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Bibliometric Analysis of Documents in Scopus, in the Field of Additive Manufacturing

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Abstract— The result of a bibliometric analysis of publications in Scopus, including the phrase *Additive manufacturing* in the abstract, or in the title, or in the keywords, is presented. The data used from Scopus was generated in September 2024. The analysis is specified in the field of engineering sciences, and for Bulgaria. Using the specialized software Vosviewer were created maps, that give an overall picture of the trends in the researched field. Such analyses are suitable for quick information about current trends on a selected topic and for tracking research on it over the years.

Keywords— *additive manufacturing, additive technologies, 3D printing, 3D modeling, bibliometric analysis, Vosviewer*

I. INTRODUCTION

Historically, the terms used to describe the processes of creating three-dimensional objects using 3D printers have undergone various changes [2], [5]. The many factors influencing the quality of printers, materials and products, as well as the methods for creating them, through this type of production, initiated the creation of the “Committee F42 on Additive Manufacturing Technologies” [1]. The F42 Committee, in partnership with “ISO/TC 261, Additive manufacturing”, and in collaboration with Committee CEN/TC 438, Additive manufacturing”, developed the standard “ISO/ASTM 52900:2015”, which adopted the term additive manufacturing (AM) for these processes [7]. In the second revised edition “ISO/ASTM 52900:2021”, the known categories and processes have been updated, as well as new ones have been added [8].

Getting to know the diversity of additive processes, the availability of new printing materials, the creation of new 3D printers, the development of their application in a number of industrial sectors, etc., require constant efforts from manufacturers and consumers. We recognize the need for ways to quickly inform about current trends in the field of additive technologies, and to track their development over the years. Modern scientific platforms, with published materials from authors from all over the world, allow such an analysis to be made.

Here we will present a bibliometric analysis of publications in Scopus, including the phrase “Additive manufacturing” globally, in the field of technical sciences, and for Bulgaria. Using the specialized software Vosviewer [19], maps have been created that give an overall picture of the trends in the researched field.

II. ANALYSIS OF DOCUMENTS IN SCOPUSM CONTAINING THE PHRASE “ADDITIVE MANUFACTURING”

According to data from the entire Scopus database, the phrase “Additive manufacturing” occurs in 85,039 documents, when searching in the “Article title, Abstract, Keywords” mode, “Fig. 1”. An increase in the number of published documents is noted after 2013, which will be the starting year of a more in-depth analysis using Vosviewer.

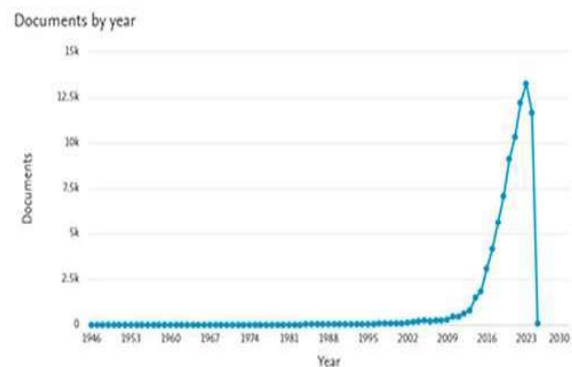


Fig. 1. Example of a figure caption

The distribution of documents according to the subject areas they refer to is given in “Fig. 2”. The most published materials are in the fields of “Engineering” (31.8%), “Material science” (24.3%) and “Physics and astronomy” (10.9%). The values by field are between 2% and 6% higher compared to those for “3D printing”.

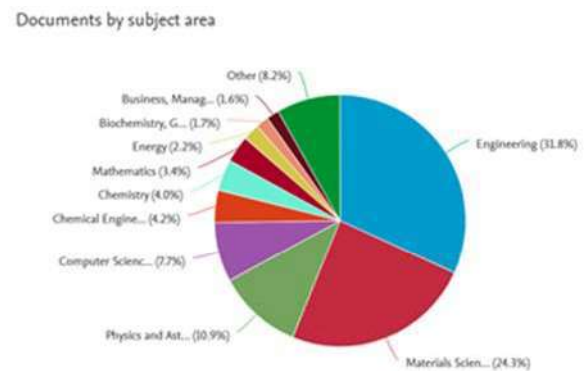
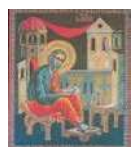


Fig. 2. Distribution of documents containing the phrase “Additive manufacturing” across the Scopus database by subject area (Source: Scopus).



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USA (20,618 items) and China (13,900 items) have the highest number of published documents in terms of "Additive manufacturing", "Fig. 3". The next countries with the most materials on the topic are Germany (8,292), India (6,121) and the United Kingdom (5,809).

Documents by country or territory

Compare the document counts for up to 15 countries/territories.

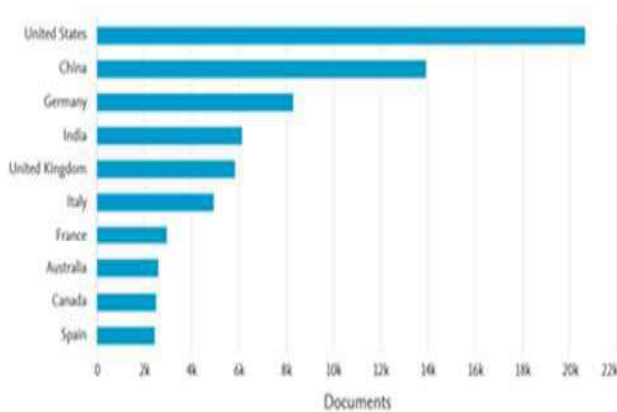


Fig. 3. Distribution of documents containing the phrase "Additive manufacturing" across the entire Scopus database, by country or territory (Source: Scopus).

A more detailed overview of the phrase "Additive manufacturing" was conducted for the period from 2013 to 2023, in the field of "Engineering". According to Scopus data, as of September 2024, a total of 45,530 documents were published during the selected period, "Fig.4".

Documents by year

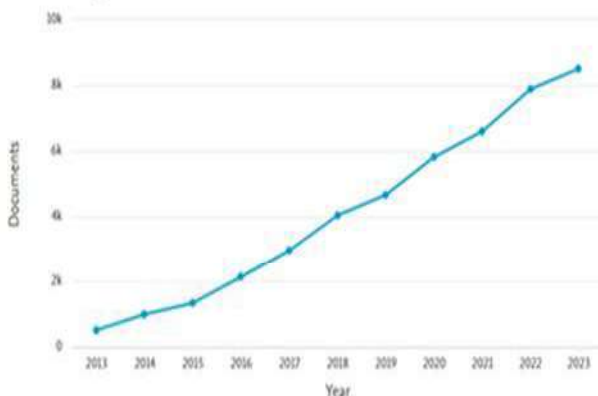


Fig. 4. Number of documents containing the phrase "Additive manufacturing", in the field of "Engineering", from Scopus, for the period 2013-2023. (Source: Scopus)

In this case too, the interdisciplinary scope of journals and conferences leads to the distribution of articles in more than one subject area. Therefore, although the condition is set to show documents only for "Engineering", there are also documents in other areas. According to the ready-made schemes, the largest percentage of published documents, in addition to "Engineering" (44.2%), are also in the fields of Material science" (21.1%), "Computer science" (9%), "Psychics and astronomy" (8.2%), "Fig.5".

Documents by subject area

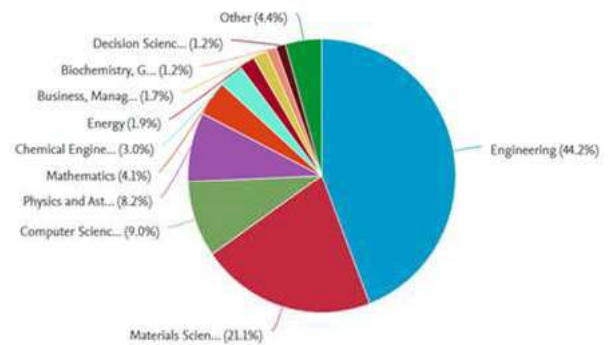


Fig. 5. Distribution of documents by subject areas in which the phrase "Additive manufacturing" occurs, for the field "Engineering" from Scopus, for the period 2013 - 2023. (Source: Scopus).

III. BIBLIOMETRIC ANALYSIS USING VOSVIEWER, IN THE FIELD OF ENGINEERING

To visualize a general scheme using Vosviewer, data from the first 20 thousand documents out of the 45,530 available on the topic, in the field of engineering sciences, were downloaded and used. "Fig. 6" shows a map of the connections between the countries that the co-authors noted when publishing their materials. An additional condition has been set in the settings to show only countries with at least 5 publications. Of all 181 countries in the analysis, 84 meet the specified condition. According to this network, authors from Bulgaria have common activities with China, Germany, India, Italy and Finland "Fig. 7".

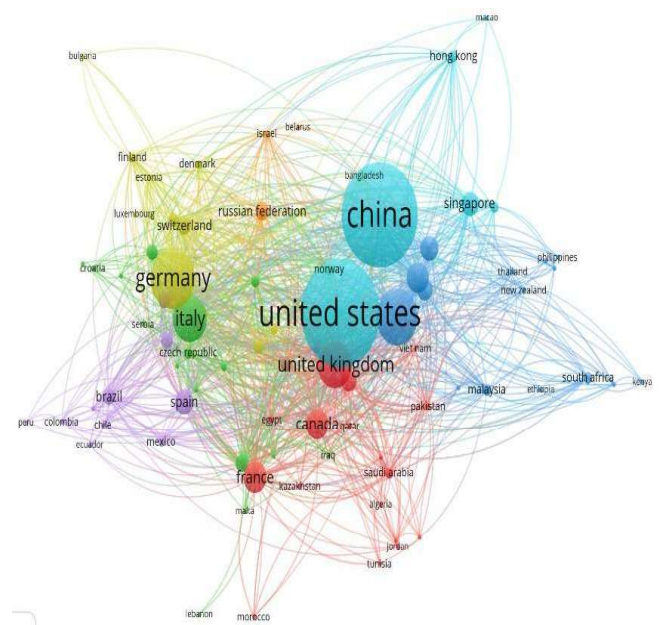


Fig. 6. Author-annotated countries in documents, containing the phrase "Additive manufacturing", in the field of "Engineering", in Scopus.

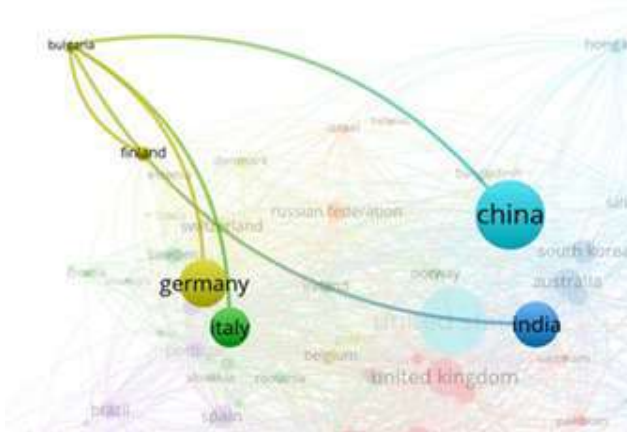


Fig. 7. Countries mentioned by authors with whom Bulgarian scientists have common publications.

“Fig. 8” shows the scheme made up of the 100 most common keywords in documents including the phrase “Additive manufacturing”. The top 5 are: additive manufacturing, additives, 3d printers, 3d printing, 3-d printing. The repetition of the phrase 3D printing is due to its presentation in several variants, according to the place of the punctuation marks used. The following most common keywords include the phrases: "powder bed", "microstructure" and "aluminum alloys". The three keywords have independent connections and with each other. They are part of the same cluster and have at least 1 connection with a keyword from all other clusters.

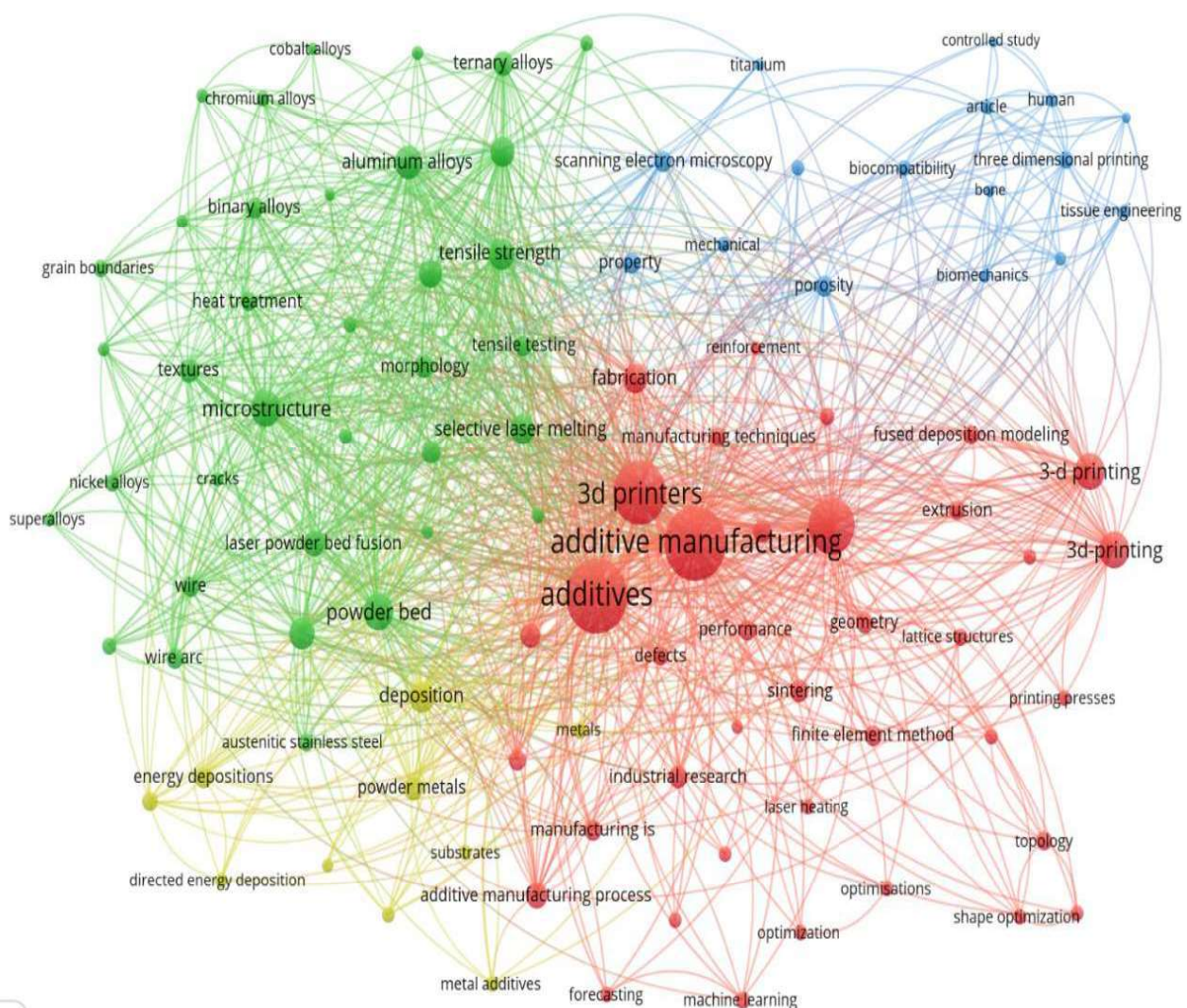


Fig. 8. Keyword in documents for the period 2013-2023, containing the phrase "Additive manufacturing", in the field of "Engineering", in Scopus, from 09.2024.

