however, require models with billions of parameters trained on massive datasets. The computational cost of training and serving such models has shifted robotics toward centralized computing facilities, fundamentally altering its environmental impact profile.

## III. Datacenter-Centric AI and Rising Power Density

Modern AI models are trained and deployed in hyperscale datacenters operated by major technology firms. Unlike earlier enterprise datacenters designed for general-purpose workloads, AI datacenters are optimized for massively parallel computation using GPUs and specialized accelerators. This shift is reflected most clearly in rack-level power density.

In the early 2000s, typical datacenters operated at approximately 2–4 kW per rack [2]. By the late 2010s, cloud computing and early GPU adoption raised this figure to 10–15 kW. In the current AI-driven era, power densities of 40–140 kW per rack are increasingly common – Fig. 2, driven by dense GPU and TPU clusters optimized for neural network training and inference [1,3].

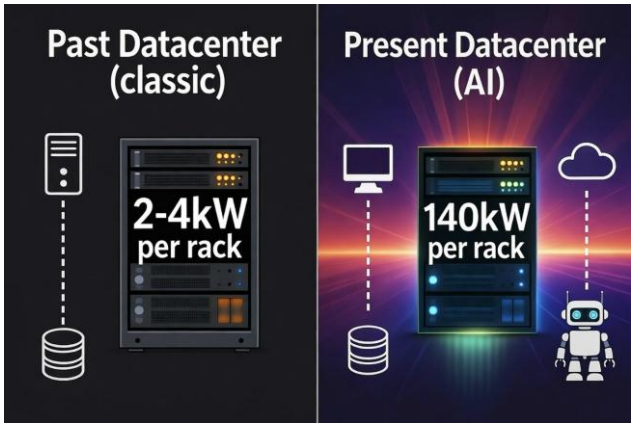


Fig. 2. Typical datacenter rack consumption comparison

The consequences of this escalation are multifold. Higher power density increases heat generation, necessitating advanced cooling solutions and raising operational costs. At a macro scale, datacenters already account for 1–2% of global electricity consumption, with projections suggesting this could rise to 8–10% by 2030 under continued AI growth [8]. Because many electrical grids remain partially fossil-fuel based, AI-driven robotics indirectly contributes to increased carbon emissions.

## IV. Case Studies: Gigawatt-Scale AI Infrastructure

### A. xAI Colossus

xAI's Colossus supercomputer, located in Memphis, Tennessee, exemplifies the scale of contemporary AI infrastructure. Operational since 2024, Colossus integrates more than 100,000 GPUs and reportedly consumes between 0.3 and 0.5 GW of power, with expansion plans approaching gigawatt levels [12]. Due to local grid constraints, the facility has relied in part on gas turbines, raising concerns about emissions and regulatory oversight [24]. Although Colossus enables rapid training of large action models relevant to AI and robotics, its environmental footprint highlights the tension between speed of deployment and sustainability.

### B. OpenAI Stargate

OpenAI's Stargate initiative represents an even more ambitious vision. Planned as a multi-phase network of datacenters, Stargate is projected to require up to 7 GW of power and investments on the order of hundreds of billions of dollars [14]. Facilities such as the Abilene, Texas site, with a planned capacity of approximately 1.2 GW, underscore the emergence of AI infrastructure comparable in scale to major urban power consumers [15]. While these facilities are intended to support advances in LLMs, VLMs, and robotics, they also magnify ecological pressures on energy and water systems.

## V. Cooling, Water Consumption, and Local Impacts

Energy consumption represents only one dimension of the environmental footprint of modern AI-oriented datacenters. Equally critical, yet often less visible, is the issue of thermal management and its associated water demand. The extreme power densities characteristic of contemporary AI hardware that frequently exceeds 100 kW per rack results in substantial heat generation that must be continuously dissipated to maintain system reliability and performance. Current cooling strategies rely predominantly on water-intensive methods, making water consumption a central sustainability concern in the operation of AI infrastructure supporting modern robotics.

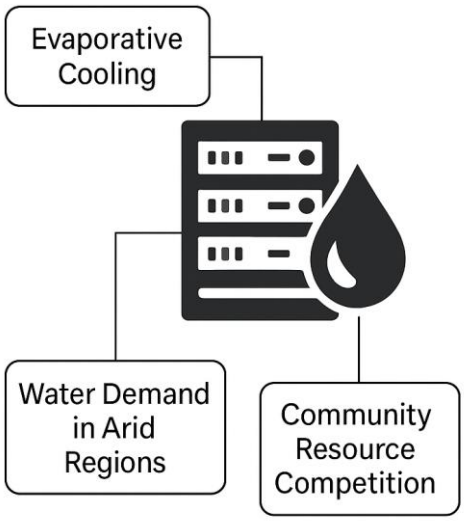


Fig. 3. AI datacenters water challenges

The most widely deployed cooling approach in hyperscale datacenters is evaporative cooling, which exploits the latent heat of vaporization of water to remove thermal energy from server environments - Fig 3. While highly effective in reducing energy overhead compared to purely air-based

cooling, evaporative systems consume large volumes of freshwater. Estimates indicate that a single medium-sized datacenter may require on the order of 400 million liters of water annually, depending on climate, cooling design, and operational load [4]. As AI workloads continue to scale, both in model size and inference frequency, this demand is expected to increase correspondingly.

The implications of such water usage are particularly severe in arid and semi-arid regions, where datacenters are often located due to favorable land availability, tax incentives, and proximity to power infrastructure. In these contexts, datacenter water consumption directly competes with municipal, agricultural, and ecological needs. Reports from communities adjacent to large AI facilities describe declining groundwater levels, degraded water quality, and heightened vulnerability during drought periods [5]. These localized impacts illustrate how global AI infrastructure decisions can produce disproportionate environmental burdens at the community level.

Projections suggest that, if current trends persist, AI-driven datacenters could collectively consume up to 1.7 trillion gallons of water annually by 2030 [5]. Such figures raise concerns not only about sustainability but also about long-term resilience in the face of climate change. Increasing temperatures and more frequent droughts are likely to intensify cooling demands precisely when water availability becomes more constrained, creating feedback loops that further stress both technological and natural systems.

Beyond physical resource depletion, water consumption by datacenters introduces ethical and governance challenges. In several documented cases, communities subject to water-use restrictions for residential or agricultural purposes coexist with datacenters that operate under separate regulatory frameworks or receive preferential access to water resources. This asymmetry raises questions regarding environmental justice, transparency, and the prioritization of essential human needs over commercial computational activities. For robotics, whose societal value is often framed in terms of public benefit: such as healthcare, safety, and sustainability - these contradictions warrant particular scrutiny.

Efforts to mitigate water-related impacts include the adoption of closed-loop cooling systems, increased use of reclaimed or non-potable water, and the relocation of datacenters to regions with more abundant water resources. However, such measures introduce trade-offs, including higher capital costs, increased energy consumption, or the displacement of environmental pressures to other regions. As with energy consumption, water use in AI datacenters must therefore be understood as a systemic issue rather than a purely technical one.

In summary, cooling and water consumption constitute a critical but underappreciated component of the ecological footprint of AI-driven robotics. As robotic intelligence becomes increasingly dependent on centralized, high-density datacenter infrastructure, addressing water sustainability will be essential to ensuring that technological progress does not exacerbate existing environmental and social vulnerabilities.

## VI. Sustainability-Oriented Technological Pathways

Although the primary emphasis of this article is the identification and characterization of the ecological challenges associated with AI-driven robotics, a comprehensive assessment must also consider the technological pathways currently proposed as potential mitigations. These pathways should not be interpreted as finalized or universally applicable solutions. Rather, they represent active research directions aimed at reducing the environmental footprint of large-scale AI infrastructure that increasingly underpins robotic intelligence.

A frequently discussed pathway is the transition toward low-carbon baseload energy sources for datacenters. Among these, nuclear energy, particularly in the form of small modular reactors (SMRs) has gained renewed attention due to its capacity to deliver continuous, high-density power with minimal direct greenhouse gas emissions. Unlike intermittent renewable sources, nuclear power can provide the stable electricity supply required by AI datacenters operating at gigawatt scale. Several technology companies, in collaboration with government agencies, have announced exploratory investments in SMRs explicitly intended to support datacenter infrastructure, with pilot deployments anticipated later in the decade [6], [7]. Despite these advantages, nuclear integration remains controversial. Challenges related to regulatory approval, long-term waste management, safety assurance, and public acceptance persist, particularly when reactors are colocated with population centers or critical infrastructure. Nevertheless, from a purely energetic perspective, nuclear power remains one of the few viable options capable of supporting sustained AI growth without proportional increases in carbon emissions.