A complete list of the 100 most common keywords in the "Engineering" are presented in Table 1, according to their analysis on "Additive manufacturing" in the field distribution by cluster.

TABLE I. KEYWORDS USED IN THE PERIOD 2013-2023, WHEN SEARCHING IN SCOPUS FOR THE PHRASE "ADDITIVE MANUFACTURING", IN THE FIELD "ENGINEERING", ACCORDING TO DATA FROM 09.2024.

Cluster	Keywords
Cluster 1 (38 items)	3-d printing; 3d printers; 3d printing; 3d-printing; additive manufacturing; additive manufacturing (am); additive manufacturing process; additive manufacturing technology; additives; computer aided design; computerized tomography; cost effectiveness; defects; extrusion; fabrication; finite element method; forecasting; fused deposition modeling; geometry; industrial research; laser heating; lattice structures; machine learning; manufacturing is; manufacturing process; manufacturing techniques; optimisations; optimization; performance; printing presses; process parameters; reinforcement; shape optimization; sintering; structural design; surface; roughness; topology; topology optimization.
Cluster 2 (36 items)	aluminum alloys; anisotropy; austenitic stainless steel; binary alloys; chromium alloys; cobalt alloys; corrosion resistance; cracks; electron beams; friction; grain boundaries; hardness; heat treatment; high strength alloys; iron alloys; laser powder bed fusion; laser powders; magnesium alloys; mechanical properties; melting; microstructure; microstructures and mechanical properties; morphology; nickel alloys; powder bed; selective laser melting; superalloys; tensile strength; tensile testing; ternary alloys; textures; titanium alloys; vanadium alloys; wire; wire arc; wire arc additive manufacturing.
Cluster 3 (16 items)	article; biocompatibility; biomechanics; bone; compressive strength; controlled study; human; mechanical; porosity; printing, three-dimensional; property; scaffolds (biology); scanning electron microscopy; three dimensional printing; tissue engineering; titanium.
Cluster 4 (10 items)	deposition; directed energy; directed energy deposition; energy depositions; laser beams; metal additives; metals; powder metals; residual stresses; substrates.

An option to summarize the clusters, according to the elements in them, is as follows:

- Cluster 1 contains keywords used to describe additive manufacturing processes and technical settings in the process itself, depending on the printer used.
- Cluster 2 includes keywords describing the necessary conditions and materials for the use of metals and alloys in additive manufacturing.
- Keywords in Cluster 3 are focused on additive manufacturing in the field of biomedicine.
- Cluster 4 lists keywords related to additive manufacturing technologies through metal processing.

The 10 most cited documents from the search for the phrase "Additive manufacturing" in Scopus, for the period 2013-2023, from the field of "Engineering", are given in Table 2. Self-citations are also included in the final number of citations. Before you begin to format your paper, first write and save the content as a separate text file. Complete all content and organizational editing before formatting. Please note sections A-D below for more information on proofreading, spelling and grammar.

TABLE II. TOP 10 MOST CITED DOCUMENTS IN SCOPUS, WHEN SEARCHING FOR THE PHRASE "ADDITIVE MANUFACTURING", FOR THE PERIOD 2013-2023, ACCORDING TO DATA FROM SEPTEMBER 2024.

№	Title, (Open access – OA)	Author, year	Times cited
1	Additive manufacturing (3D printing): A review of materials, methods, applications and challenges.	Ngo, T. et al. (2018)	5 442
2	3D bioprinting of tissues and organs.	Murphy, S., Atala, A. (2014)	5 153
3	Metal additive manufacturing: A review.	Frazier, W. (2014)	4 573
4	3D printing of polymer matrix composites: A review and prospective.	Wang, X. et al. (2017)	2 543

№	Title, (Open access – OA)	Author, year	Times cited
5	Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing, second edition.	Gibson, I., Rosen, D., Stucker, B. (2015)	2 284
6	A 3D bioprinting system to produce human-scale tissue constructs with structural integrity.	Kang, H.-W. et al. (2016)	2 050
7	The status, challenges, and future of additive manufacturing in engineering.	Gao, W. et al. (2015)	2 042
8	Three-dimensional scaffolds for tissue engineering applications: Role of porosity and pore size.	Loh, Q., Choong, C. (2013)	1 996
9	The metallurgy and processing science of metal additive manufacturing.	Sames, W. et al. (2016)	1 892
10	3D bioprinting of vascularized, heterogeneous cell-laden tissue constructs.	Kolesky, D. et al. (2014)	1 680

Four of the most cited papers provide a detailed literature review of the existing materials, applications and technologies for additive manufacturing at the time of the study [6], [13], [17], [21]. All of them are open access. Four other papers consider additive manufacturing when using metals [14], [20], [22], with [25] being the only one in the table with closed read access. Liu and Shin investigated "the microstructures and properties of DED, SLM and EBMbuilt Ti6Al4V components, taking into account manufacturing constraints" [14]. Additive manufacturing in the field of biomedicine was investigated by Murphy and team who focused on the need for an interdisciplinary approach, since the creation of such tissues involves "selection of materials, cell types, growth factors, technical challenges related to the sensitivity of living cells and tissue construction" [15]; and by Wand and team, who considered the potential of using porous metals for "orthopedic regenerative medicine and the design of bone scaffolds and implants that replicate the biomechanical properties of host bones" [24].

IV. SCOPUS LITERATURE REVIEW IN THE FIELD OF ENGINEERING SCIENCES, FOR BULGARIA

The additional review in Scopus, when searching for the phrase “Additive manufacturing” for the field “Engineering”, is limited only to the country/territory of at least 1 co-author from Bulgaria. “Fig. 9” shows the publication activity with this restriction. During the period 2013-2023, a total of 33 documents fall within the specified parameters.

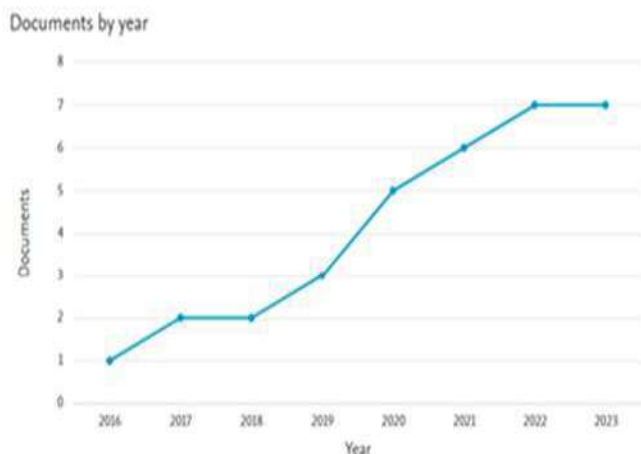


Fig. 9. Number of documents for Bulgaria containing the phrase “Additive manufacturing”, in the field of “Engineering” from Scopus, for the period 2013 - 2023 (Source: Scopus)

Their interdisciplinary focus includes the areas shown in “Fig. 10”. The most documents are in “Engineering” (38.3%), Material science (14.1%), Computer science (11.8%), Energy (10.6%) and Physics and astronomy (7.1%)

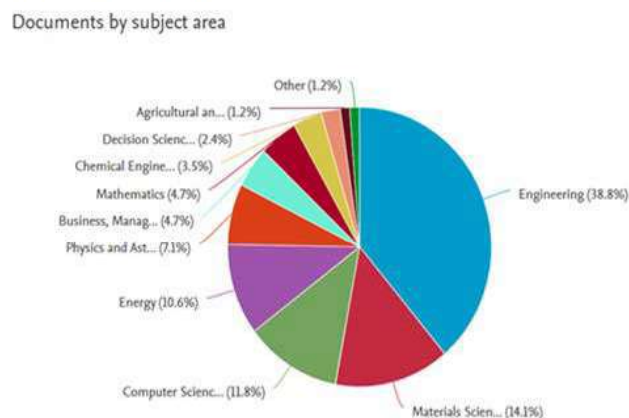


Fig. 10. Distribution of documents by subject areas, in which the phrase “Additive manufacturing” occurs, for Bulgaria, from the “Engineering” field, for the period 2013-2023 (Source: Scopus)

The type of documents is in the following distribution: conference publications (44.5%), journal articles (19.4%), book chapters (9.1%) and analysis (3.0%).

In addition to Bulgaria, some of the 33 documents have co-authors from 14 other countries, such as China, Germany, Belgium, India, Italy and others, “Fig. 11”.

Table 2. shows the 10 most cited documents by authors from country/territory Bulgaria, when searching for the

phrase “Additive manufacturing” in Scopus, for the period 2013-2023, in the field “Engineering”. The number of citations in Scopus automatically takes into account and includes self-citations.

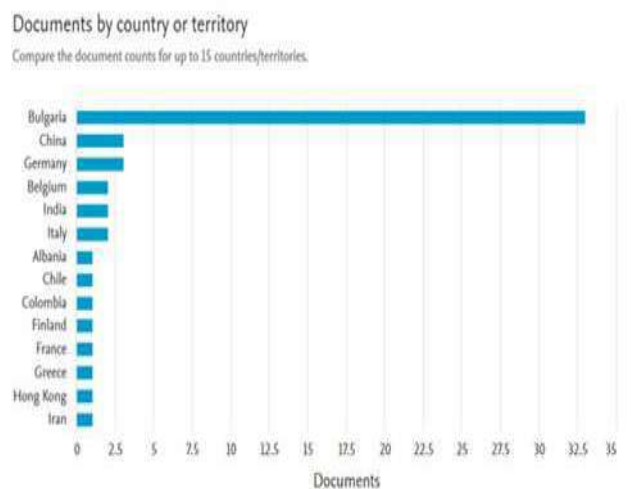


Fig. 11. Distribution of documents with phrase “Additive manufacturing”, in Scopus, from the field “Engineering”, for the period 2013-2023, with authors from the country/ territory – Bulgaria (Source: Scopus)

The authors, from the country/ territory Bulgaria, with the most published documents in which the phrase “Additive manufacturing” occurs in the title and/or abstract and/or keywords, are shown in “Fig. 12”. According to the data from the ready-made analysis in Scopus, Marinova, I., Mateev, V., and Ralchev, M. have the most published materials - 9 issues, in which all three are co-authors. The remaining authors of documents, from the country/territory Bulgaria, have up to 2 published materials on the topic.

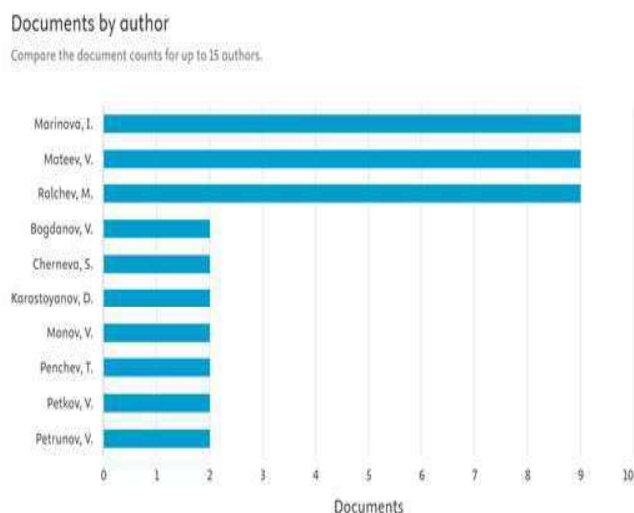


Fig. 12. Authors from country/ territory – Bulgaria, with the most published documents containing the phrase “Additive manufacturing”, in Scopus, in the field of “Engineering”, for the period 2013-2023. (Source: Scopus)

There is a diversity in the research areas of authors from the country/ territory of Bulgaria. Two of the documents in the table are closed access. From their publicly available

abstracts it is clear that they consider: “a method for magnetic material production suitable for 3D printing by Fused Filament Fabrication (FFF) technology... suitable for fabrication of complex shaped magnetic cores” [10]; and the “orientation of the manufactured products in 3D printing, using the technology of deposition of molten material, on the need to add supporting material” [16]. New methods in the production and use of materials for additive manufacturing are also considered in other documents. For example, Spinelli and team focused “on the basis of Polylactic acid (PLA) filled with two types of highly conductive nano-carbon materials, i.e. multi-walled carbon nanotubes (MWCNTs), graphene nanoplates (GNPs) and a combination of both fillers (MWCNT/GNP)” [4].