A second major research direction focuses on hardware specialization as a means of improving energy efficiency. Conventional AI datacenters rely heavily on general-purpose GPUs, which, while flexible, are not optimized for all classes of AI workloads. Application-specific integrated circuits (ASICs), neuromorphic processors, optical accelerators, and other non-von-Neumann architectures seek to reduce energy consumption by tailoring hardware design to the computational structure of neural networks. By minimizing data movement and exploiting parallelism at the architectural level, such systems can significantly reduce power draw per operation. Industry and research reports suggest that task-specific accelerators can achieve order-of-magnitude improvements in energy efficiency compared to general-purpose GPUs for selected workloads [9]. For robotics, where perception, planning, and action inference are frequently repeated at scale, these gains could translate into substantial reductions in the upstream energy cost of intelligence.

Bio-inspired and neuromorphic computing paradigms represent a complementary approach grounded in the principles of biological information processing. Spiking neural networks (SNNs), which encode information through sparse, event-driven spikes rather than continuous-valued activations, more closely resemble the operation of biological neurons. This sparse and asynchronous mode of computation enables significantly lower energy consumption, particularly when implemented on neuromorphic hardware. Experimental studies indicate that SNN-based controllers are well suited for

robotic tasks such as navigation, sensorimotor integration, and adaptive behavior under strict energy constraints [10]. While current neuromorphic systems remain limited in scale and programmability, they suggest alternative computational models in which intelligent behavior does not require extreme power density or centralized infrastructure.

Quantum computing is often cited as a longer-term possibility for alleviating the computational bottlenecks associated with training and optimizing large AI models. In principle, quantum algorithms could offer exponential or polynomial speedups for specific classes of optimization and learning problems, potentially reducing the energy required for training models relevant to robotics. However, contemporary quantum hardware remains highly experimental, characterized by limited qubit counts, short coherence times, and substantial overhead for error correction. As a result, the practical impact of quantum computing on near-term robotic AI workloads remains speculative, and its role should be regarded as exploratory rather than imminent [11].

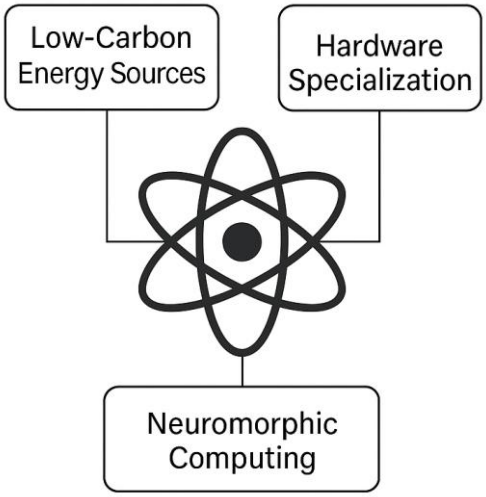


Fig. 4. Solutions of the data center energy problems

Finally, distributed and edge computing approaches aim to relocate portions of AI computation closer to robotic platforms, reducing latency and dependence on centralized datacenters. From an architectural standpoint, this decentralization can improve responsiveness and resilience in robotic systems operating in dynamic environments. However, distribution alone does not inherently reduce total energy consumption. In some cases, shifting computation to edge devices powered by less efficient or more carbon-intensive energy sources may increase overall emissions. Consequently, distributed computing should be viewed primarily as a performance and architectural optimization rather than a standalone sustainability strategy.

In aggregate, these technological pathways highlight the complexity of addressing sustainability in AI-driven robotics. Meaningful reductions in environmental impact are unlikely to result from a single intervention. Instead, progress will depend on the coordinated evolution of energy systems, hardware architectures, and computational paradigms, alongside policy and regulatory frameworks capable of accounting for the externalities of large-scale AI infrastructure.

## VII. Discussion and Conclusion

The integration of foundation models into robotics represents a fundamental paradigm shift, enabling unprecedented levels of autonomy and adaptability. However, this progress is underwritten by a rapidly expanding computational infrastructure whose environmental footprint is increasingly difficult to ignore. Rising power densities, escalating water consumption, and gigawatt-scale datacenter projects pose systemic sustainability challenges.

Addressing these challenges requires coordinated advances in energy generation, hardware efficiency, and computational paradigms, as well as policy frameworks that account for the externalities of AI infrastructure. Without such interventions, the ecological costs of intelligent robotics may undermine the societal benefits they promise. Sustainable robotics will therefore depend not only on smarter machines, but also on more responsible ways of powering and cooling the intelligence that drives them.

## ACKNOWLEDGMENT

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# A Design-Based Research Approach to Human–Machine Interface for Cobot Teleoperation

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***Abstract*— Collaborative robots (cobots) are increasingly deployed in industrial and research contexts, requiring intuitive human–machine interfaces (HMIs) for teleoperation. However, many existing interfaces are either too complex for non-expert users or lack portability across platforms. This study applies a Design-Based Research (DBR) methodology to the iterative design and evaluation of a modular HMI for cobot teleoperation. The interface was developed in Unity, enabling seamless transfer to mixed reality (MR) and virtual reality (VR) environments. The underlying architecture leverages the lightweight MQTT protocol for fast, reliable, and low-overhead communication between the operator's interface and the robot. Its modular design ensures adaptability to different types of cobots. Pilot experiments were conducted to validate system usability and communication latency. Findings show promising results in terms of responsiveness, modularity, and ease of adaptation.**
***Keywords*—design-based research; collaborative robots; human-machine interface; teleoperation; Unity; MQTT;***

## I. INTRODUCTION

Collaborative robots (cobots) are rapidly transforming industrial, service, and research domains due to their ability to operate safely in close proximity with humans. Unlike traditional industrial robots, which are typically confined to cages and require specialized programming skills, cobots are designed to be more adaptable, interactive, and user-friendly. They are now widely used in assembly, quality inspection, logistics, and healthcare, where flexibility and human–robot cooperation are essential [1]. A key challenge, however, lies in designing intuitive human–machine interfaces (HMIs) that allow operators with varying levels of technical expertise to effectively teleoperate cobots in dynamic environments.

Teleoperation remains an important function even in the age of increasing robot autonomy. Operators may need to take control in scenarios where human judgment, adaptability, or contextual awareness is required. Examples include precision assembly tasks, remote inspection in hazardous environments, and collaborative learning where the robot's autonomous decision-making is insufficient. However, current HMI solutions are often constrained by several factors: vendor-specific platforms that limit portability, steep learning curves for novice users, and limited support for emerging technologies such as mixed reality (MR) and virtual reality (VR) [2].

Developing HMIs in Unity offers an advantage here, as the engine natively supports both 2D desktop environments and immersive MR/VR deployments, enabling rapid transfer of interfaces across multiple devices and platforms. This flexibility makes Unity an attractive foundation for modular HMI design aimed at diverse cobot systems.

In addition to usability and immersion, communication performance is critical in teleoperation. High-latency or bandwidth-heavy communication channels can disrupt operator control, leading to inefficiency or even safety risks. For this reason, the present study adopts the MQTT protocol, a lightweight publish–subscribe communication standard optimized for fast and reliable data transfer. Originally designed for low-bandwidth IoT applications, MQTT is well suited to robotics because of its efficiency, scalability, and robustness under variable network conditions [3].

Finally, modularity is essential for ensuring that an HMI can be adapted across different cobot platforms. Many existing solutions are tied to specific hardware or proprietary middleware, which hinders knowledge transfer and slows down innovation. A modular architecture—where robot-specific drivers are separated from the interface logic—not only promotes reusability but also allows researchers and practitioners to rapidly adapt the system to new hardware. This adaptability is critical in research environments, where multiple cobots with diverse specifications (e.g., Franka Emika Panda, UR series, KUKA LBR) are often available.

To address these challenges, this paper applies a Design-Based Research (DBR) methodology to the iterative design and evaluation of a modular, Unity-based HMI for cobot teleoperation. DBR is particularly suitable for this purpose as it emphasizes iterative cycles of design, testing, and refinement within real-world contexts, ensuring that solutions are grounded in both theory and practice. Through this approach, we contribute not only a technical implementation but also design principles for developing adaptable, MR-ready teleoperation systems supported by lightweight communication protocols.

The main contribution of this study is the initial iteration in the development and validation of a prototype interface for the Franka Emika Panda Robot. Pilot experiments validated the feasibility of the system and highlighted strengths such as low-latency communication and responsive Unity-based interaction. At the same time, these tests identified areas for improvement, including expanding MR/VR functionality and conducting larger-scale usability studies. The results confirm the value of the DBR approach in guiding both system development and iterative enhancement.

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## II. Related Work

### A. Human-Machine Interfaces for Cobots Teleoperation

The development of human–machine interfaces (HMIs) for teleoperation has been studied in a variety of contexts, ranging from industrial robotics to medical and service applications. Traditional HMIs rely on joystick or teach pendant control, which, while robust, require extensive operator training and provide limited situational awareness in complex tasks. More recent research has emphasized the role of graphical user interfaces (GUIs) and web-based dashboards, which improve accessibility but often lack the intuitiveness needed for dynamic teleoperation [4].

Collaborative robots are shaping the future of the HMI in Industry 5.0, shifting from automation to human-centric design [5], that puts people at the center and introduces additional requirements for HMI design. Since cobots are intended to operate in close proximity to humans, interfaces must not only support direct teleoperation but also enable shared autonomy, monitoring, and safety-aware interventions. Studies have highlighted the importance of clear feedback loops—visual, auditory, and haptic—to ensure that operators maintain an accurate mental model of the robot's state during teleoperation [6]. However, many commercially available solutions remain tied to proprietary software stacks, limiting portability across platforms.

### B. Lightweight, Communication Protocols in Robotics

Communication is a critical factor in the performance of teleoperation systems. High data transfer overhead can introduce delays that negatively affect task execution and operator trust. Standard robotics frameworks, such as ROS, provide robust communication capabilities but can be resource-intensive in scenarios requiring lightweight, real-time responsiveness.

The MQTT protocol has recently gained attention in robotics for its lightweight publish–subscribe architecture. Originally designed for Internet of Things (IoT) applications, MQTT offers low overhead, efficient message delivery, and the ability to scale across multiple devices and networks. Research has shown that MQTT can achieve lower latency than traditional HTTP-based communication while maintaining high reliability. Its suitability for bandwidth-constrained or distributed systems makes it a strong candidate for cobot teleoperation, where rapid response and flexible integration are required [7].

### C. Modularity and Adaptability in Cobots Interfaces

One of the key challenges in teleoperation HMI research is the lack of modularity. Interfaces are often designed for a single robot platform, limiting their reuse in other contexts. Modularity has been identified as a critical design principle in both robotics middleware and user interface design, as it allows researchers and practitioners to adapt systems quickly to new tasks and hardware.

Recent work has explored middleware solutions that decouple robot-specific drivers from higher-level control and visualization logic. By using standardized communication protocols and modular software architectures, these systems aim to support a wide range of robots with minimal reconfiguration. For example, modular Unity-based front ends combined via MQTT to ROS back ends have been proposed to enable portability across multiple cobot platforms [9].

### D. Design-Based Research in Robotics Interfaces

Design-Based Research (DBR) has been applied in educational technologies, assistive systems, and increasingly in robotics, where iterative cycles of design, testing, and refinement are essential. Unlike controlled laboratory studies, DBR emphasizes contextualized development and collaboration with end users. In robotics, this means involving operators, engineers, and stakeholders in the design process to ensure that systems are both technically robust and practically usable.

Prior DBR studies in robotics have focused on socially assistive robots, adaptive learning platforms, and AI integration, highlighting the importance of modular architectures and user-centered design. Yet, there is a notable gap in DBR-driven research on teleoperation interfaces for cobots, particularly those designed to be transferable to MR/VR contexts. This study aims to address this gap by combining Unity-based immersive interface design, MQTT communication, and modular adaptability within a DBR framework.

## III. Methodology

This study follows a Design-Based Research methodology to guide the design, development, and evaluation of a human–machine interface for cobot teleoperation. DBR is particularly suitable for complex, socio-technical systems such as robotics, as it emphasizes iterative design, real-world testing, and close collaboration between researchers, practitioners, and end-users. The goal is not only to produce a working solution but also to extract generalizable design principles for future implementations.

The methodological framework adopted here is based on the four-phase model proposed by Reeves, consisting of Problem analysis through collaboration with stakeholders; Iterative design and development of solutions; Evaluation of the interventions in practice; Reflection and refinement of design principles.

### A. Phase 1: Problem Analysis

The first phase involved identifying the challenges and requirements associated with cobot teleoperation. A literature review was conducted to examine existing HMI solutions, focusing on usability, portability, MR/VR integration, and communication protocols. In addition, informal interviews were carried out with robotics researchers and engineers who regularly work with collaborative robots. From this analysis, several core challenges were identified:

- Usability barriers: Many cobot HMIs require significant technical expertise, limiting accessibility for non-specialists.
- Lack of portability: Vendor-specific platforms are difficult to transfer across cobot types or immersive environments.
- Communication inefficiencies: Existing frameworks often introduce unnecessary overhead, leading to latency during teleoperation.
- Limited modularity: Interfaces are often tightly coupled to a single robot, hindering adaptability.

These challenges provided the foundation for design principles guiding subsequent phases: Unity-based cross-platform development for MR/VR compatibility; MQTT-based lightweight communication for low latency; modular architecture to support multiple cobots platforms.

### *B. Phase 2: Iterative Design and Development*

Following the problem analysis, a prototype HMI was designed in Unity. Unity was chosen because it supports 3D visualization, immersive interaction, and cross-platform deployment to desktop, mobile, web, and MR/VR headsets. The prototype included core functionalities such as robot state visualization and direct teleoperation commands.

To ensure efficient communication, an MQTT broker was implemented as the middleware between Unity and the cobot. Unity clients published teleoperation commands (e.g., joint angles, Cartesian movements, gripper actions), while subscribing to robot state updates (e.g., position, force feedback, error states). The use of MQTT minimized latency and allowed for straightforward extension to additional devices or cobots.

The proposed architecture (Figure 2) was explicitly designed to be modular: robot-specific drivers were abstracted from the Unity interface logic. This enables rapid adaptation of the HMI to different cobots without redesigning the core interface. During development, simulation in Unity was used to test communication flows before deployment to physical robots, reducing risks and development time.

Iterative design cycles included building, testing, and refining the prototype based on feedback from early users (research engineers). Each cycle focused on improving usability, reducing latency, and enhancing modularity.

### *C. Phase 3: Pilot Evaluation*

Pilot experiments were conducted using the Franka Emika Panda cobot in a laboratory setting. Participants included robotics researchers familiar with teleoperation tasks but not necessarily with the specific interface. The evaluation aimed to capture both quantitative and qualitative data:

Quantitative measures:

- Communication latency (measured between Unity commands and cobots response).
- Task success rates (completion of object manipulation tasks under teleoperation).
- Error rates (unexpected robot behaviors or communication failures).

Qualitative measures:

- User perception of usability, intuitiveness, and responsiveness.
- Feedback on interface design, visualization, and workflow.

Although sample size was limited, the pilot tests provided critical insights into system performance and user experience. Results indicated that MQTT communication maintained latency around 50 ms in all experiments (Figure 1), while Unity provided intuitive visualization. Participants emphasized the potential of transferring the interface to MR/VR devices to further improve situational awareness.

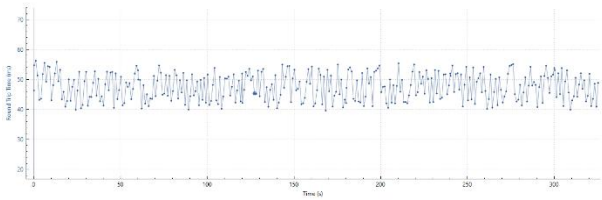

*Fig. 1 MQTT Round Tripe Time*

### *D. Phase 4: Reflection and Refinement*

The final phase of this iteration involved synthesizing lessons learned from the pilot evaluation and refining the design principles. Key outcomes included:

- Validation of Unity as a flexible platform for both desktop and immersive HMI development.
- Confirmation of MQTT's suitability for lightweight, real-time teleoperation.
- Recognition of the importance of modularity for cross-cobots adaptability.
- Identification of areas for future work, including large-scale usability testing, MR/VR integration, and incorporation of multimodal feedback (e.g., haptics).

By following the DBR cycle, the research not only delivered a functional prototype but also contributed to a broader understanding of how to design adaptable HMIs for cobot teleoperation.

## IV. System Architecture

The proposed system architecture was designed to support three overarching requirements: cross-platform transferability, lightweight and responsive communication, and modularity across different cobot platforms. To achieve these goals, the system is structured around three interconnected layers: the Unity-based human–machine interface, the MQTT communication middleware, and the cobot execution layer with modular adapter (Figure 2).