TABLE III. 10 MOST CITED DOCUMENTS BY AUTHORS FROM COUNTRY/TERRITORY BULGARIA, CONTAINING THE PHRASE “ADDITIVE MANUFACTURING” IN SCOPUS, FOR THE PERIOD 2013-2023, IN THE FIELD OF “ENGINEERING”

№	Title, (open access – OA)	Author, year	Times cited
1	Rheological and electrical behaviour of nanocarbon/poly(lactic) acid for 3D printing applications (OA).	Spinelli, G. et al. (2019).	62
2	Application of additive manufacturing for mass customisation: understanding the interaction of critical barriers (OA).	Shukla, M., Todorov, I., Kapletia, D. (2018)	59
3	Cicada-inspired fluorinated hydroxyapatite nanostructured surfaces synthesized by electrochemical additive manufacturing (OA).	Ge, X. et al. (2020)	39
4	Localised electrochemical processes on laser powder bed fused 316 stainless steel with various heat treatments in high-temperature water (OA).	Que, Z. et al. (2022)	16
5	Industry 4.0 for fashion products - Case studies using 3D technology (OA).	Spahiu, T. et al. (2021)	12
6	3D Printing of Magnetic Materials by FFF Technology.	Ralchev, M., Mateev, V., Marinova, I. (2020)	12
7	Food biotechnology: Innovations and challenges (OA).	Cabrera-Barjas, G. et al. (2021)	6
8	Development of a Fused Deposition Modeling System to Build Form-Fit Joints Using an Industrial Robot(OA).	Schwicker, M., Nikolov, N. (2022)	5
9	Using of 3D Printing Technologies in the Manufacture of Mechatronic Products.	Nikolov, S., Dimitrova, R., Dimitrov, S. (2022)	5
10	Innovative processing routes in manufacturing of metal matrix composite materials (OA).	Ružić, J. et al. (2021)	5

In [26] a “comparison of microstructure and high-temperature electrochemical behaviours between LPBF 316 and wrought 316 in simulated pressurized water reactor environment” was made, which is “critical for expanding their applications in nuclear and other high-temperature water

environments”. Ružić and team identified mechanical alloying as a suitable approach for the preparation of metal matrix composites (MMCs), showing “that by using adequate process parameters to obtain starting materials (reaching the specific size, shape, and reactivity) the control of volume fraction and distribution of reinforcements within the matrix can be achieved” [9]. In [11] the results of testing a robotic system (ARMS) to expand the scope of freedom in the application of the additive process FDM are presented. Cabrera-Barjas and team examined “food technology innovations and advances which will include agri-food technology, food packaging, 3D-food printing technology and biotechnology approaches” [3]. Ge and team designed an “antibacterial surface by combining the cicada wing-like nanopillar structure and the FHA together to potentially exert the advantages of physical and chemical antibacterial strategies simultaneously for battling the antibiotic-resistant pathogenic bacteria more effectively” [23]. Spahiu and team presented options for making different kinds of fashion items, noting the benefits of virtual environments for for detection and correction before printing [18]. Shukla and team are analyzing the reasons for the existing barriers for using additive technologies for mass customization, applying Interpretative Structural Modelling (ISM). Their literature review was supported by the opinions of experts in the field [12].

V. CONCLUSION

The analysis of the search results for the phrase "Additive manufacturing", in the field of "Engineering", globally and for Bulgaria, and most cited documents reviewed in Scopus, emphasize research related to: biomedicine and the use of metals in additive manufacturing; current reviews of generally existing technologies, materials and processes for additive manufacturing.

The Vosviewer software allows the analysis to be focused on leading authors, keywords, countries, as well as on the interrelationships between the elements included in the maps. Cluster distribution helps identify current scientific problems, insufficiently studied ones, citation patterns in scientific circles, as well as distinguishing the areas of their application.

Similar bibliometric analysis help to: coordinate trends in scientific and market phrases; discover interested organizations and co-authors for future joint activities; select appropriate scientific journals for sharing results, and others. Visual maps help to highlight key discoveries and track their impacts over time.

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Design and Architecture of Robotized Unmanned Ground Vehicle (UGV)-Based Intrusion Detection Perimeter Security Systems

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Abstract - Perimeter security is critical for protecting military installations, industrial complexes, and critical infrastructure. Recent advances in robotics, sensor technologies, and machine learning have spurred the development of robotized Unmanned Ground Vehicle (UGV)-based intrusion detection systems (IDS) that promise to enhance security by offering autonomous, continuous, and dynamic surveillance capabilities. This paper introduces a novel design and architecture for such systems that emphasizes modularity, advanced sensor fusion, robust autonomous navigation, and integrated cybersecurity measures. Our proposed architecture incorporates an innovative multi-layered design comprising a hardware layer with enhanced UGV platforms and heterogeneous sensor arrays, a perception layer utilizing adaptive sensor fusion, a decision-making layer employing ensemble machine learning techniques for intrusion detection, and a secure communication and integration layer. Extensive experiments conducted in both controlled and real-world environments demonstrate significant improvements in detection accuracy, response time, and operational reliability compared to conventional systems. We discuss the design rationale, detailed implementation, experimental evaluation, and potential future directions for this emerging technology.

Keywords— *Unmanned Ground Vehicle-UGV, Intrusion Detection, Perimeter Security, Sensor Fusion, Autonomous Navigation, Cybersecurity, Machine Learning*

I. INTRODUCTION

Traditional perimeter security systems have relied heavily on fixed installations such as closed-circuit television (CCTV) cameras, motion detectors, and human patrols. Although these methods offer baseline surveillance, they are inherently limited by static coverage, high operational costs, and the inability to rapidly adapt to evolving threat landscapes. The advent of unmanned systems [1], [2], [3], [4] has introduced a new paradigm in security operations. In particular, robotized UGVs offer mobility, flexibility, and the capacity to navigate challenging terrains, making them ideal candidates for autonomous perimeter monitoring.

Recent technological advances have enabled the integration of sophisticated sensors (e.g., thermal cameras, LiDAR, radar, and acoustic detectors) with advanced machine learning algorithms [5], [6], [7], [8] that enhance detection capabilities. However, despite these advancements, significant challenges remain in terms of system scalability, environmental adaptability, secure data transmission, and

real-time decision making. Motivated by these challenges, our work proposes a novel design and architecture that rethinks the integration of hardware and software modules in UGV-based IDS.

1) Historically, perimeter security has relied on stationary systems such as CCTV networks, infrared sensors, and manual patrols. While these systems have proven effective in certain contexts, they are often hampered by limited spatial coverage, high maintenance costs, and vulnerability to blind spots. Studies have noted that static sensors can be easily circumvented or disabled, and human operators are prone to fatigue and error. As threats become more sophisticated, the need for a more agile and comprehensive approach has become evident. Robotic surveillance represents a transformative shift in security technology. Early robotic systems were limited in their autonomy and required extensive manual intervention. Initial implementations used pre-programmed routes and basic sensor inputs, which restricted their adaptability in unstructured environments. Over time, improvements in robotics, particularly in the fields of autonomous navigation and sensor integration have paved the way for UGVs that can independently patrol, analyze, and respond to security events in real time.

The miniaturization and enhanced performance of sensors have significantly expanded the capabilities of modern security systems. Thermal cameras, high-resolution visible-light cameras, LiDAR, radar, and acoustic sensors now provide high-fidelity data that can be fused to create a comprehensive environmental model. Sensor fusion techniques have evolved from simple averaging methods to sophisticated probabilistic models that employ Kalman filters, Bayesian inference, and deep learning to handle noisy and heterogeneous data sources. The literature demonstrates that multi-modal sensor fusion is critical for reducing false alarms and enhancing detection reliability.

Machine learning, [9], [10], [11], [12] particularly deep learning, has revolutionized pattern recognition and anomaly detection. In security applications, supervised models—such as convolutional neural networks (CNNs) and support vector machines (SVMs)—have been used to classify visual and acoustic signals. Unsupervised techniques, including clustering and autoencoders, are applied to detect deviations



from normal activity. Ensemble learning approaches that combine multiple models have been shown to improve classification accuracy and robustness. The integration of these algorithms into UGV-based systems has emerged as a promising direction for enhancing intrusion detection.

As UGV-based systems become increasingly connected and networked, cybersecurity has emerged as a paramount concern. Autonomous systems [13], [14], [15], [16] are exposed to risks such as unauthorized access, data interception, and malware attacks. Research in this area emphasizes the importance of implementing robust encryption, authentication protocols, and real-time intrusion prevention systems (IPS). Standards and frameworks for cybersecurity in industrial control systems are being adapted for autonomous platforms, underscoring the need for continuous monitoring and rapid response mechanisms.

II. PROPOSED DESIGN AND ARCHITECTURAL INNOVATIONS

A. Architectural Overview

Our proposed architecture for robotized UGV-based intrusion detection systems is based on a modular, multi-layer design that improves scalability, maintainability, and performance. The system architecture is composed of six key layers, shown on Figure 1:

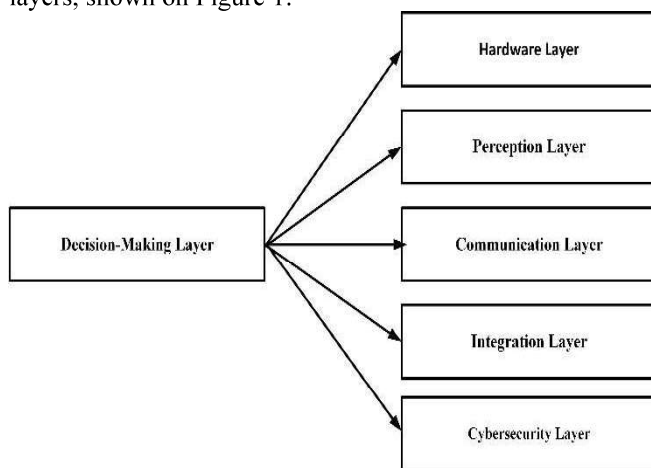


Fig.1 UGV based Intrusion Detection System.

Cybersecurity Layer: Embeds advanced encryption, authentication, and network monitoring to protect against cyber threats.

Hardware Layer: Comprises the UGV platform, sensor suite, power systems, and communication hardware.

Perception Layer: Responsible for sensor data acquisition, preprocessing, and low-level fusion.

This layered design not only modularizes system functions but also simplifies the incorporation of future technological advancements. An integral aspect of our design is the integration of a diverse sensor suite, carefully arranged to minimize occlusion and maximize coverage:

Thermal and Infrared Cameras: These sensors detect heat signatures and are particularly effective in low-light or night-time conditions. **High-Resolution Visible Cameras:** Provide detailed imagery for visual verification and object recognition.

Decision-Making Layer: Integrates high-level sensor fusion, intrusion detection algorithms, and autonomous navigation control.

Communication Layer: Facilitates secure, real-time data exchange between UGVs and central command.

Integration Layer: Provides interfaces and APIs for interoperability with legacy security systems and third-party solutions.

Radar Systems: Capable of long-range detection and reliable performance in adverse weather conditions such as fog or rain.

Acoustic Sensors: Capture environmental sounds to detect anomalous activities that may not be visible or thermal in nature.

B. Software and Control Architecture

Our software framework is developed on a modular architecture that decouples sensor processing, decision making, and control operations. This separation of concerns enhances maintainability and facilitates parallel development and testing. The framework consists of several key modules and is shown on figure 2 below.

Sensor Data Processing Module: Handles real-time data acquisition, noise reduction, and preliminary feature extraction from raw sensor data.

Fusion Engine: Implements both deterministic (e.g., Kalman filtering) and probabilistic (e.g., Bayesian inference) fusion techniques to generate a coherent environmental model.

Intrusion Detection Module: Applies ensemble machine learning models to classify events and detect anomalies. This module integrates both supervised and unsupervised algorithms to handle known and unknown threat patterns.

Navigation and Control Module: Incorporates simultaneous localization and mapping (SLAM) and dynamic path-planning algorithms to ensure the UGV maintains accurate positioning and can navigate safely in real time.

Communication and Integration Module: Manages secure data exchange with the central command center and provides APIs for integration with external security systems.

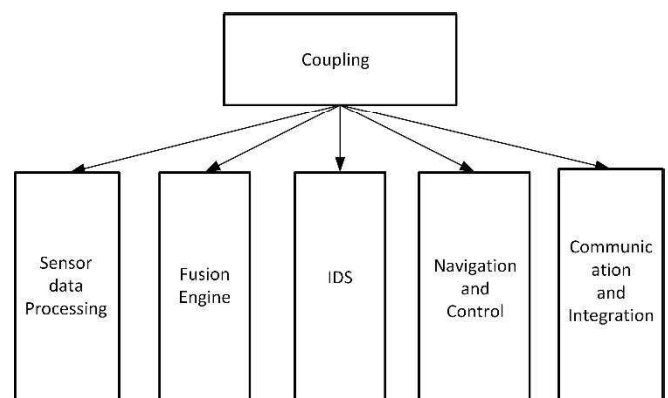


Fig.2 Software and Control Architecture framework

The modular architecture decouples sensor processing, decision making, and control operations. This separation of concerns enhances maintainability and facilitates parallel development and testing.

At the heart of the proposed system is an intelligent decision-making engine.

The key features of the engine include:

Ensemble Learning for Intrusion Detection: Multiple classifiers (e.g., CNNs, SVMs, auto encoders) operate in parallel, with their outputs combined through voting schemes and adaptive thresholding to increase detection robustness.

Predictive Analytics: Time-series analysis and trend detection algorithms are employed to forecast potential intrusion events based on historical sensor data and contextual information.

Context-Aware Adaptation: The decision-making process is enhanced by incorporating environmental context, such as weather conditions and time of day, allowing the system to dynamically adjust its sensitivity and thresholds.

C. Cybersecurity and System Integration Strategies

Given the mission-critical nature of security systems, the architecture includes a dedicated cybersecurity layer. This layer is responsible for:

Secure Communication: All data transmitted between the UGV and the command center is encrypted using AES and transmitted over secure channels employing TLS protocols.

Authentication and Authorization: Digital certificates, multi-factor authentication, and role-based access control ensure that only authorized personnel and devices can interact with the system.

Real-Time Intrusion Prevention: A dedicated network monitoring module continuously scans for anomalies in data traffic, applying predefined rules and machine learning-based anomaly detectors to identify potential cyber-attacks.

Interoperability Standards: The system adheres to industry standards such as ONVIF for video integration and IEEE protocols for wireless communication, facilitating seamless integration with existing security infrastructures.

III. ADVANCED SENSOR FUSION AND DATA PROCESSING

Sensor fusion refers to the process of integrating data from multiple sensors to generate an enhanced understanding of the environment. In the context of UGV-based IDS, fusion is critical for achieving robust performance in the face of sensor noise, occlusions, and variable environmental conditions. Our system employs a two-stage fusion strategy:

Low-Level Fusion: Raw sensor data from modalities such as LiDAR, cameras, and radar are first combined using deterministic techniques like Kalman filtering and complementary filters. This stage focuses on noise reduction and obtaining initial state estimates.

High-Level Fusion: Processed data and extracted features are subsequently combined using probabilistic methods such as Bayesian inference and particle filters. Deep learning models (e.g., CNNs and RNNs) further enhance fusion by learning complex feature representations from multi-modal inputs.

The data processing pipeline is designed to operate in real time and comprises several stages:

Data Acquisition: Continuous collection of raw data from the entire sensor suite.

Preprocessing: Application of filtering, calibration, and normalization techniques to prepare the data for fusion.

Feature Extraction: Automated extraction of salient features such as thermal gradients, motion vectors, and spatial edges using specialized algorithms tailored to each sensor.

Fusion Engine: Integration of processed data into a unified environmental model that supports both navigation and intrusion detection.

Decision-Making Input: The fused model serves as input for high-level decision-making algorithms that evaluate potential intrusion events.

Deep learning-based fusion is implemented on high-performance embedded processors to meet real-time constraints. Convolutional neural networks are trained on extensive datasets to identify complex patterns and anomalies across sensor modalities. Furthermore, recurrent neural networks facilitate temporal analysis by incorporating time-dependent features into the decision-making process.

Real-time sensor fusion in a mobile, dynamic environment poses challenges such as computational overhead and latency. Our implementation leverages parallel processing techniques and hardware acceleration (e.g., GPUs and FPGAs) to optimize performance. Adaptive fusion algorithms dynamically adjust processing parameters based on current environmental conditions, thereby ensuring robust operation even under rapidly changing circumstances.

IV. AUTONOMOUS NAVIGATION AND OBSTACLE AVOIDANCE

Autonomous navigation is critical for UGV-based security systems. The system must navigate complex terrains, avoid obstacles, and maintain continuous surveillance of designated areas. Environmental challenges include variable terrain, dynamic obstacles (such as vehicles and pedestrians), and unpredictable weather conditions.

Global path planning involves computing an optimal patrol route over a known map of the area. Our system employs classical algorithms such as A* and Dijkstra's algorithm to generate an initial route that maximizes area coverage while minimizing travel time and energy consumption. This global planner ensures that all critical areas along the perimeter are monitored.

Local path planning [17], [18], provides the ability to react to immediate obstacles that were not accounted for in the global plan. Techniques such as the Dynamic Window Approach (DWA) and Rapidly-Exploring Random Trees (RRT) allow the UGV to compute safe, collision-free trajectories in real time. Reactive control systems [19], [20], [21] further modify the UGV's course in response to sudden changes in the environment, such as moving obstacles or unexpected terrain variations.

Simultaneous Localization and Mapping (SLAM) is implemented to provide accurate real-time localization and mapping, particularly in GPS-denied environments. By fusing data from LiDAR, cameras, and inertial measurement units (IMUs), the SLAM module continuously updates a 3D map of the environment. This map not only guides navigation but also supports the sensor fusion engine by providing spatial context to the collected data.

The UGV employs a combination of LiDAR, radar, and vision-based techniques for obstacle detection. [22], [23],

[24] Acoustic sensors contribute additional data in environments where visual cues are insufficient. Upon detecting an obstacle, the control system initiates pre-defined avoidance maneuvers while maintaining the integrity of the global patrol route.

A. Intrusion Detection Algorithms

The primary function of the IDS is to reliably distinguish between benign environmental events and genuine intrusions. Challenges include:

Environmental Variability: Differentiating natural phenomena (e.g., animals, weather changes) from human intrusions.

Sensor Noise: Dealing with noisy sensor data that can lead to false alarms.

Real-Time Decision Making: Balancing detection sensitivity and specificity while operating in real time [25], [26], [27].

The proposed intrusion detection module employs a hybrid strategy that combines both supervised and unsupervised learning:

Supervised Learning: Deep neural networks (DNNs), including CNNs, are trained on labeled datasets containing various intrusion scenarios. These models learn to identify visual, thermal, and acoustic signatures of intrusions.

Unsupervised Learning: Auto encoders and clustering algorithms detect anomalies by identifying patterns that deviate from established norms. This is particularly useful in detecting novel or previously unseen events.

Ensemble Methods: Multiple classifiers are integrated using voting schemes and adaptive thresholding. This ensemble approach improves detection robustness by reducing the impact of individual model weaknesses.

Before classification, raw sensor data undergoes preprocessing steps such as normalization, noise reduction (using Gaussian and median filters), and feature extraction. Feature engineering is tailored to each sensor modality—for example, edge detection for camera data and spectral analysis for acoustic signals—to generate discriminative features that enhance classifier performance.

The intrusion detection module continuously evaluates the fused sensor data, assigns confidence scores to potential intrusion events, and employs an adaptive decision framework that adjusts detection thresholds based on contextual data (e.g., time of day, weather conditions). When a threshold is exceeded, the system triggers an alert that may include automated responses such as UGV repositioning or initiating video recording.

B. Cybersecurity and System Integration

The integration of UGVs into networked security systems increases their vulnerability to cyber-attacks, such as unauthorized control, data interception, and malware infections. Ensuring the integrity and confidentiality of the system is paramount for operational reliability.

Our architecture employs robust encryption (AES) and secure transmission protocols (TLS) for all communications. Digital certificates and multi-factor authentication ensure that only authorized devices and operators can access system functionalities. The communication layer is designed to be

resilient, maintaining low latency even under high-security conditions.

A dedicated cybersecurity module monitors network traffic and system logs in real time. This module employs machine learning-based anomaly detectors to identify potential cyber threats and can autonomously isolate compromised segments of the network, ensuring continued operation of the remaining system.

Interoperability is achieved through standardized APIs and adherence to protocols such as ONVIF for video integration and IEEE 802.11 for wireless communication. This ensures that the UGV-based IDS can be seamlessly integrated into existing security infrastructures, augmenting and complementing static systems.

C. Communication and Cybersecurity

High Detection Accuracy: Advanced sensor fusion and ensemble learning contribute to reliable intrusion detection with rapid response times.

Robust Autonomous Navigation: The integration of SLAM and dynamic path planning ensures continuous and safe operation in complex, dynamic environments.

Resilient Cybersecurity: Secure communication protocols and real-time network monitoring effectively protect against cyber threats, ensuring system integrity.

Scalability and Interoperability: The modular design enables seamless integration with existing security systems and facilitates future upgrades.

V. CONCLUSION

Our proposed architecture offers several distinct advantages:

Modular and Scalable Design: The layered architecture permits independent updates and integration with heterogeneous systems, supporting both current operational needs and future advancements. **Enhanced Sensor Fusion:** The combination of deterministic and probabilistic fusion techniques, bolstered by deep learning models, provides robust environmental mapping and reduces false alarms. **Intelligent Autonomous Navigation:** Advanced SLAM and path-planning algorithms allow the UGV to navigate safely and adaptively, even in challenging or GPS-denied environments.

Optimized Intrusion Detection: Ensemble machine learning methods improve classification accuracy and enable real-time decision making, balancing sensitivity and specificity.

Comprehensive Cybersecurity: Integrated encryption, authentication, and intrusion prevention mechanisms ensure that the system remains secure against evolving cyber threats. While the system demonstrates considerable promise, several challenges persist:

Environmental Variability: Extreme weather conditions and rapidly changing environments can still affect sensor performance, necessitating further refinements in adaptive fusion and calibration.

Computational Demands: Real-time processing of high-dimensional sensor data requires significant computational resources, which may impact battery life and operational endurance.

Integration with Legacy Systems: Although standardized interfaces facilitate integration, practical challenges remain when interfacing with older, non-standardized security systems.

Evolving Cyber Threats: As attackers develop more sophisticated methods, continuous updates to the cybersecurity framework will be essential.

Compared to traditional fixed surveillance and earlier mobile robotic systems, our design offers:

Greater Coverage and Flexibility: The mobility of UGVs combined with advanced sensor fusion provides dynamic, continuous coverage of complex perimeters.

Improved Decision-Making: The integration of machine learning algorithms into both sensor fusion and intrusion detection results in faster, more accurate responses.

Enhanced Resilience: Robust autonomous navigation and cybersecurity measures ensure operational continuity even in adverse conditions and under cyber-attack scenarios.

The versatility of the proposed system makes it suitable for a wide range of applications, including:

Military and Defense: Autonomous patrols of military bases and sensitive installations where real-time threat detection is critical.

Critical Infrastructure: Protection of power plants, water treatment facilities, and transportation hubs against unauthorized access.

Energy Optimization: Development of low-power processing techniques and integration of renewable energy sources to extend UGV operational endurance.

Deep Learning Enhancements: Exploration of emerging deep learning architectures that can further reduce false alarm rates and improve detection speed.

Interoperability Protocols: Standardization of interfaces and development of open APIs to ensure seamless integration with diverse security systems.

Cybersecurity Innovations: Continuous evolution of cybersecurity measures, potentially incorporating blockchain-based authentication and AI-driven threat analysis, to protect against increasingly sophisticated cyber-attacks.

Industrial Security: Surveillance of large industrial complexes and manufacturing facilities, especially those with multiple entry points and complex perimeters.

Border Security: Augmenting traditional border surveillance with autonomous, high-coverage monitoring solutions.

VI. CONCLUSION

This paper has presented a novel design and architecture for robotized UGV-based intrusion detection perimeter security systems. By adopting a modular, layered approach that integrates enhanced sensor fusion, robust autonomous navigation, and advanced machine learning algorithms with stringent cybersecurity measures, our proposed system addresses many of the limitations inherent in traditional security solutions. Experimental evaluations demonstrate that the new architecture achieves high detection accuracy, rapid response times, reliable navigation, and resilient communication even in challenging environments. Although challenges remain particularly in adapting to extreme

environmental conditions and evolving cyber threats—the presented research lays a solid foundation for future innovations in autonomous perimeter security.

As security demands continue to evolve, the need for agile, intelligent, and integrated systems becomes more critical. Our work demonstrates that robotized UGV-based IDS can provide a comprehensive solution for modern perimeter security challenges. With ongoing research into adaptive algorithms, energy-efficient computing, and advanced cybersecurity measures, the potential for these systems to revolutionize security practices across various sectors is substantial.

Future work can focus on several promising avenues:

Adaptive Sensor Fusion: Research into algorithms that dynamically adjust fusion parameters based on continuous environmental feedback.

Energy Optimization: Development of low-power processing techniques and integration of renewable energy sources to extend UGV operational endurance.

Deep Learning Enhancements: Exploration of emerging deep learning architectures that can further reduce false alarm rates and improve detection speed.

Interoperability Protocols: Standardization of interfaces and development of open APIs to ensure seamless integration with diverse security systems.

Cybersecurity Innovations: Continuous evolution of cybersecurity measures, potentially incorporating blockchain-based authentication and AI-driven threat analysis, to protect against increasingly sophisticated cyber-attacks.

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Mathematical Model and Kinematic Analysis of Rocker-Bogie Suspension Design for UGV Applications

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Abstract – Unmanned Ground Vehicles (UGVs) deployed in complex, unstructured environments demand suspension systems that ensure robust wheel–terrain contact, stability, and adaptability. The Rocker-Bogie mechanism originally developed for planetary rovers has emerged as an attractive solution due to its passive adaptability, kinematic redundancy, and energy efficiency. This paper presents a new mathematical model and kinematic analysis of the Rocker-Bogie suspension design as applied to UGVs. We derive the forward kinematics, establish differential relationships via the Jacobian matrix, and detail an iterative approach for inverse kinematics. Furthermore, we develop a Lagrangian dynamic formulation to capture the transient behavior and shock absorption characteristics of the suspension. Simulation studies illustrate the model's validity over a range of terrain profiles, and sensitivity analyses highlight the influence of key design parameters. Finally, we discuss adaptive control strategies and avenues for future research, aiming to optimize Rocker-Bogie UGV performance in challenging environments.

Keywords— *Unmanned Ground Vehicle-UGV, Rocker-Bogie suspension design, Kinematic design, Mathematical model*

I. INTRODUCTION

The evolution of unmanned ground vehicles (UGVs) over recent decades has been driven by the need for reliable mobility across diverse and often harsh terrains. In applications ranging from military reconnaissance to search-and-rescue operations and hazardous material handling, the capability to traverse irregular and unpredictable surfaces is paramount. Conventional suspension systems, such as rigid axles or independent suspensions have demonstrated limitations in maintaining continuous wheel terrain contact when confronted with obstacles, slopes, and rough ground. In contrast, the Rocker-Bogie suspension system, which was initially developed for extraterrestrial rovers, exhibits superior performance due to its unique passive adaptability and kinematic redundancy.

The Rocker-Bogie mechanism achieves terrain conformity by employing two interconnected subassemblies (the rocker and the bogie) that work in tandem to distribute the vehicle's load and maintain at least one wheel per side in contact with the ground at all times. For UGVs, the adaptation of the Rocker-Bogie design involves modifications in geometry, material selection, and control strategies to meet terrestrial operational demands. In particular, the integration of a

mathematical model that encapsulates the system's kinematics and dynamics is essential for understanding its behavior and optimizing design parameters.

The Rocker-Bogie suspension system is composed of two primary assemblies: the rocker and the bogie. The rocker serves as a larger, primary beam that attaches directly to the rover body, while the bogie is a secondary assembly pivoted to the rocker. Each of these assemblies is connected to wheels via independent joints that allow for angular movement relative to the body of the rover. The configuration can be visualized as a multi-link chain where the interaction of the various joints governs the overall kinematics of the system.

Key design principles include:

Passive Adaptation: The system is designed to automatically adjust to terrain irregularities without the need for active control inputs.

Wheel-Terrain Conformity: Maintaining continuous wheel contact with the surface is critical for traction. This is achieved through careful balancing of the degrees of freedom and pivot locations.

Load Distribution: The design minimizes the effect of uneven loading by distributing forces across the multiple joints and links.

The literature has extensively discussed the benefits and limitations of the Rocker-Bogie design. Researchers have modeled its behavior under various conditions, emphasizing its robustness in dynamic environments [1]. Recent studies have further elaborated on the dynamic response of the mechanism, integrating finite element analysis (FEA) with kinematic simulations to predict behavior under stress [2].

II. RELATED WORKS

Existing literature on Rocker-Bogie systems includes:

Kinematic Modeling: Several works have derived the geometric relationships between joint angles, link lengths, and wheel positions, primarily in the context of planetary rovers. These models have been adapted for UGVs by incorporating terrestrial load distributions and terrain profiles.

Dynamic Analysis: Researchers have employed Lagrangian mechanics and multibody dynamics to analyze energy transmission, shock absorption, and transient responses in Rocker-Bogie suspensions.



Control Strategies: The inherent kinematic redundancy of the system has been leveraged to develop adaptive and robust control schemes that optimize for stability, energy consumption, and terrain conformity.

Experimental Validation: Field tests and laboratory experiments with prototype vehicles have confirmed many of the theoretical predictions, although challenges remain in bridging the gap between idealized models and real-world behavior.

Our work seeks to build on these contributions by presenting a complete mathematical model that integrates both kinematic and dynamic aspects, with an emphasis on its application to UGVs.

III. MATHEMATICAL MODEL AND KINEMATIC ANALYSIS

In a typical Rocker-Bogie UGV, the suspension is arranged symmetrically about the longitudinal axis. Each side of the vehicle consists of two main articulated subassemblies:

Rocker Assembly: This assembly is connected directly to the UGV chassis via a primary pivot. It is responsible for supporting the bulk of the vehicle's mass and adapting to pitch changes.

Bogie Assembly: Connected to the rocker by a secondary hinge, the bogie introduces additional degrees of freedom. In most designs, two wheels are attached to the rocker while a third wheel is mounted on the bogie. This configuration ensures redundant contact with the terrain, even when one subassembly is significantly perturbed.