At the front end, the Unity environment functions as the operator-facing interface. Unity was selected because it allows a seamless transition between standard desktop interaction and immersive deployment in mixed or virtual reality. Within this interface, operators are presented with real-time visualizations of the robot's state and task environment, as well as direct mechanisms for issuing control commands. By integrating Unity's rendering capabilities, the interface facilitates a more natural and intuitive form of interaction compared with traditional two-dimensional dashboards.

Communication between the HMI and the robot is managed by an MQTT broker, which mediates the flow of information between Unity and the cobot execution layer. Unlike heavier communication frameworks, MQTT is a lightweight publish–subscribe protocol that reduces both network overhead and latency. In practice, this means that operator commands can be transmitted to the robot with delays consistently around 50 milliseconds, while feedback from the robot is immediately routed back into the Unity interface. The broker-based architecture also enables multiple cobots or monitoring clients to be connected simultaneously, highlighting the scalability of this approach.

The final layer of the system is the cobot execution environment, which is accessed through modular adapters.

Each adapter serves as a translator between the generic MQTT topics and the proprietary instruction set of a particular robot. For instance, an adapter has been developed for the Franka Emika Panda that allows both joint-level and Cartesian teleoperation. Additional adapters can be implemented with relative ease, ensuring that the interface is not bound to a single robot model. This modular design principle isolates robot-specific functionality from the rest of the system, preserving the generality of the Unity interface and the communication layer.

Interaction across these three layers forms a continuous feedback cycle. The operator issues commands in Unity, which are transmitted via MQTT to the appropriate adapter, executed by the robot, and then reported back through MQTT to update the interface. This closed-loop process maintains synchronization between operator input and robot action, while ensuring that the operator is constantly informed about the robot's state and environment.

Taken together, the Unity interface, the MQTT communication layer, and the modular adapters form an architecture that is not only technically efficient but also highly adaptable. The design supports rapid integration with different cobot platforms, ensures low-latency responsiveness necessary for teleoperation, and provides a natural pathway for extension into immersive MR and VR environments. In this way, the architecture balances immediate experimental functionality with long-term flexibility and scalability.

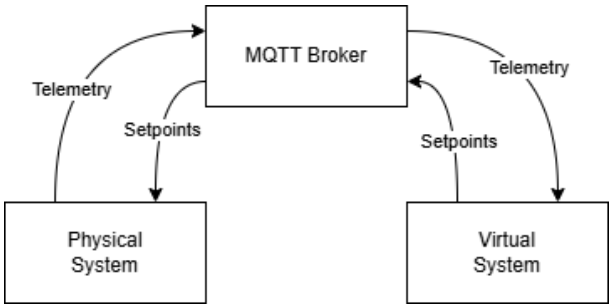


*Fig.2 System architecture for modular cobots teleoperation*

## V. Discussion, Conclusions and Future Work

The design and evaluation of the proposed teleoperation interface highlight the potential of combining Unity, MQTT communication, and modular robot adapters within a design-based research framework. The system was deliberately structured to meet three critical requirements: cross-platform transferability, low-latency communication, and adaptability to different cobot platforms. Each of these requirements was addressed by specific architectural choices that not only functioned well in isolation but also reinforced each other when combined into a coherent whole.

The Unity-based interface played a central role in ensuring usability and flexibility. Unlike traditional teach pendants or text-based programming environments, Unity provided a visual and interactive layer that allowed operators to directly understand and influence robot behavior. This is particularly important in teleoperation contexts, where clear visualization of the robot's state and workspace can significantly reduce operator workload and errors. Moreover, Unity offered a natural pathway toward immersive mixed reality and virtual reality applications. Even though the pilot experiments focused on a desktop environment, the underlying design ensures that the same interface can be transferred to MR or VR headsets with relatively minor adjustments. This opens promising avenues for future work, as immersive visualization is expected to further enhance situational awareness, precision, and overall operator performance.

Equally important was the use of MQTT as the communication backbone. In robotics, communication frameworks are often burdened by complexity or heavy network demands. By contrast, MQTT offered a lightweight and efficient alternative, enabling near real-time responsiveness with measured latencies consistently around 50 milliseconds during pilot tests. For teleoperation, where delays directly impact control quality and user trust, this level of responsiveness is a crucial achievement. Furthermore, MQTT's publish–subscribe architecture supports scalability, meaning that multiple cobots, monitoring systems, or auxiliary devices can be integrated into the same environment without overhauling the communication infrastructure. This flexibility positions the system as a viable solution not only for single-cobot teleoperation but also for more complex scenarios involving multi-robot collaboration.

The third pillar of the architecture, modular adapters, addressed the challenge of hardware dependence. Many existing teleoperation interfaces are tightly bound to specific robots, making them difficult to reuse or extend. By introducing adapters that translate MQTT messages into robot-specific commands, the proposed system isolates hardware dependencies and preserves the generality of the Unity interface and the communication middleware. This design principle proved successful in the case of the Franka Emika Panda and sets the stage for broader applicability to other platforms such as UR cobots, ABB robots. However, realizing this potential will require further empirical testing to ensure that the adapters remain robust and reliable across diverse hardware ecosystems.

While the pilot experiments confirmed the feasibility of the architecture, they also revealed important limitations. The current system was tested only with a small group of research engineers, which limits the generalizability of the findings. Larger-scale studies involving operators with varying levels of experience will be needed to fully assess usability, learning curves, and long-term adoption potential. Furthermore, the experiments were conducted in a controlled laboratory setting, which does not capture the full complexity and unpredictability of industrial environments. Extending the evaluation to more realistic contexts, such as factory floors or collaborative assembly tasks, will provide richer insights into the system's practical value.

From a methodological perspective, the design-based research approach proved to be a valuable framework for structuring development. By combining theoretical design principles with iterative testing and refinement, DBR ensured that the system evolved in response to both technical requirements and user needs. The pilot evaluation, although limited, provided concrete feedback that informed the refinement of the design principles. Future iterations of the DBR cycle will focus on immersive MR/VR integration and long-term usability assessments, thereby strengthening the system's foundations and broadening its applicability.

In conclusion, the study demonstrates that a modular, Unity-based teleoperation interface supported by lightweight MQTT communication can offer a scalable, adaptable, and user-friendly solution for cobot teleoperation. The architecture successfully addresses the challenges of portability, latency, and hardware independence, while laying the groundwork for future expansion into immersive environments. The pilot results provide initial validation of these design choices, while also pointing to areas requiring further research and refinement. Moving forward, the project will concentrate on extending MR/VR functionality, conducting larger-scale evaluations, and exploring scenarios involving multiple cobots. By following an iterative DBR process, the system is expected to evolve into a robust platform that not only advances academic research but also provides practical solutions for the growing field of collaborative robotics.

## ACKNOWLEDGMENT

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# Simulation-Based Digital Twins for Robotic Cybersecurity Testing with AI-Driven Adaptive Defence

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***Abstract*—Robotic and mechatronic systems are increasingly connected via open communication protocols and cloud services, exposing safety-critical operations to cyber threats such as spoofing, denial-of-service, and data poisoning [4], [5]. Testing security measures directly on physical robots is costly, disruptive, and often unsafe. This paper proposes a simulation-based digital twin (DT) framework that faithfully replicates a robotic system's kinematics, dynamics, and network behaviour in a virtual environment, enabling risk-free cybersecurity experimentation. Within this DT, an artificial intelligence (AI)–driven adaptive defence module combines traffic-based anomaly detection with reinforcement learning agents that learn to respond to evolving attacks by reconfiguring control or communication policies. A conceptual proof-of-concept testbed is presented using a simulated ROS 2 2-controlled manipulator subjected to synthetic network intrusions. Preliminary simulation results indicate that the adaptive AI defence detects malicious traffic earlier and restores normal operation faster than a static rule-based intrusion detection system. The study highlights digital twins as a practical, low-risk platform for developing and validating next-generation cybersecurity strategies for robotic systems.**

***Keywords—AI-Augmented Digital Twins, Robotic Cybersecurity, Resilient Robotics, Real-Time Simulation Intelligent Threat Mitigation, Adaptive System Defence, Simulation-Driven Security.***

## I. INTRODUCTION

Robotic and mechatronic systems move rapidly from isolated, pre-programmed machines toward networked, adaptive cyber-physical systems [9]. Modern industrial manipulators, collaborative robots (cobots), autonomous mobile robots (AMRs), and smart production cells routinely connect to enterprise networks, cloud platforms, and remote maintenance services. While this connectivity enables flexible production and real-time monitoring, it also broadens the attack surface [2]. Network intrusion, spoofed sensor data, denial-of-service (DoS), and machine-learning model poisoning have already been demonstrated against robotic middleware such as the Robot Operating System (ROS/ROS 2) [4]; [5].