A simplified schematic (see Figure 1) illustrates the key components of the Rocker-Bogie suspension system. In our model, the suspension is abstracted as a multi-link mechanism, where each link is considered a rigid body with known geometric parameters and each joint provides one degree of rotational freedom.

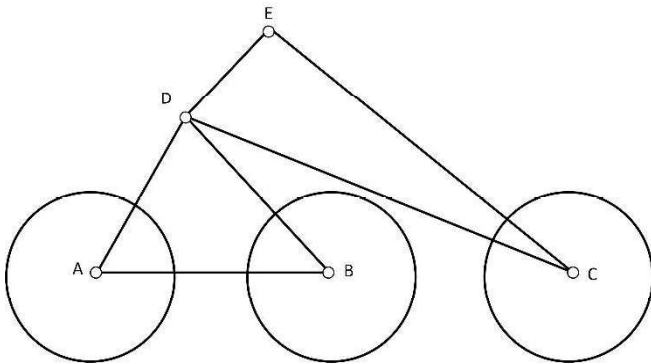


Fig.1 Rocker-Bogie suspension system

To facilitate a tractable mathematical analysis, we adopt the following assumptions:

Rigid Body Approximation: All links are assumed to be perfectly rigid. Elastic deformations are neglected.

Ideal Revolute Joints: Joints are modeled as frictionless revolute hinges with no backlash.

Planar Motion (Initial Analysis): The primary analysis is conducted in the sagittal (vertical) plane. An extension to

three-dimensional (spatial) dynamics is discussed in later sections.

Continuous Wheel Contact: It is assumed that wheels maintain contact with the terrain at all times and that slip is negligible.

Symmetric Mass Distribution: The UGV is assumed to have a symmetric mass distribution with respect to its longitudinal axis, which simplifies the dynamics.

Small Angle Approximations: In portions of the analysis, small angle approximations are used to linearize certain expressions. However, the full nonlinear model is derived for completeness.

These assumptions allow us to develop clear and concise analytical expressions that capture the essential behavior of the Rocker-Bogie system.

We begin by establishing a global inertial coordinate system $\{X, Y, Z\}$ with Z representing the vertical direction. For the initial planar analysis, we confine our discussion to the XZ plane. Each link of the suspension is associated with a local coordinate frame. The transformation from one link's frame to the next is expressed using homogeneous transformation matrices.

For a given link i with length L_i and joint angle θ_i , the transformation matrix T_i is defined as:

$$T_i = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & L_i \cos \theta_i \\ \sin \theta_i & \cos \theta_i & L_i \sin \theta_i \\ 0 & 0 & 1 \end{bmatrix}. \quad (1)$$

The overall transformation from the base (attached to the UGV chassis) to the end of link nn is then given by the product

$$T = T_1 T_2 \cdots T_n = \prod_{i=1}^n T_i. \quad (2)$$

The configuration of the mechanism is fully described by the vector of joint angles

$$q = \{\theta_1, \theta_2, \dots, \theta_n\}. \quad (3)$$

The forward kinematics problem requires determining the position $\mathbf{p}$ of the wheel contact point in terms of the joint angles and link lengths. In homogeneous coordinates, the position is given by

$$\mathbf{p} = T \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ z \\ 1 \end{bmatrix}. \quad (4)$$

Expanding the above expression, the x and z coordinates are:

$$x(q) = \sum_{i=1}^n L_i \cos \left(\sum_{j=1}^i \theta_j \right), \quad (5)$$

$$z(q) = \sum_{i=1}^n L_i \sin \left(\sum_{j=1}^i \theta_j \right). \quad (6)$$

For the Rocker-Bogie UGV, we conceptually separate the kinematic chain into two segments - one corresponding to the

rocker assembly and the other to the bogie assembly. Let $\mathbf{qR}$ denote the set of joint angles in the rocker and $\mathbf{qB}$ the set in the bogie. Then the position of a wheel contact point is expressed as

$$\mathbf{p}_{wheel} = \mathbf{p}_0 + \mathbf{p}_R(\mathbf{qR}) + \mathbf{p}_B(\mathbf{qB}), \quad (7)$$

where $\mathbf{p}_0$ is the location at which the suspension attaches to the vehicle chassis. This formulation permits the independent design of rocker and bogie geometries so that wheel trajectories closely follow the terrain surface.

The sensitivity of the end-effector's position to variations in the joint angles is captured by the Jacobian matrix $\mathbf{J}(\mathbf{q})$. The Jacobian relates the joint velocity vector $\dot{\mathbf{q}}$ to the velocity $\dot{\mathbf{p}}$ of the wheel contact point:

$$\dot{\mathbf{p}} = \mathbf{J}(\mathbf{q}) \dot{\mathbf{q}}. \quad (8)$$

For the k -th joint, the partial derivative of the end-effector position with respect to θ_k is given by

$$J_k(\mathbf{q}) = \frac{\partial \mathbf{p}}{\partial \theta_k}. \quad (9)$$

Differentiating the expressions for $\mathbf{x}(\mathbf{q})$ and $\mathbf{z}(\mathbf{q})$ yields

$$\frac{\partial x}{\partial \theta_k} = - \sum_{i=k}^n L_i \sin \left(\sum_{j=1}^i \theta_j \right), \quad (10)$$

$$\frac{\partial z}{\partial \theta_k} = \sum_{i=k}^n L_i \cos \left(\sum_{j=1}^i \theta_j \right). \quad (11)$$

Thus, the k -th column of the Jacobian is

$$J_k(\mathbf{q}) = \begin{bmatrix} - \sum_{i=k}^n L_i \sin \left(\sum_{j=1}^i \theta_j \right) \\ \sum_{i=k}^n L_i \cos \left(\sum_{j=1}^i \theta_j \right) \end{bmatrix}. \quad (12)$$

Stacking the columns for $k=1,2,\dots,n$ results in the full Jacobian matrix

$$\mathbf{J}(\mathbf{q}) = [\mathbf{J}_1(\mathbf{q}) \quad \mathbf{J}_2(\mathbf{q}) \quad \dots \quad \mathbf{J}_n(\mathbf{q})]. \quad (13)$$

The Jacobian not only provides insight into how joint velocities affect wheel position but also plays a critical role in solving the inverse kinematics problem.

The inverse kinematics problem involves determining the set of joint angles $\mathbf{q}$ that will produce a desired wheel contact position $\mathbf{p}_d$:

$$\mathbf{p}(\mathbf{q}) = \mathbf{p}_d \quad (14)$$

Because the kinematic equations are nonlinear and the system may be redundant, iterative numerical methods are typically employed to solve for $\mathbf{q}$. One common approach is the damped least-squares (DLS) method. The update rule for the joint angles at iteration k is

$$\mathbf{q}^{(k+1)} = \mathbf{q}^{(k)} - [\mathbf{J}(\mathbf{q}^{(k)})^T \mathbf{J}(\mathbf{q}^{(k)}) + \lambda \mathbf{I}]^{-1} \mathbf{J}(\mathbf{q}^{(k)})^T (\mathbf{p}(\mathbf{q}^{(k)}) - \mathbf{p}_d), \quad (15)$$

λ is a small damping parameter that ensures numerical stability (especially near singular configurations),

$\mathbf{I}$ is the identity matrix,

$\mathbf{p}(\mathbf{q}^{(k)})$ is the current estimate of the wheel contact point.

Convergence is monitored by checking whether the norm $\|\Delta \mathbf{q}\|$ falls below a predetermined threshold. In practice, the inherent kinematic redundancy in the Rocker-Bogie system allows for multiple solutions; additional criteria such as minimizing joint motion or avoiding extreme joint angles can be incorporated into the optimization process.

IV. DYNAMIC MODELING USING LAGRANGIAN MECHANICS

While the kinematic analysis determines the geometric relationships between joint angles and wheel positions, dynamic modeling is essential for understanding the suspension's response to external disturbances, shocks, and varying terrain conditions. The dynamic behavior is influenced by inertial forces, gravitational loads, and energy dissipation through damping elements. A dynamic model is also necessary for the development of control strategies aimed at mitigating transient disturbances.

The Lagrangian method provides a systematic way to derive the equations of motion for a mechanical system. The Lagrangian $\mathcal{L}$ is defined as the difference between the kinetic energy T and the potential energy V :

$$\mathcal{L}(\mathbf{q}, \dot{\mathbf{q}}) = T(\mathbf{q}, \dot{\mathbf{q}}) - V(\mathbf{q}). \quad (16)$$

For the Rocker-Bogie system, the generalized coordinates are the joint angles $\mathbf{q}$ and their time derivatives $\dot{\mathbf{q}}$.

The kinetic energy of the system is the sum of the kinetic energies of each individual link. For link i with mass m_i , moment of inertia I_i about its center of mass, and center-of-mass velocity $\dot{\mathbf{p}}_i$, the kinetic energy is given by

$$T_i = \frac{1}{2} m_i \|\dot{\mathbf{p}}_i\|^2 + \frac{1}{2} I_i \dot{\theta}_i^2. \quad (17)$$

Expressing $\dot{\mathbf{p}}_i$ in terms of the joint velocities $\dot{\mathbf{q}}$ via appropriate Jacobian matrices allows us to write the total kinetic energy as

$$T(\mathbf{q}, \dot{\mathbf{q}}) = \frac{1}{2} \dot{\mathbf{q}}^T \mathbf{M}(\mathbf{q}) \dot{\mathbf{q}}, \quad (18)$$

where $\mathbf{M}(\mathbf{q})$ is the configuration-dependent mass (or inertia) matrix.

In terrestrial UGV applications, gravitational potential energy is the dominant component. For link i , if the vertical position of its center of mass is z_i , then

$$V_i = m_i g z_i, \quad (19)$$

with g representing the gravitational acceleration. The total potential energy is therefore

$$V(\mathbf{q}) = \sum_{i=0}^n m_i g z_i \quad (20)$$

In some designs, additional potential energy terms due to elastic elements (e.g., preloaded springs at the joints) may be incorporated into $V(\mathbf{q})$.

The equations of motion are derived by applying the Euler-Lagrange equation for each generalized coordinate θ_i :

$$\frac{d}{dt} \left(\frac{\partial \mathcal{E}}{\partial \dot{\theta}_i} \right) - \frac{\partial \mathcal{E}}{\partial \theta_i} = \tau_i, \quad (21)$$

where τ_i represents the generalized torque applied at the i -th joint. For a passive Rocker-Bogie system, these torques often include contributions from joint stiffness and damping, modeled as

$$\tau_i = -k_i(\theta_i - \theta_{i,0}) - c_i \dot{\theta}_i, \quad (22)$$

with k_i and c_i denoting the stiffness and damping coefficients, and $\theta_{i,0}$ the equilibrium angle.

Substituting the expressions for T and V into the Euler-Lagrange equations results in a set of nonlinear second-order differential equations:

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + K(q - q_0) + G(q) = \tau_{ext}, \quad (23)$$

where:

$C(q, \dot{q})$ represents the Coriolis and centrifugal terms, $K(q - q_0)$ captures the restoring torques due to joint stiffness, $G(q) = \nabla_q V(q)$ is the gravitational force vector, τ_{ext} accounts for external torques (e.g., impacts from terrain irregularities).

Due to the complexity of the derived dynamic equations, numerical integration techniques such as Runge-Kutta methods are employed to simulate the suspension's transient behavior over time. These simulations help evaluate shock absorption performance, chassis oscillations, and energy dissipation under various terrain conditions. The insights gained from the dynamic analysis are crucial for both design optimization and the development of control strategies.

For safe and effective UGV operation, it is essential that the wheels remain in continuous contact with the terrain. This condition can be mathematically expressed as

$$z_i \geq z_{terrain}(x_i), \quad (24)$$

where z_i is the vertical position of the i -th wheel and $z_{terrain}(x_i)$ is the terrain elevation at the corresponding horizontal location x_i . The kinematic design must ensure that even in the presence of disturbances, the overall configuration of the Rocker-Bogie system preserves sufficient wheel contact to maintain stability and traction. The static equilibrium configuration of the suspension corresponds to a local minimum of the potential energy $V(q)$. To analyze the stability of an equilibrium configuration q^* , we examine the Hessian matrix of the potential energy:

$$H(q^*) = \left. \frac{\partial^2 V}{\partial q^2} \right|_{q=q^*} \quad (25)$$

If $H(q^*)$ is positive definite, then small perturbations about q^* will be met with restoring forces that drive the system back to equilibrium. This analysis is particularly important for designing the elastic (spring) elements that contribute to the system's passive shock absorption.

The compliance of the Rocker-Bogie system is determined by the stiffness and damping properties of the joints. The joint torque model (see formula 22) illustrates how the system absorbs and dissipates energy. Performance metrics in this context include:

Peak Chassis Acceleration: Lower peak accelerations indicate better shock absorption.

Energy Dissipated: The energy absorbed by the damping elements during transient events quantifies the system's ability to smooth out disturbances.

Recovery Time: The rate at which the system returns to equilibrium after a shock is an important performance measure.

An important feature of the Rocker-Bogie mechanism is its kinematic redundancy. Multiple joint configurations can achieve the same wheel-terrain contact point. This redundancy allows designers to optimize for additional criteria such as:

Minimizing Energy Consumption: By selecting configurations that reduce the amount of motion or avoid extreme joint angles.

Maximizing Stability Margins: By choosing configurations that keep the center of gravity well within the support polygon.

Avoiding Singular Configurations: By steering clear of joint configurations where the Jacobian loses rank and the system becomes less controllable.

The analysis of the null space of the Jacobian matrix provides a mathematical basis for redundancy resolution.

To validate our mathematical model, we performed simulations using MATLAB.

The simulation environment incorporated multiple terrain profiles including a sinusoidal terrain described by

$$z_{terrain}(x) = A \sin\left(\frac{2\pi x}{\lambda}\right) \quad (26)$$

where A is the amplitude and λ is the wavelength.

A. Jacobian Analysis and Inverse Kinematics Convergence

The Jacobian matrix $J(q)$ was computed for various configurations. Near configurations where the determinant of $J(q)$ approaches zero, the system is near a kinematic singularity; however, the damped least-squares inverse kinematics algorithm successfully converged in fewer than 20 iterations for typical test cases.

Dynamic simulations were performed to assess the response of the suspension to abrupt terrain changes. Time-history plots of chassis vertical acceleration indicate that the passive compliance inherent in the Rocker-Bogie design effectively attenuates high-frequency shocks. In one simulation, a sudden step obstacle produced peak accelerations that were reduced by over 50% due to the damping elements. Fourier analysis of joint motion confirmed that the system suppresses resonant frequencies, and energy dissipation analyses revealed that the damping parameters could be tuned to balance shock absorption with energy efficiency.

Sensitivity Analysis

A sensitivity study was conducted by varying key parameters (joint stiffness, damping coefficients, and link lengths) by $\pm 10\%$ and observing the effects on performance metrics.

Key findings include:

Stiffness Variations: A 10% reduction in stiffness increased wheel slip by approximately 15% on rough terrain, while a 10% increase reduced slip at the cost of higher impact forces.

Damping Variations: Increased damping improved shock absorption but reduced the system's responsiveness to rapid terrain changes.

Link Length Variations: Changes in link lengths altered the effective stride and the curvature of the wheel trajectories, impacting both stability margins and energy consumption.

B. Integration of Mathematical and Kinematic Analyses

The integrated mathematical framework presented in this paper unifies the kinematic and dynamic aspects of the Rocker-Bogie suspension. Our derivations for forward kinematics and the Jacobian matrix provide precise relationships between joint motions and wheel trajectories, ensuring that the UGV maintains continuous terrain contact. Meanwhile, the dynamic model derived using Lagrangian mechanics explains how the system absorbs shocks and dissipates energy. Together, these models offer a tool for both design optimization and control strategy development.

The Rocker-Bogie suspension offers significant advantages for UGV applications:

Continuous Wheel Contact: By ensuring that at least one wheel on each side remains in contact with the terrain, the design enhances traction and vehicle stability.

Passive Adaptability: The suspension adapts automatically to terrain irregularities, reducing the need for complex active control systems.

Energy Efficiency: The predominantly passive operation reduces power consumption a critical consideration for long-duration missions.

Robust Shock Absorption: The combination of elastic and damping elements effectively mitigates the impact of high-frequency disturbances.

Kinematic Redundancy: Multiple configurations can achieve the same wheel position, providing flexibility to optimize additional performance criteria.

These features are particularly important for UGVs operating in harsh and unpredictable environments, where reliability and efficiency are paramount.

C. Challenges and Limitations

Despite its many advantages, the Rocker-Bogie system also faces challenges:

Nonlinear Complexity: The derived kinematic and dynamic equations are highly nonlinear, which complicates real-time control and optimization.

Singular Configurations: The Jacobian matrix may approach singularity in certain configurations, reducing the system's controllability. Effective regularization techniques and

adaptive control strategies are needed to overcome this limitation.

Parameter Sensitivity: The performance is highly sensitive to variations in joint stiffness, damping, and geometric parameters. Variations due to manufacturing tolerances or wear may necessitate periodic recalibration or adaptive parameter tuning.

Extension to Three Dimensions: While our planar analysis offers valuable insights, UGVs operate in a fully three-dimensional environment. Extending the model to capture spatial dynamics introduces additional complexity and computational challenges.

V. CONCLUSION

This paper has presented a new mathematical model and kinematic analysis of the Rocker-Bogie suspension design for UGV applications. Our work integrates detailed derivations of forward kinematics, the Jacobian matrix, and an iterative inverse kinematics algorithm with a dynamic model based on Lagrangian mechanics. Key conclusions are as follows:

The derived kinematic model accurately predicts the positions of wheel contact points, ensuring continuous terrain conformity.

The Jacobian matrix analysis provides insight into the sensitivity of the system and identifies potential singular configurations.

The dynamic model confirms that passive compliance—combined with appropriate damping—effectively attenuates shocks and reduces chassis oscillations.

Sensitivity analyses underscore the importance of precise parameter calibration and highlight opportunities for adaptive control.

Kinematic redundancy inherent in the Rocker-Bogie design offers flexibility for optimizing additional performance criteria such as energy consumption and stability.

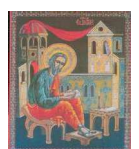
Overall, the integrated framework developed herein lays a robust foundation for both the design and control of Rocker-Bogie UGVs operating in challenging environments.

This paper presents a rigorous, integrated mathematical framework for the analysis and design of Rocker-Bogie suspension systems for UGVs. By combining detailed kinematic formulations with dynamic modeling via Lagrangian mechanics, we have developed a foundation for understanding the complex interactions within the suspension. Simulation studies validate the theoretical models and highlight the importance of parameter tuning and adaptive control strategies. The insights provided here are intended to inform future research and development efforts aimed at optimizing UGV performance in challenging, unstructured environments.

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The Phenomenon of Blow During Landing, Support, Grip and Locomotion

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Abstract—The physical phenomenon Impact accompanies most of the processes in robotics and mechanics as a whole. In this material, attention will be paid to the processes of landing, support, grip and locomotion and the manifestation of the Impact phenomenon in these processes. Some theoretical statements of this phenomenon will be shown and conditions for the synthesis of some characteristic kinematic chains of these processes will be derived. An interesting fact is the phenomenon of self-centering of the kinematic chains of the mechanisms of these processes.

Keywords— *landing, support, grip, locomotion, self-centering*

I. INTRODUCTION

In each of the processes – landing, support, grip and locomotion [1], at a given moment there is the phenomenon of Impact [2]. These processes are processes of interaction between two bodies. This phenomenon manifests itself, usually at the initial moment of these processes, that is, at the moment of the first contact between the two bodies. It is usually assumed that the phenomenon of impact is a harmful phenomenon and designers aim to minimize its consequences. The reason for this is the impact force, which acts for a very short time interval, but is of very high values and in most cases leads to destruction or at least to unpredictable deformations [3].

Essentially, the phenomenon of Impact has two physical manifestations. One is when the two bodies have a certain speed towards each other [4] and at a given moment they meet and hit each other.

The other is when the two bodies (in this case the concept of “two bodies” is conditional) are connected to each other and represent a single whole and as a result of some force they break their connection and take their own trajectories.

It is known from mechanics that when a body breaks down into separate parts, the trajectories of these parts are such that the total trajectory of their total mass remains unchanged [5].

When two or more bodies are combined [6], there is an increase in the mass of the combined body and therefore there is a change in the trajectory.

In this material, we will take a brief look at the Theory of Impact and will derive some dependencies in which the impact force from the Impact phenomenon has a positive effect.

A. Theoretical statements from the Theory of Impact.

When two bodies come into contact, the physical phenomenon of impact occurs. Entering the theory of impact, the physical phenomenon of Impact is characterized by an impact in a very small time interval. In this time interval, the so-called impact force acts, which takes on very high values.

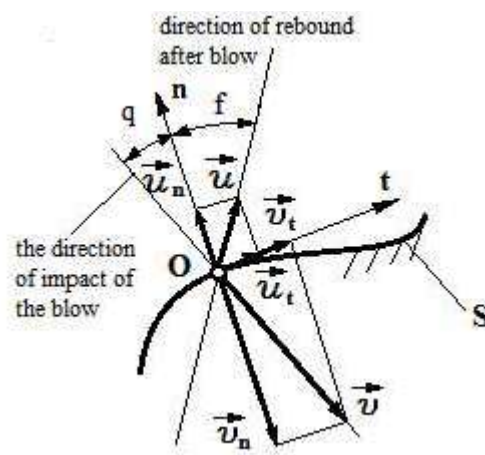


Fig. 1 Schematic diagram of the impact of a material point on a stationary surface.

If we hit a material point with mass m on a stationary surface $\mathbf{S}(\mathbf{x}, \mathbf{y}, \mathbf{z}, t) = \mathbf{0}$, at an angle α to the normal $\mathbf{n}$ (Fig. 1) of the surface S , with a speed v , then the reaction to the impact will depend on the physic mechanical properties of the matter of the material point and the surface S , at the moment of impact. In this material we will limit ourselves only to the shape of the bodies, assuming that the physic mechanical characteristics are uniformly distributed over their surface and volume.



The normal to the surface at the point of impact is given by the expression:

$$\mathbf{n} = \text{grad } S(\mathbf{x}, \mathbf{y}, \mathbf{z}, \mathbf{t}) = \mathbf{0} \quad (1)$$

At the moment of contact of the material particle with the surface S and when leaving the point of contact, regarding the velocity (Fig. 1), the following equality is valid:

$$\text{grad } S \cdot \mathbf{v} + \frac{dS}{dt} \geq 0 \quad (2)$$

At the initial moment of impact t_0 the basic equation of the impact theory, projected onto the normal and tangent, takes the form:

$$\begin{aligned} m\mathbf{u}_n - m\mathbf{v}_n &= I_n^m \\ m\mathbf{u}_t - m\mathbf{v}_t &= I_t^m \end{aligned} \quad (3)$$

This system of equations is indeterminate, because the equations are two, and the unknowns are 4, i.e. I_t^m , I_n^m , $\mathbf{u}_t$ и $\mathbf{u}_n$. Newton added two additional empirical relationships based on a large number of experiments and observations.

- *The ratio of the absolute values of the normal projections of the relative velocities before and after contact is a constant value and depends only on the physicomaterial properties of the matter.*

$$\frac{u_n}{v_n} = h \quad (4)$$

This coefficient is called *the coefficient of recovery*. It varies in the range between 0 and 1, i.e. $0 < h < 1$. At $h = 0$ there is a completely plastic impact, that is, all the energy of the impact is spent on plastic deformation. At $h = 1$ there is a completely elastic impact, that is, there is a complete recovery of the motion after the impact, albeit in a different direction.

- *The ratio of the absolute values of the normal projections of the relative velocities before and after contact is a constant quantity and depends only on the physicomaterial properties of the matter.*

$$\frac{u_t}{v_t} = 1 - c \quad (5)$$

Where: c is called *the coefficient of instantaneous friction*.

The two empirical relationships introduced by Newton make it possible to solve equations [3] and find the velocities and impulses during the impact.

As is evident from the above considerations, the impact theory is not an exact theory built on the basis of exact physical quantities and their specific change depending on the change in the surrounding conditions. This is an approximate theory, but it is still based on numerous experiments and the results, which have been confirmed by practice with satisfactory accuracy.

The relationship between the angle of attack q and the angle of reflection after the impact f is as follows.

$$\tan q = \frac{v_t}{v_n}, \tan f = \frac{u_t}{u_n} \quad (6)$$

Or

$$\frac{\tan f}{\tan q} = \frac{1-c}{h} \quad (7)$$

The magnitude of the shock impulse is found by the formula

$$I^m = \sqrt{(1+h)^2 \cos^2 q + c^2 \sin^2 q} \quad (8)$$

1. Kinetic energy.

The momentum of the system after transformation takes the form:

$$m\mathbf{u} - m\mathbf{v} = I^m \quad (9)$$

From which we obtain

$$\frac{mu^2}{2} - \frac{mv^2}{2} = \frac{1}{2} I^m \cdot (\mathbf{v} + \mathbf{u}) \quad (10)$$

An equality is obtained, which shows that the change in kinetic energy when a material point hits a surface is equal to the product of the momentum of the impact force and half the sum of the attack velocity and the reflected velocity.

The kinetic energy lost as a result of this phenomenon is

$$\Delta T = -\frac{1}{2} m(\mathbf{v} - \mathbf{u})^2 \quad (11)$$

Carnot's theorem expresses the loss of kinetic energy using the coefficient of restitution

$$\Delta T = -\frac{1}{2} m \frac{1-h}{1+h} (\mathbf{v} - \mathbf{u})^2 \quad (12)$$

At $h = 1$ there is a completely elastic impact and $\Delta T = 0$, that is, there is no loss of kinetic energy. At $h = 0$ there is practically no second phase of the impact and all kinetic energy is lost.

When the kinetic energy changes in a mechanical system, Carnot's theorem takes the form

$$\Delta T = -\frac{1-h}{1+h} \sum_{i=1}^n \frac{1}{2} m_i (\mathbf{v}_i - \mathbf{u}_i)^2 \quad (13)$$

where i is the number of participating material objects in the mechanical system.

2. Oblique impact of two bodies

The impact of two bodies is called oblique if the absolute velocities of their centers of gravity are not directed along the line connecting them.

$$m_1 \cdot \mathbf{u}_1 + m_2 \cdot \mathbf{u}_2 = m_1 \cdot \mathbf{v}_1 + m_2 \cdot \mathbf{v}_2 \quad (14)$$

After projecting this equality onto the normal and tangent at the point of contact, we obtain.

$$|m_1 \cdot u_{1n} + m_2 \cdot u_{2n} = m_1 \cdot v_{1n} + m_2 \cdot v_{2n} \quad (15)$$

$$[m_1 \cdot u_{1t} + m_2 \cdot u_{2t} = m_1 \cdot v_{1t} + m_2 \cdot v_{2t}$$

To this system of determination, we add the two empirical dependencies from Newton's theorem for the coefficients of restoration and the momentary friction.

$$h = -\frac{u_{1n}-u_{2n}}{v_{1n}-v_{2n}}; c = -\frac{u_{1t}-u_{2t}}{v_{1t}-v_{2t}} \quad (16)$$

II. CHARACTERISTICS OF LANDING STRIKE, SUPPORT, GRIP AND LOKOMOTION

A. Landing blow

Landing is a complex process that takes into account parameters and circumstances from different disciplines of engineering sciences. Landing can be a controlled or uncontrolled process, it can be under the influence of an external force or due to the opposite direction of the movement of the two bodies, etc. *That is, landing is a process in which two bodies approach each other, in which at least one of them controls its movement parameters.*

At the first moment of contact of the two bodies, the phenomenon of Impact occurs for a short time, which affects both bodies.

From d'Alembert's principle for Impact it follows:

$$I^m + (m \cdot v - m \cdot u) = 0 \text{ or } I^m + [-J(m \cdot v)] = 0 \quad (17)$$

This expression shows the relationship of the Impact phenomenon with the inertial characteristics of the impacting bodies and is called *the inertial impact impulse*.

The conclusion that can be made is that the smaller the inertial characteristics during landing, the weaker the impact will be.

The effect of self-centering is manifested in all the listed processes, but it is most noticeable during landing. If the landing gear is multi-point, then the probability that all contact points will simultaneously make contact with the second body tends to zero. The first point that establishes contact with the second body triggers the Impact phenomenon, as a result of the impact force and the excited friction force, a moment is generated at the point of impact, which tends to rotate the first body around the point of contact towards the center of mass of the first body.

B. Impact on support

In essence, the support is a point, line, plane, surface or volume (in the case of a fixed support) between two bodies that are pressed against each other by an external attractive force acting on both bodies.

Impact at landing and impact at support are analogous. The difference between these two processes is that in impact at landing it is between two bodies that have no connection with each other before the start of the Impact phenomenon. In Impact at support there is a preliminary connection between the two bodies.

In this case, d'Alembert's principle takes the form:

$$I_a^m + I_k^m + [-J(m \cdot v)] = 0 \quad (18)$$

Where:

I_a^m – is the impact impulse of the active forces of the system;

I_k^m – is the impact impulse of the forces of the connections.