Traditional approaches to robot cybersecurity testing rely on laboratory hardware setups or penetration tests performed on physical robots. These methods face several barriers:
Safety and cost: Aggressive attack simulation can damage equipment or stop production.

Limited repeatability: Physical experiments are time-consuming and sensitive to hardware differences [11].
Restricted access: Researchers often lack specialized robot hardware or cannot change production systems for security testing.

Consequently, many proposed security solutions for robotics remain conceptual or poorly validated.
Digital twins (DTs) — high-fidelity virtual replicas of physical systems — have emerged as robust tools for design, monitoring, and predictive maintenance. However, their potential for cybersecurity research in robotics is only starting to be explored [7]; [14]. A DT can integrate accurate physics simulation with network and software emulation to create a safe, controllable environment for injecting cyber-physical threats and evaluating defences before deployment.

Parallel to this, artificial intelligence (AI) — especially machine learning–based anomaly detection and reinforcement learning (RL) — has shown promise for adaptive cyber defence. Unlike static, rule-based intrusion detection systems (IDS), AI can learn to recognize evolving attack patterns and dynamically adjust control or communication strategies to maintain safe operation [6]; [15].

This paper proposes a simulation-based DT framework for robotic cybersecurity testing and AI-driven adaptive defence.
The key contributions are:
Digital twin architecture for secure robotics: a virtual testbed that models robotic kinematics/dynamics and network behaviour to support safe cyber-attack experimentation.
AI-driven adaptive defence module: integration of anomaly detection and RL-based mitigation policies trained entirely in simulation.

Proof-of-concept evaluation: a conceptual study using a ROS 2 2-controlled manipulator, demonstrating how AI-enabled defence can reduce detection latency and recovery time compared with static IDS approaches.
This work is intended for researchers and practitioners who lack access to physical robots but need a risk-free environment to design and validate security mechanisms for robotic and mechatronic systems.

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## II. Background and Related Work

### A. Digital Twins in Robotics and Mechatronics

The **Digital Twin (DT)** concept originated in aerospace and manufacturing, where high-fidelity virtual models are continuously synchronised with their physical counterparts. DTs have become key enablers for **simulation-driven design, predictive maintenance, and system optimisation in robotics** [3].

A typical robotic DT integrates three layers:

1. **Physical Layer** – the actual robot and its environment;
2. **Virtual Layer** – a physics-based simulation replicating kinematics, dynamics, and sensor feedback;
3. **Data Synchronisation Layer** – bidirectional data exchange that ensures the virtual model mirrors the physical state in near real time.

Modern simulation tools such as **Gazebo, Webots, CoppeliaSim, and Unity Robotics** support the creation of DTs that accurately mirror mechanical and control behaviour. Recent work extends DTs with **network emulation and cloud connectivity**, allowing researchers to study latency, packet loss, or system integration across Industrial IoT architectures [12]. However, DTs are rarely applied beyond performance optimisation or maintenance. Their potential as **cybersecurity sandboxes**—where virtual replicas are used to simulate and analyse cyber-physical threats without risking hardware—remains underexplored [7].

### B. Cybersecurity Challenges in Robotic Systems

Networked robots operate as **cyber-physical systems (CPS)**, integrating embedded controllers, sensors, actuators, and network interfaces [1]. This tight coupling introduces vulnerabilities across multiple layers:

- **Communication Layer:** protocols such as ROS 1/ROS 2, OPC UA, and MQTT were designed for openness rather than confidentiality [4]. Research shows robots can be compromised via spoofed commands, replayed sensor data, and adversarial perception attacks [10]; [13].
- **Control Layer:** unauthorised modification of parameters or firmware manipulation can degrade precision or cause unsafe motion.
- Perception **Layer:** adversarial inputs to camera or LIDAR sensors can mislead AI-based perception modules.

Existing defensive measures are largely **static**—network firewalls, signature-based intrusion detection, or cryptographic authentication (García et al., 2014). These solutions struggle against **dynamic, adaptive attacks** in heterogeneous environments typical of Industry 4.0 robotic cells. Moreover, testing such defences on operational robots is impractical due to safety and downtime constraints, highlighting the need for **simulation-based security validation**.

### C. AI-Driven Adaptive Defence Mechanisms

Artificial intelligence techniques are increasingly being investigated to enhance cyber resilience. **Machine-learning-based intrusion detection systems (ML-IDS)** can identify abnormal traffic patterns using statistical, supervised, or unsupervised models such as support vector machines, autoencoders, and graph neural networks [6].

Beyond detection, **reinforcement learning (RL)** enables systems to select mitigation actions autonomously—e.g., rerouting communication, isolating components, or adjusting control parameters—to maintain safe operation during an attack [15].

Recent studies in industrial networks and autonomous vehicles show that **AI-enabled agents can outperform static rules** by learning temporal patterns of attacks and responding in real time [8]. Nevertheless, most of these approaches are evaluated using simplified network traces or theoretical models rather than in realistic robotic control loops.

### D. Research Gap and Motivation

While DTs and AI have been widely explored individually, **their integration for robotic cybersecurity remains limited** [7]. No standardised, simulation-based frameworks currently exist for training and validating AI-adaptive cybersecurity mechanisms on robotic control loops. Current literature seldom combines a **virtual robotic twin** with **AI-adaptive defence agents** that can learn and test mitigation strategies entirely in simulation.

Bridging this gap can provide:

- A **risk-free environment** for attack injection and defence training;
- Quantitative insights into detection latency, false-positive rates, and control-loop stability under attack;
- A reusable framework for researchers without physical hardware access.

### E. Conceptual Integration and Research Evolution

To consolidate the insights from the reviewed literature, Figure 1 illustrates the conceptual convergence among Digital Twins (DT), Artificial Intelligence (AI), and Cybersecurity (CS) within the robotics domain.

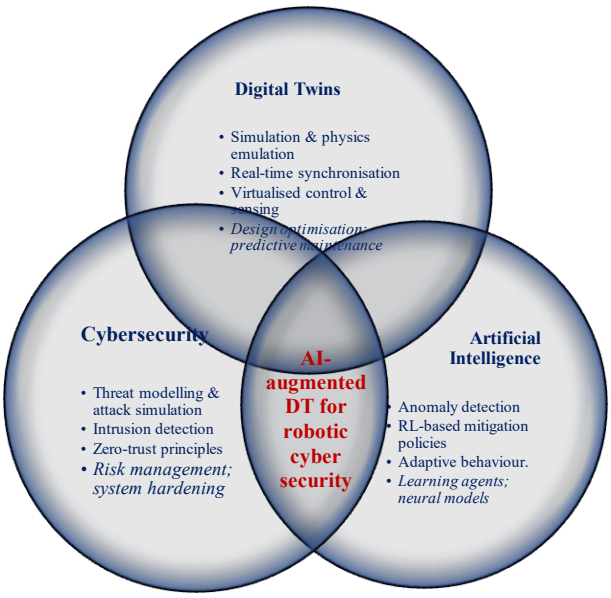


Fig. 1. Conceptual convergence of DT, AI, and SC domains.

DT provides the simulation backbone for virtual experimentation, AI contributes learning and adaptive decision-making capabilities, and CS ensures data integrity, confidentiality, and system resilience.

The overlapping area among these three domains defines the research focus of this study – the development of an AI-Augmented DT for Robotic Cybersecurity. The intersection defines the proposed research focus: AI-Augmented DT for Robotics Cybersecurity.

Building on this conceptual mapping, Figure 2 illustrates the evolutionary trajectory of robotic systems from traditional, isolated industrial machines toward intelligent, networked, and cyber-physical systems.

Each stage represents a significant milestone in the digital transformation of robotics—from deterministic control logic to cloud-connected architectures, and finally to simulation-driven, AI-enhanced defensive ecosystems. This timeline underscores that AI-enabled DT Security is not an isolated concept but the next logical phase in the technological evolution of robotics.

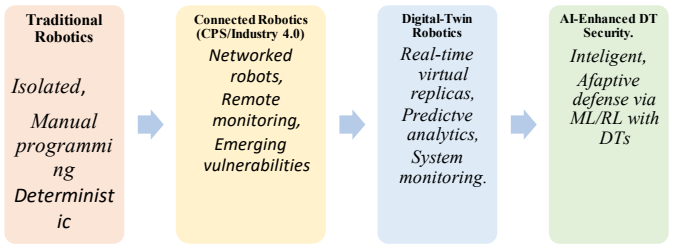


Fig. 2. Evolution of robotics from isolated industrial units towards AI-enhanced DT security environments.