The expression can be summarized as follows: The impact impulses of the active forces and the forces of the connections on the one hand and the inertial impact impulse on the other hand are balanced. This leads to an analogous conclusion on the control of the Impact phenomenon, as in the landing process.

As an example, the structure of the human foot and its function in the control of the impact phenomenon are shown.

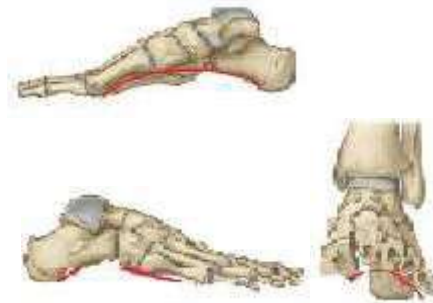


Fig.2. The human foot has three arches – Medial, Lateral and Transverse

The function of these arches (Fig.2.) is to absorb the impact force that occurs when the foot contacts the road (like springs). They sequentially straighten and release their energy, as a motive force to move the body forward.

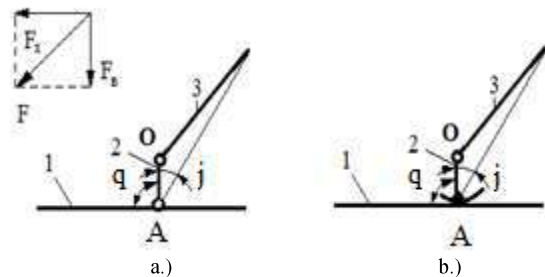


Fig.3 Bounce-back impact during gait

The contact point A is of essential importance for the foot. The contact is usually with a discontinuous second derivative of the law of motion, that is, there is an impact.

In human gait, the so-called bounce-back impact is used (Fig. 3, a). By means of a suitably selected kinematic design of the foot and the values of the angles q and j , the horizontal component of the force F_x continues to act after the contact is established, as a driving force. The contact point A of the foot is formed as a curve, that is, a cam mechanism (Fig.3,b.), increasing the step so that the horizontal force is driving for the system. In space, this heel is formed by a suitable volume

with a shape corresponding to the action of the driving force and its components.

C. Impact during gripping

In point 2.2. for the support process it was mentioned that for this process to exist, it is necessary to have an external force that presses the two bodies against each other. If this external pressing force is zeroed or becomes negative, the support phenomenon cannot be realized, in this case, it is necessary to synthesize a grip. *During gripping, external forces and moments can acquire different values, without limitation, whether they are positive, negative or zeroed.*

The gripping process is a process in which more attention is paid to the forces of the connections between the two bodies. This process emphasizes the control of the size of the connections between the bodies, in order to realize the gripping phenomenon.

In practice, the grip is synthesized as a support to which additional mechanisms are synthesized that grip the other body, providing clamping forces between the gripping mechanism and the second body.

There are many examples of gripping mechanisms in biomechanics.

D. Impact during locomotion

Locomotion is a periodic process of the phenomena of support or grip. In practice, we can speak of a body that changes its shape and the position of the center of gravity in the presence of locomotion. *Considered in depth, this phenomenon occurs between two bodies that, without breaking the connections between them, perform relative motion.* The periodic nature of locomotion suggests that the impact process is also periodic. Therefore, the impact force during locomotion will represent a periodic discontinuous function in time, with periodic peaks of amplitude.

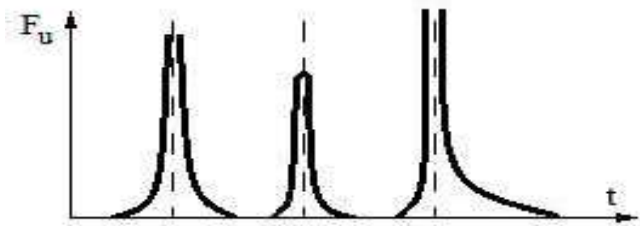


Fig. 4. Sample graph of impact force during locomotion.

From Fig.4. the periodic nature of the impact force during locomotion is noticeable. The first amplitude is almost symmetrical, which shows that the impact force arises and is extinguished without using its resource. The second amplitude shows that the kinematic system has an option to limit the amplitude of the impact force. The third amplitude shows that the kinematic system uses the energy resource of the impact force. The periods between impacts are not equal, since they are set by the kinematic system itself depending on the locomotion process.

III. CONCLUSION

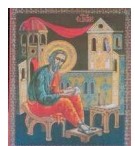
Not always a physical phenomenon, which is usually considered negative, has only negative results in practice.

1. As is evident from the material presented, the physical phenomenon Impact also has positive sides. The quantities involved in this phenomenon have applications in landing, synthesis of supports and grips, as well as in locomotion.

2. An important phenomenon of the Impact phenomenon is the self-centering effect that it generates on the actions of the kinematic chains of the mechanisms of the listed processes.

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Visual Analysis of Digital Electrocardiographic Signals Using 2D and 3D Poincaré Plot

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Abstract— The article presents the results of visual analysis of heart rate variability (HRV) of digital electrocardiographic (ECG) signals. The study covers subjects with cardiovascular diseases and athletes, analyzed before and after training. The analysis was performed using a software application developed in the MATLAB environment, and the 2D and 3D Poincaré method was applied to evaluate the data. Visualization of cardiac data (RR intervals) using this method allows for a quick assessment of changes and detection of anomalies that may be indicators of disease states. In addition, the method is useful for analysing the response of athletes to physical exertion during training. From the obtained graphical results of the studied athletes, it follows that during training, the RR data, which take into account the intervals between consecutive heartbeats, become more uniform and the graphs appear compressed, i.e. the variability of the intervals between heartbeats decreases. Similar results are also observed when studying subjects with the following cardiovascular diseases: arrhythmia, heart failure and syncope. The results obtained show that the Poincaré method is effective for visual assessment of heart rate variability in both healthy athletes and patients with cardiovascular diseases. Through the graphical representation of RR intervals, physiological adaptations to physical exertion can be quickly identified, as well as for the detection of potential pathological changes. This makes the method useful both in clinical medicine - for early diagnosis and monitoring of cardiovascular diseases, and in sports medicine - for assessing the physical fitness of athletes, regulating the training process, optimizing recovery after exertion and predicting potential health problems or injuries.

Keywords— Electrocardiogram (ECG) signal, Heart Rate Variability (HRV), RR time intervals, Poincaré plot.

I. INTRODUCTION

One of the priority areas of scientific research in modern clinical and sports medicine is related to the search for highly informative, non-invasive methods for studying heart rate variability and determining the cardiac health of athletes. One of the widely used methods for studying the bioelectrical activity of the heart is the electrocardiogram (ECG), and an

important diagnostic parameter that can be determined from it is heart rate variability (HRV), taking into account the difference between consecutive heartbeats (RR intervals) [4]. HRV can be a useful tool for studying the influence of various cardiovascular diseases, as well as mental [1,2] and physical exertion during training [9,10,11], on the heart rate of patients and athletes. ECG signals provide important information about cardiac activity, which can be used not only in non-invasive medical examinations, but also for monitoring the cardiac health of patients and athletes, using specially developed software applications [4]. Methods for analysis and assessment of HRV fall into two main classes: linear and nonlinear. Linear methods perform HRV analysis in the time and frequency domains [12]. These methods are used in the clinical practice of doctors because they are standardized and their reference values are known. Nonlinear methods are potentially promising tools, but currently they are used to a limited extent, since they are not standardized and are in the process of active research. According to a document [3] of the European Society of Cardiology and the North American Society of Electrophysiology, the study of the applicability of linear and nonlinear mathematical methods for HRV analysis is defined as one of the most important priority areas for research, prediction and improvement of human cardiac health. This document confirms the relevance of this type of research. The Poincaré method allows for a graphical representation of the dynamics of heart rate variability, allowing for a quick visual assessment of the cardiac condition. By analysing the distribution of points in the Poincaré diagram, various conditions can be identified – from normal physiological reactions to pathological changes associated with cardiovascular diseases. With the development of technology, the use of automated software applications for HRV analysis is expanding, implementing algorithms for ECG signal processing in environments such as MATLAB, R or Python. In recent years, there has been increased interest in the integration of artificial intelligence (AI) and machine learning (ML) methods for automatic classification of heart rhythms and prediction of cardiac risks.



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Despite their advantages, nonlinear methods, including analysis using Poincaré diagrams, still face challenges related to the lack of established clinical standards and reference values. Future research in this area is aimed at validating these methods using large clinical databases and developing new hybrid approaches combining linear and nonlinear techniques for more precise assessment of cardiac health. The study of nonlinear methods for HRV analysis has significant academic interest, especially in the field of clinical and sports medicine. The potential for developing new software products opens up opportunities for more effective use and application of HRV analysis in real-world settings. In addition to patients with cardiovascular diseases and professional athletes, these methods may also be useful for the wider population, including people with chronic diseases and the elderly, who also need balanced physical activity.

The present article aims to present the results of a study of HRV in patients with various cardiac diseases and athletes. The Poincaré method was used for the analysis, which allows for a visual assessment of heart rate variability. Using a developed software application in the MATLAB environment, the RR intervals are visualized, which allows for monitoring their changes and calculating the quantitative parameters SD1 and SD2 - indicators of short-term and long-term heart rate variability. It is expected that the obtained results will contribute to a better understanding of the relationship between HRV and cardiac health, as well as support the future development of standardized analysis methodologies to be integrated into clinical and sports practice.

II. POINCARÉ PLOT METHOD

A. Poincaré plot algorithm

The Poincaré method is a relatively new technique that can be used for visual analysis of the nonlinear dynamics of ECG signals to detect periodic or chaotic structures in them [6,8,13,14]. It can be used to visualize the time RR intervals between successive heartbeats, as well as to provide information about the dynamics of the heart rhythm. The algorithm for plotting with the method is as follows:

Step 1: Preparing the data for analysis.

An electrocardiographic device records the ECG signals and determines the RR intervals, which are the time intervals between successive R peaks of the electrocardiogram. Once the RR intervals are recorded in a file, the data can be processed to remove the artefacts and unwanted noise, by applying filters or data processing algorithms to improve the quality of the RR interval series. Modern electrocardiographic devices provide information about the RR intervals of the recorded ECG signals.

Step 2: Constructing the Poincaré graph.

Each RR interval is represented as a function of the previous interval and is plotted as a point in a rectangular coordinate system, with the abscissa of each point being the current $RR(n)$ interval and the ordinate being the next $RR(n+1)$ interval in the time series. When forming the graph shown in Figure 1, a segment of points is obtained, the centre

of which is located on the identity line. The identity line is represented by the function $x=y$ ($RR(n)=RR(n+1)$). If the point is located above the identity line, this indicates that the current interval is longer than the previous one and vice versa. Additional elements, such as ellipses, can be added when constructing the graphs.

The ellipse is a basic analytical method for assessing heart rate variability, which visually represents the short-term and long-term heart rate variability and can be used to assess the cardiac health of the studied individual. The centre of the ellipse is located on the identity line, and its parameters are SD1 (Standard Deviation 1) and SD2 (Standard Deviation 2). SD1 represents the standard deviation of the points that are perpendicular to the identity line. This parameter is related to short-term HRV and its higher value means a healthier heart rate. SD2 represents the standard deviation of the points that are along the identity line. This parameter is related to long-term HRV and is usually associated with greater physical exertion, fatigue or disease. A higher value of the SD1/SD2 ratio is associated with higher HRV and better cardiac health.

Step 3: Visual analysis.

The visual analysis is performed based on the following parameters [5,4,7,8]:

- The shape of the figure formed by the Poincaré points, which depends on the characteristics of the dynamical system and is related to its stable or chaotic behaviour. Some of the shapes that can be observed are:
 - o a comet that is characterized by a narrow lower part and widening towards the top. This form means a stable or periodic dynamic mode in the system;
 - o a torpedo, which is observed in systems with quasi-periodic or chaotic behaviours;
 - o a fan, which is characterized by a widening or narrowing shape of the Poincaré graph. This is observed in systems with chaotic attractors or close to the limit of chaos;
 - o a complex shape that consists of several segments and is characteristic of fractal structures.
- Symmetry of the points relative to the identity line indicates the equilibrium state of the system.

Step 4: Quantitative analysis.

The quantitative analysis is determined by the values of the parameters: SD1, SD2 and the ratio SD1/SD2 and are used to further assess the dynamic behaviour of the system.

Step 5: Generate a protocol.

As a result of the analysis, a protocol is generated that includes numerical and graphical information. The protocol can be saved in text format or as a PDF file.

B. Pseudocode for generating Poincaré plot

The pseudocode for generating the Poincaré plot is shown in Fig. 2. It can be used in various medical and sports applications, providing valuable information about the dynamics of the heart rate. Specifically, the plot can be applied in the following cases:



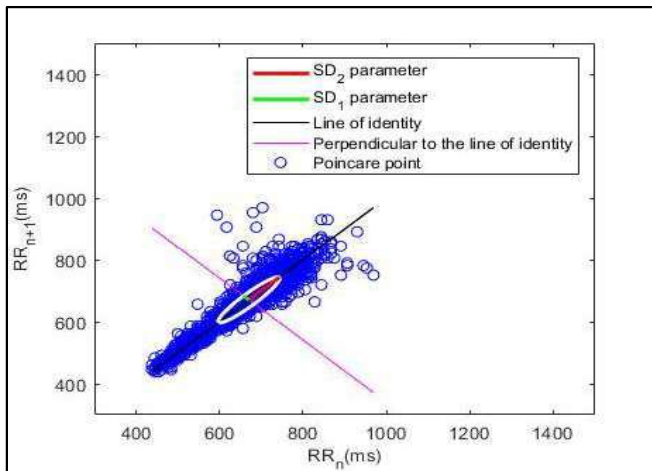


Fig. 1 Components of the Poincaré plot method.

- Early diagnosis of cardiovascular diseases – Analysis of heart rate variability using Poincaré plots allows the detection of abnormalities associated with diseases such as arrhythmia, hypertension and autonomic dysfunction. By visualizing the points in two-dimensional space, characteristic patterns can be identified that signal the risk of heart problems.
- Tracking recovery in athletes after exercise – The Poincaré graph is a useful tool for assessing the state of the autonomic nervous system after exercise. By analysing short-term and long-term heart rate variability, the degree of recovery of the body can be determined and the training regimen can be optimized.
- Assessment of stress and the psychophysiological state of the individual;
- Analysis of the effectiveness of drug therapy in patients with heart disease;
- Studying the impact of various factors (such as sleep, diet, and physical activity) on heart rate.

This visualization method provides an easy and intuitive way to analyse complex physiological processes, making it a valuable tool in medicine, sports, and scientific research.