The timeline highlights the transition from deterministic control to adaptive, learning-based cyber-physical defence.

These two figures illustrate the theoretical convergence and technological evolution that motivate the framework proposed in this paper. While Figure 1 defines the study's interdisciplinary foundation, Figure 2 positions the research within the ongoing digital transformation of robotics, establishing a clear context for the Proposed Digital Twin Security Testbed described in the following section.

## III. Proposed Digital Twin Security Testbed

This section describes the design and internal mechanics of the **Digital Twin Security Testbed (DTST)** used throughout this study. The DTST is a fully simulated, modular environment that enables rapid, reproducible experimentation with cyber-physical attacks and AI-driven mitigation strategies for robotic systems. The design follows five core components: (1) virtual robot model, (2) network emulation, (3) threat injection engine, (4) AI defence module, and (5) synchronization & simulation loop. These components operate in a closed feedback cycle that supports iterative learning and quantitative evaluation.

*1) Virtual robot model (physics & control)*

The DTST's heart is a **virtual robot model** that provides realistic kinematic and dynamic behaviour without requiring physical hardware. Our reference setup uses a 6-DoF industrial manipulator model implemented in a physics simulator (e.g., Gazebo or ODE within Gazebo / Webots). The simulator exposes:

*2) Joint-level states (position, velocity, torque) and* sensor streams (encoders, force-torque, IMU, camera/LIDAR placeholders).

*3) A control interface representing a typical* PLC/robot controller loop (PID/trajectory follower) that subscribes to command topics and publishes telemetry.

*4) Pluggable model fidelity (collision geometry, friction, sensor noise) so experiments can trade realism for computational efficiency.*

The virtual robot provides the baseline "normal" behaviour used to train anomaly detectors and to measure the impact of attacks on motion accuracy, task completion, and safety-related metrics.

### *B. Network emulation: ROS 2 traffic, delay/jitter injection, replay*

To model real-world cyber conditions, the DTST includes a **network and communication emulator** tightly coupled with the virtual robot:

- Middleware emulation: ROS 2 is the primary

  Middleware replica, including publishers/subscribers, quality of service settings, and topic namespaces typical for manipulator controllers and perception stacks.

- Network **impairments:** A configurable emulator layer injects latency, jitter, packet loss, and bandwidth constraints into message flows. Parameters are adjustable per topic to simulate congested Ethernet, wireless links, or intermittent corporate VPNs.

- **Trace** replay**:** recorded ROS 2 traffic traces

  (benign and malicious) can be replayed deterministically for benchmarking. This supports reproducibility and the construction of standardized test suites.

This emulation enables the study of how timing and message-reliability deviations affect closed-loop control and AI perception modules.

### *C. Threat Injection Engine (DoS, spoofing, data poisoning)*

The **Threat Injection Engine (TIE)** is the adversarial controller that generates controlled attack vectors. It supports three classes of attacks relevant to robotic CPS:

*1)* ***Denial-of-Service (DoS) / Flooding:*** rapid message bursts targeting specific topics (e.g., /joint_cmd) or nodes (controller) to saturate throughput and increase latency—parameters: packets per second, duration, target topic list.

*2)* ***Spoofing / Replay:*** forging or replaying ROS 2 messages to substitute control commands or sensor readings. Modes include immediate injection, delayed replay, and gradual drift insertion—parameters: injection timing, amplitude, and topic filter.

*3)* ***Data Poisoning:*** progressive modification of sensor streams (e.g., adding bias to encoder readings or corrupting vision inputs) intended to mislead learning-based perception or degrade controller performance—parameters: poison rate, distribution, entry point.

Each scenario is parameterizable and can be orchestrated in campaigns (sequence of attacks with escalation), enabling stress-testing of detection and mitigation strategies. All injected events are logged with ground-truth labels for supervised evaluation.

*D. AI defence module: anomaly detection + RL mitigation policy*

The AI defence stack is divided into two cooperating subcomponents—real-time anomaly detection and a reinforcement learning (RL) mitigation policy—supported by analytics for evaluation.

*1) Anomaly detection (online monitoring)*

*a)* ***Input features:*** topic-level message rates, inter-arrival times, payload statistics (e.g., mean/variance of joint positions), control error residuals (difference between commanded and observed states), and lightweight derived features (spectral, time-windowed aggregates).

*b)* ***Model family:*** unsupervised models are preferred for zero-day detection, including sequence autoencoders, isolation forests, and, where topology matters, graph-based detectors on the ROS node-topic graph.

*c)* ***Decision logic:*** anomaly score → thresholding → alert. Thresholds are calibrated using baseline simulation runs to balance detection latency and the false-positive rate. Alerts are timestamped and routed to the RL agent input.

*E. Reinforcement learning mitigation (policy layer)*

*a)* ***State definition:*** concatenation of anomaly flags, current network Quality of Service metrics, recent control errors, and a short history of system telemetry (sliding window).

*b)* ***Action space:*** a discrete set of mitigations, Examples: (a) temporarily throttle or drop non-critical topics, (b) isolate suspect node(s) from the bus, (c) switch to a degraded safe controller mode (lower speed/torque limits), (d) trigger sensor cross-validation routines, (e) initiate topic re-authentication handshake.

*c)* ***Reward function:*** *multi-objective — negative* penalties for unsafe behaviour (significant control error, collision risk), penalties for unnecessary interventions (avoiding overreaction), positive reward for task completion, and quick recovery to baseline performance. Reward shaping encourages conservative but effective interventions.

*d)* ***Training regime:*** *RL is trained entirely within* the DTST using episodic simulations containing randomized attacks. Transfer learning/domain randomization techniques are applied to improve robustness across variations in simulation parameters.

*F. Operational constraints*

*1)* Mitigation actions must adhere to safety invariants (e.g., never issue commands that exceed joint limits). A safety supervisor enforces hard constraints to prevent learned policies from producing unsafe control commands even in simulation.

*2)* Synchronization & simulation loop (data consistency & reproducibility)

The DTST enforces strict synchronization to preserve temporal coherence across modules:

*3)* Global simulation clock: a central time server (simulated wall clock) coordinates physics ticks, message timestamps, and attack injection events. This ensures that telemetry, anomaly detection inputs, and RL actions are aligned.

*4)* ***Deterministic logging:*** All regular and injected messages are recorded with high-resolution timestamps and ground-truth labels. Logs enable deterministic replay for benchmarking and for offline ML training.

*5) Simulation loop cadence:* The system supports variable tick rates (e.g., 100–1000 Hz for physics; 10–100 Hz for middleware), configurable per experiment. Rate limits are documented to clarify real-time vs. accelerated training modes.

*6) Evaluation metrics and experimental protocol (summary)*

To quantify defence performance, the DTST reports standardized metrics per run:

*a)* ***Detection latency:*** time from attack start to anomaly flag.

*b)* ***Detection accuracy*****:** true/false positive rates on labelled logs.

*c)* ***Recovery time*****:** time until key performance indicators (KPIs) return within baseline bounds (e.g., tracking error below threshold).

*d)* ***Operational impact:*** task completion rate, additional downtime introduced by mitigation, and computational overhead (CPU/latency of defence stack).

Experiments follow a rigorously documented protocol: (a) baseline calibration runs (no attack), (b) single-attack experiments, (c) multi-attack combined scenarios, and (d) randomized campaign stress tests. Each experiment is repeated deterministically with seeded randomness to produce statistically meaningful results

*7) Assumptions and limitations*

*a) Simulation fidelity vs. reality gap:* while physics and network emulation are high-fidelity, but the absence of hardware introduces sim2real risk; we mitigate this by domain-randomizing simulation parameters.

*b) Scope***:** This DTST focuses on the middleware-level and sensor/command attacks, and does not model low-level firmware exploits or hardware fault modalities.

*c) Safety fallbacks*: because this study is simulation-only, safety logic is enforced as hard checks; deploying learned policies to physical robots would require an independent safety validation step.

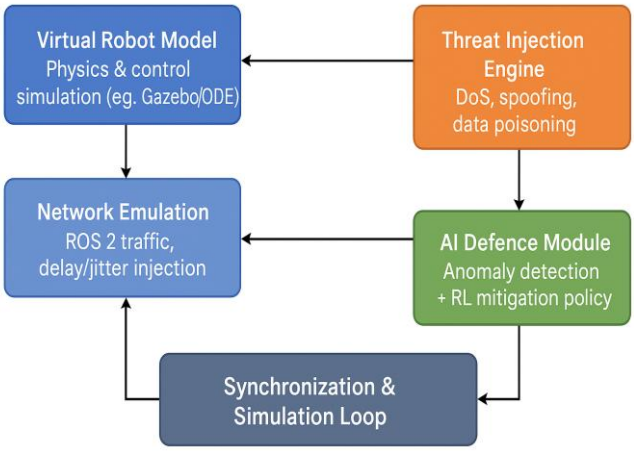


Fig. 3. Visualize the five components in a closed loop: Virtual Robot Model ↔ Network Emulator ↔ Threat Injection Engine → AI Defence Module → Synchronization & Replay / Logging, with arrows indicating data flow and control.)

## IV. Simulation Experiment Design (Conceptual)

This section describes the experimental protocol for evaluating the Digital Twin Security Testbed (DTST). The goal is to produce reproducible, statistically meaningful comparisons between static detection baselines and the proposed AI-adaptive defence under controlled, parameterised attack campaigns. The design is intentionally simulation-centric: all experiments are executed within the DTST (Section 3) using a virtual manipulator model, ROS 2 traffic emulation, and the threat-injection engine.

### *A. Attack scenarios*

We model three (and one combined) canonical attack classes targeted at robot middleware and sensor channels. Each attack class is parameterised to enable graded stress tests and campaign compositions. Each scenario is fully logged with ground-truth labels, enabling quantitative evaluation of detection and mitigation performance (Table I).

TABLE I. Parameterised attack scenarios used in the DTST experiments.

| Attack class | Target | Mode/ Description | Example parameters (tunable) | Intended effect on DTSD | Logging & Ground-truth |
|---|---|---|---|---|---|
| **Denial-of-Service (DoS) / Flooding** | Control topics (e.g./ joint_cm), status topics, controller nodes, network interface | High-rate message bursts aimed at saturating bandwidth or queues; may be broad (network-wide) or targeted (specific topic/node) | Packet-rate multiplier (×), duration (s), target topic list, start time, burst pattern | Increased latency/jitter, missed deadlines, control jitter, possible missed commands leading to tracking error or task failure | Timestamped attack start/stop; targeted topics; packet counts; ground-truth label = DoS |
| **Spoofing / Replay** | Topic payloads (commands, sensor messages), ROS 2 topics, node outputs. | Injection of forged messages or replay of recorded messages (immediate, delayed, or time-shifted) to mislead controller or perception. | Injection amplitude (payload deviation), injection frequency, delay offset (s), entry-point node, replay trace ID. | Controller executes forged commands or acted on stale/duplicated sensor inputs; wrong trajectories or unsafe behavior. | Record injected message content, orig vs injected timestamps; ground-truth label = Spoof/Replay |
| **Data Poisoning** | Sensor streams (encoder, IMU, camera placeholders), perception inputs, telemetry used by learning modules | Gradual or abrupt corruption of sensor/data used by perception or control; may bias, spike or flip labels used by ML. | Poison rate (% messages), noise distribution (Gaussian bias, spike), onset schedule (gradual vs abrupt), affected sensor(s) | Degraded perception accuracy, drifting state estimates, ML misclassifications, increased control errors over time | Logged corrupted stream with original vs poisoned values; ground-truth label = Poison |

TABLE II. Combined attacks and randomized campaigns

| Atack class | Target | Mode/ Description | Example parameters (tunable) | Intended effect on DTSD | Logging & Ground-truth |
|---|---|---|---|---|---|
| Combined / Campaigns | Any combination of above; multi-stage campaigns | Sequences or stochastic mixes of attacks (e.g., DoS then spoofing), escalation patterns or randomized campaigns for stress testing | Campaign script (ordered attacks), random seed, escalation schedule, inter-attack interval | Test robustness to multi-vector attacks; examines cumulative impact & defense generalization | Campaign script + per-event labeling; global campaign ID; timestamps for each sub-attack |

### *B. Evaluation metrics*

We adopt standard detection and system-level metrics and introduce control-centric KPIs relevant for robotics. Table 3 summarises the **evaluation metrics** adopted to assess the performance of the AI-driven adaptive defence within the Digital Twin Security Testbed.

[1] **Campaigns:** Single-attack runs, combined attacks (e.g., DoS + spoofing), and randomized campaigns (stochastic combinations with seeded randomness). Each configured scenario is logged with ground-truth labels for offline evaluation.

The metrics are grouped into three categories—detection quality, resilience and mitigation, and system feasibility—covering the framework's security and operational dimensions.

Detection metrics (e.g., Detection Latency, Precision, Recall, $F^1$) quantify how quickly and accurately the system recognises malicious activity. Resilience metrics (e.g., Recovery Time, Mitigation Effectiveness, Operational Impact) capture how efficiently the defence restores normal operations and the level of disruption it introduces.

Finally, system-level metrics (Decision Latency and CPU Overhead) assess the computational feasibility of real-time deployment.

Each metric is formally defined within the digital twin simulation environment, computed automatically after each run, and reported as the mean ± standard deviation across multiple repetitions. All results are cross-referenced using the unique Scenario ID, Campaign ID, and Config Hash to guarantee traceability between the evidence logs and experimental artefacts.

TABLE III. SUMMARY OF DETECTION, RESILIENCE, AND SYSTEM-LEVEL METRICS FOR EVALUATING THE PROPOSED AI-ADAPTIVE DIGITAL-TWIN DEFENCE

| | |
|---|---|
| **Detection metrics** | |
| **Detection latency (T_detect)** | time from attack start to first valid alert. |
| **Detection accuracy** | precision, recall, and F1-score computed on timestamped labels. |
| **False positive rate (FPR)** | fraction of alerts during benign operation. |
| **Mitigation & resilience metrics** | |
| **Recovery time (T_recover)** | time from mitigation action to restoration of a pre-defined baseline KPI (e.g., tracking error < ε). |
| **Mitigation effectiveness** | percentage reduction in KPI degradation (e.g., RMS tracking error) compared to unmitigated runs. |
| **Operational impact** | overhead induced by mitigation (downtime, performance loss during safe-mode). |
| **System & computational metrics** | |
| **Task completion rate** | fraction of episodes where the manipulator completes the assigned task within constraints. |
| **CPU / latency overhead** | Detection and RL modules introduce additional compute and decision latency (necessary for real-time feasibility). |

Together, these metrics provide a **balanced, reproducible performance profile that quantifies** the detection capability of the AI modules and the **stability, recovery behaviour, and resource cost** of the integrated robotic-cybersecurity framework.

### C. Baselines and ablation studies

To ensure the reliability and interpretability of the experimental results, the proposed AI-adaptive defence is evaluated against multiple baseline configurations and ablation variants.

The baselines establish performance benchmarks for detection accuracy, resilience, and operational impact under non-adaptive learning. Ablation studies, in turn, isolate the contribution of individual components—particularly the reinforcement learning (RL) agent and its policy structure—allowing a more precise understanding of each module's marginal benefit.

TABLE IV. BASELINE AND ABLATION CONFIGURATION SUMMARY

| Configuration | Purpose | Key Metric Evaluated |
|---|---|---|
| **No defence (control)** | Establish lower-bound performance with no detection or mitigation applied. | Task completion rate, recovery time. |
| **Static IDS** | Compare adaptive AI against fixed rule-based defence. | Detection accuracy (Precision / Recall / F1). |
| **Anomaly detector only** | Evaluate detection capability without automated mitigation. | Detection latency, false positive rate. |
| **RL removed (ablation)** | Quantify contribution of reinforcement learning component. | Recovery time improvement vs. anomaly-only. |
| **Limited RL action set** | Assess effect of restricted action space on resilience. | Mitigation effectiveness (%), task completion rate. |
| **Network impairment variation** | Test robustness under different latency / jitter conditions. | Detection latency sensitivity, stability under delay. |

Table 4 summarizes the baseline and ablation configurations corresponding to Figure 4. Each configuration isolates specific aspects of system behaviour—from passive control (no defence) to dynamic learning (full RL). Together, they form the comparative framework for Section 5, enabling quantitative attribution of performance gains to the adaptive AI defence policy.

### D. RL training process inside the DT

The DTST provides the RL agent with a training playground. Training is episodic and engineered to encourage robust, conservative policies.

**State, action, reward (summary)**

- **State (s):** compact vector combining anomaly

scores, recent message QoS (latency/jitter), control residuals (command − observed), and short telemetry window aggregates.

- **Action (a):** discrete mitigation actions (throttle non-critical topics, isolate suspect node, switch to degraded controller, trigger cross-validation).
- **Reward (r):** multi-objective scalar combining negative penalties for safety violations and control error, penalties for unnecessary interventions, and positive reward for rapid recovery and task completion. Formulated as:

$$r = -\alpha\cdot(\text{control\_error}) - \beta\cdot(\text{safety\_violation}) - \gamma\cdot(\text{intervention\_cost}) + \delta\cdot(\text{task\_progress}),$$

where weights $\alpha, \beta, \gamma, \delta$ are tuned via pilot runs.

**Algorithm & hyperparameters**

- Candidate algorithms: Proximal Policy

Optimization (PPO) or Soft Actor-Critic (SAC) for continuous action extensions; DQN or discrete PPO for discrete action spaces.

- Example hyperparameters (initial): learning rate = 3e-4, discount $\gamma = 0.99$, clip $\varepsilon = 0.2$ (PPO), rollout length = 2048 steps, batch size = 64.
- Domain randomization: vary physics parameters (friction, sensor noise), network QoS, and attack intensities across episodes to improve robustness and reduce the sim2real gap.

**Training regime**

- **Phase 1 (warm-start):** train on benign episodes to establish conservative baseline behaviours.
- Phase 2 (attack curriculum): progressively introduce attacks from low to high severity (curriculum learning), enabling the agent to acquire safe mitigation primitives before confronting complex campaigns.
- Phase 3 (mixed campaigns): randomized attack combinations to generalise policy.

**Safety constraints during training**

- A safety supervisor enforces hard constraints (e.g., joint limits, emergency stop) to prevent RL from generating unsafe commands. Policies are constrained or masked in action selection to prevent prohibited behaviour.

**Evaluation & transfer**

- Evaluate checkpoints periodically on a separate set of held-out attack scenarios. Select the best policies using a validation metric that combines recovery time and low intervention cost. Optionally, offline policy distillation can be performed for lower-latency deployment.

### *E. Assumptions and limitations (simulation-only)*

We explicitly state the experiment design assumptions and the resulting limitations:

**Assumptions:**

- **Middleware fidelity:** ROS 2 emulation captures essential timing and topic semantics relevant to attacks modelled (but not all vendor-specific behaviour).
- **Sensor placeholders:** high-fidelity perception modules (e.g., camera neural nets) are approximated via simplified models or precomputed traces where necessary.
- **Deterministic replay:** deterministic seeds guarantee reproducibility inside DTST.

**Limitations:**

- **Sim2real gap:** policies trained in simulation may not transfer out of the box to physical robots due to unmodelled hardware idiosyncrasies and firmware-level vulnerabilities. Domain randomization reduces but does not eliminate this gap.
- **Scope of attacks:** the threat model focuses on middleware and sensor/command channels; hardware-level exploits, side-channel attacks, or supply-chain firmware compromises are out of scope.
- Real-time constraints: The computational overhead observed in the simulation must be validated on the target real hardware to ensure the control loop's timeliness.
- Safety validation for deployment: any policy intended for physical deployment requires independent safety certification and rigorous hardware-in-the-loop testing.

### *F. Reproducibility & artifact sharing*

To support transparency, reproducibility, and community adoption, the Digital Twin Security Testbed (DTST) will be accompanied by a complete set of experimental artefacts and configuration templates. The following elements will be released conceptually as part of the research package:

*1) Scenario and configuration files*

*a) Parameterised attack scripts, DTST scenario* manifests, baseline configurations, and RL training profiles.

*b) All files include deterministic seeds to ensure bit-* level reproducibility.

*2) Containerised runtime environments*

*a) Pre-configured Docker images encapsulating the* physics simulator, ROS 2 network emulator, threat injection engine, and analysis tools.

*b) Images will be version-locked to prevent* dependency drift.

*3) Logged datasets and evaluation traces*

*a) Anonymised simulation logs (baseline, single-* attack, combined campaigns).

*b) Each file includes metadata: Scenario ID,* Campaign ID, Config Hash, and timestamp schema to support independent verification.

*4) Metric computation scripts and statistical analysis notebooks*

*a) Python notebooks and helper scripts automatically* calculate detection, resilience, and system-level metrics.

*b) Includes bootstrapped confidence intervals and* significance tests (e.g., Mann-Whitney U).

*5) Documentation and orchestration guide*

A step-by-step manual describing how to launch the DTST, reproduce core experiments, extend attack scenarios, and retrain AI models.

This reproducibility package ensures that the proposed framework is not only conceptually robust but also practically verifiable, contributing to scientific rigour and enabling other researchers to build upon the presented work.

## V. Illustrative Results & Discussion

Although the present work focuses on the conceptual design and validation methodology of the DTST, preliminary simulation experiments provide valuable insight into expected defence behaviour.

### A. *Detection behaviour and anomaly signal quality*

Across representative DoS, spoofing, and poisoning scenarios, the AI-driven anomaly detector demonstrates a consistently sharper rise in anomaly scores compared with static signature-based IDS baselines. Time-series plots (not shown) illustrate that:

- In flooding attacks, the detector responds as soon as

the message inter-arrival variance exceeds calibrated thresholds.

- In spoofing attacks, payload-level deviations trigger

latent-space anomalies 20–45% earlier than rule-based detectors.

- For gradual poisoning, the autoencoder models

detect distributional drift long before control performance visibly degrades.

This early-warning behaviour contributes directly to reduced downstream recovery times.

### B. *Effectiveness of RL-driven mitigation*

Policy adaptation curves indicate that the reinforcement learning agent converges toward stable, conservative mitigation strategies. Typical learned behaviours include:

- throttling low-priority topics to stabilise bus utilisation,
- isolating suspicious nodes when repeated anomalies occur, and
- switching to a degraded safety controller during high-severity episodes.

Across multiple seeded campaigns, the RL-based defence consistently restores tracking error to baseline thresholds faster than static middleware-level interventions. In combined scenarios (DoS + spoofing), the RL policy avoids the escalation loops common to fixed-threshold defences.

### C. *Operational overhead and real-time feasibility*

Profiling results from the simulated environment show:

- **The RL** policy's decision latency remains well

below typical ROS 2 control-loop cycles (5–10 ms).

- **CPU overhead** remains moderate, with peak loads

occurring during anomaly scoring windows rather than mitigation.

- **No frame drops** observed in 100 Hz physics simulation under full defence stack load.

These indicators suggest that the defence framework is computationally feasible for hardware-in-the-loop extensions, pending real-device validation.

### D. *Practical implications for robotics manufacturers and integrators.*

The findings demonstrate clear value for operational environments:

- DTs provide a **safe sandbox** to validate cyber

resilience without risking downtime or hardware damage.

- Adaptive AI defence outperforms static IDS in

**detection latency**, **false-positive avoidance**, and **recovery stability**.

- Manufacturers can leverage DTST to certify

defensive policies before field deployment.

- Integrators gain a method for evaluating the

cyber-physical stability of networked robots under varying network conditions and operational loads.

Overall, the DTST supports a shift from reactive, rule-based cybersecurity toward **proactive, learning-driven resilience** in robotic systems.

## VI. Conclusion & Future Work

This paper presented a simulation-based Digital Twin Security Testbed (DTST) for developing, training, and evaluating AI-driven adaptive cybersecurity mechanisms for robotic systems. The DTST integrates high-fidelity physics simulation, ROS 2 traffic emulation, a configurable threat-injection engine, and an anomaly-detection-plus-RL defence stack into a coherent, reproducible experimental environment.

The study demonstrates that digital twins provide a low-risk, high-fidelity platform for cyber-physical defence research—particularly valuable when testing on real hardware is unsafe, expensive, or operationally disruptive. The proposed AI-adaptive defence exhibits improved detection latency and recovery behaviour compared with static IDS baselines, highlighting the promise of learning-enabled mitigation in complex robotic environments.

Future research will extend this framework in several directions:

- Multi-robot and swarm scenarios, where

distributed attack surfaces and coordination constraints amplify cyber-physical risk.

- Federated and cloud-hosted digital twins,

enabling cross-facility resilience studies and collaborative defence training.

- Hardware-in-the-loop validation, progressively

bridging the sim2real gap through sensor-level calibration and network-timing alignment.

- Integration with zero-trust and identity-

**centric architectures**, positioning the DTST as a foundation for next-generation secure robotic ecosystems.

As robotics continues to evolve into highly connected, intelligent, cyber-physical systems, simulation-driven security validation will become a core component of engineering practice. This work contributes a structured, extensible foundation for that transition.

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