Algorithm for generating Poincaré plot

1. Input: RR_intervals (array of RR intervals).
2. If length of RR_intervals < 2, then return "Insufficient data".
3. Initialize empty array X and Y.
4. For $i=1$ to $\text{length}(\text{RR_intervals})-1$:
 - $X(i)=\text{RR_intervals}(i)$;
 - $Y(i)=\text{RR_intervals}(i+1)$.
5. Compute SD1 and SD2:
 - $\text{SD1} = \text{standard deviation of } (Y-X)/\sqrt{2}$;
 - $\text{SD2} = \text{standard deviation of } (Y+X)/\sqrt{2}$.
6. Plot Poincaré diagram:

- Scatter plot of (X, Y);
 - Plot identity line ($y=x$);
 - Plot perpendicular to the line of identity;
 - Plot ellipse with SD1 and SD2.
7. Output: Poincaré plot, values of SD1 and SD2.

Fig. 2 Pseudocode for generating Poincaré plot.

The pseudocode description is as follows:

1. Input: The input is a list (array) of RR intervals – the time between two consecutive heartbeats, measured in milliseconds (ms) or seconds (sec).
2. It checks whether the list contains at least two elements. If not, the algorithm stops with an appropriate message.
3. Creating two empty arrays X and Y that will contain the corresponding coordinates of the points in the Poincaré graph.
4. Initialization of the coordinates (X, Y): It is implemented by taking two consecutive RR-intervals:
 - $X(i) = \text{RR}(i)$;
 - $Y(i) = \text{RR}(i+1)$.
5. Calculation of the parameters SD1 and SD2.
 - SD1 (short-term variability) is calculated as the standard deviation of the differences between consecutive RR intervals divided by $\sqrt{2}$.
 - SD2 (long-term variability) is calculated as the standard deviation of the mean of consecutive RR intervals divided by $\sqrt{2}$.
6. The graph is generated :
 - A scatter plot is used to plot all points (X, Y).
 - The diagonal line ($y = x$) is added, which shows the ideal case without variability.
 - An ellipse is drawn based on SD1 and SD2 to visualize the distribution of points.
7. The output is a plot that shows the scatter of the points and visualizes the heart rate variability. The values of SD1 and SD2 are output, which can be used for quantitative analysis..

This method of HRV visualization provides an easy and intuitive way to analyse complex physiological processes, making it a valuable tool in medicine, sports, and scientific research.

III. DATA

This article presents the graphical results of the studied cardiological signals recorded with a Holter device. The data are divided into two groups:

1. Group 1: Healthy individuals, patients with cardiovascular diseases: arrhythmia, heart failure and

syncope. The duration of the recordings is 24 hours with approximately 100,000 RR intervals.

2. Group 2: Athletes training in wrestling. The duration of the recordings is 30 minutes with about 2000 RR intervals recorded before and after training.

IV. RESULTS AND DISCUSSION

A. HRV analysis of patients with cardiovascular diseases with 2D Poincaré plot

Figure 3 shows the graphical results obtained with the Poincaré method for a healthy individual, patients with heart failure, arrhythmia and syncope. Based on the obtained graphical results, the following conclusions can be drawn:

1. The Poincaré points for the subjects are symmetrical about the identity line, indicating that they do not have rhythm disturbances. The points that are above the identity line are colored blue, and those below the identity line are colored red.
2. Healthy individual (Fig. 3A): The points are evenly distributed around the identity line. A relatively tight cloud of points is observed, which has the shape of a comet with a pointed lower part that widens towards the top. The graph is an indication of normal heart rate variability.
3. Heart failure patient (Fig. 3B): The points are more scattered, grouped into several segments, indicating reduced heart rate variability. This pattern may be an indicator of reduced autonomic regulation of the heart.
4. Arrhythmia patient (Fig. 3C): The graph is fan-shaped, with the points more randomly spaced. This is typical of an irregular heart rhythm.
5. Syncope patient (Fig. 3D): The distribution of dots resembles a torpedo and reflects sudden changes in heart rate. There are areas with a greater concentration of dots, suggesting instability in heart rate regulation.

Summary: 2D Poincaré diagrams are a useful tool for assessing cardiac activity and can aid in the diagnosis of various cardiac conditions.

The 3D Poincaré plot (Fig. 4) can provide additional information that is not as obvious in the standard 2D version. Here are a few key advantages:

B. HRV analysis of patients with cardiovascular diseases with 3D Poincaré plot

1. Additional dimension of information: In the classic 2D Poincaré plot, each point represents a pair of consecutive intervals $RR(n)$ versus $RR(n+1)$. In the 3D Poincaré plot, another dimension is added, often $RR(n+2)$, which allows for a better understanding of long-term dependencies and dynamics of the heart rate.
2. Better recognition of complex patterns:

In the 2D graphs, some points may overlap, making analysis difficult. In 3D space, different layers or cluster structures may be observed, indicating specific rhythmic abnormalities.

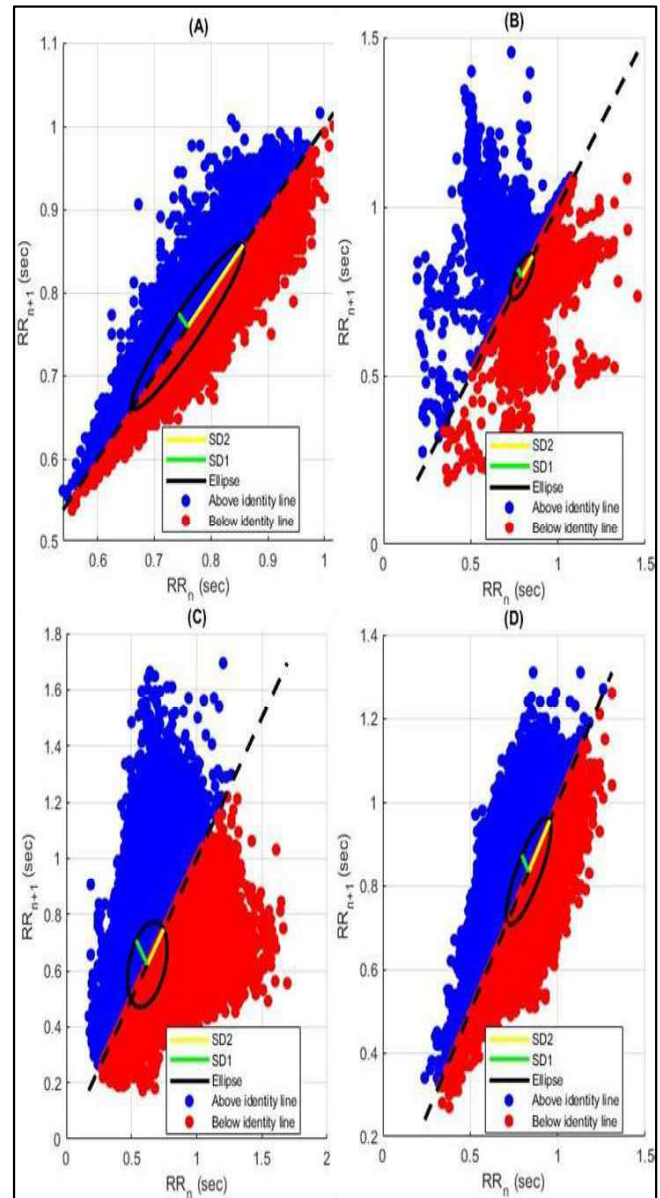


Fig. 3 2D Poincaré plot for subjects: (A) normal, (B) heart failure, (C) arrhythmia and (D) syncope.

3. Long-term relationships and trends: Heart rate variability can be analysed over a longer time range, revealing trends not visible in 2D. This is especially useful in patients with arrhythmia, atrial fibrillation, or autonomic dysfunction.
4. Better visualization of chaotic and deterministic structures: In healthy individuals, 3D graphics often retain an ordered structure. In patients with heart disease, increased chaos may be observed, which is more easily noticeable in 3D.
5. 3D Poincaré plots not only expand visualization, but also add a new level of analysis. They can help with more accurate diagnostics, earlier disease detection, and a better understanding of heart rhythm dynamics.

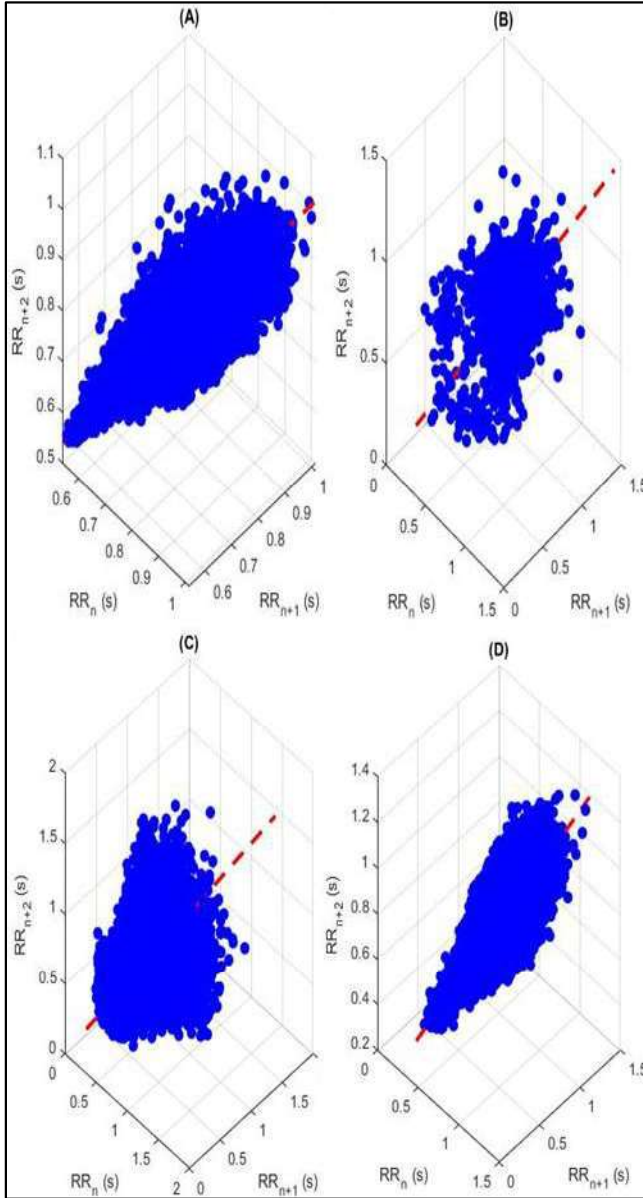


Fig. 4 3D Poincaré plot for subjects: (A) normal, (B) heart failure, (C) arrhythmia and (D) syncope.

B. HRV analysis of athletes before and after training

Figure 5 and Figure 6 show the graphical results obtained with the Poincaré method of athletes before and after training. Based on the graphical results, the following conclusions can be drawn:

1. The graphs of the six athletes studied before training (Fig.5) have the shape of a comet, with a pointed lower part that widens towards the top. The shape of the graphs shows that the athletes are cardio logically healthy and have a high HRV, according to previous publications [4, 8]. The Poincaré points for all six athletes are symmetrical about the identity line, indicating that the athletes do not have rhythm disturbances.
2. The graphs of athletes after training (Fig. 6) are compressed because the intervals between heartbeats

become more even as a result of physical exertion during training and the HRV decreases.

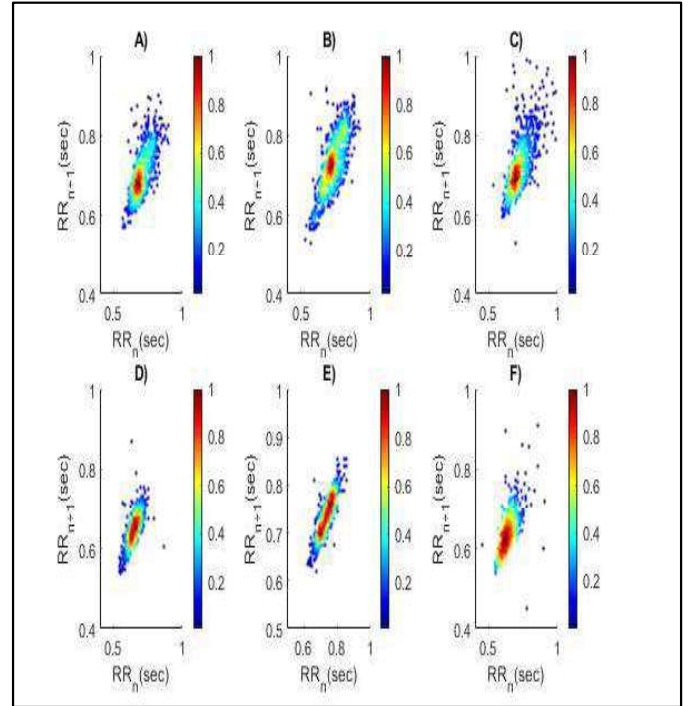


Fig. 5 Poincaré plots of athletes before training

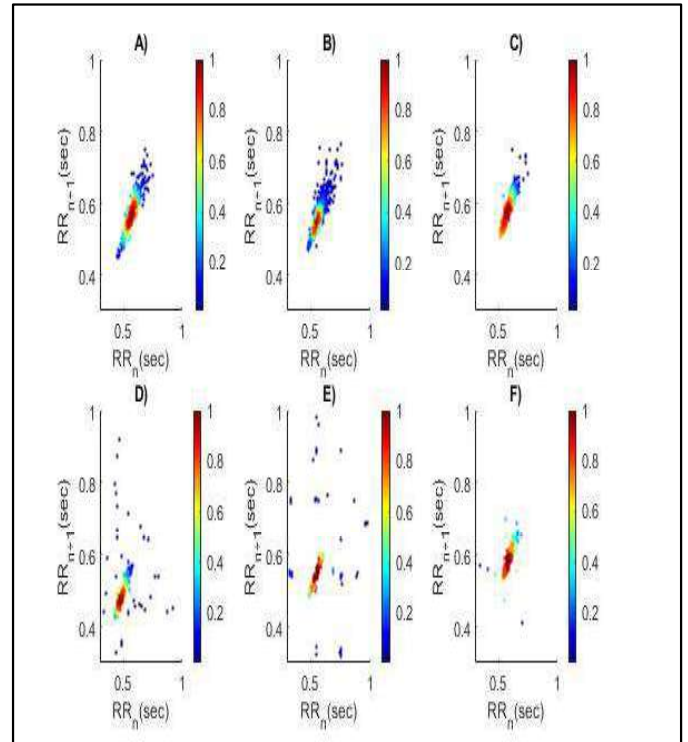


Fig. 6 Poincaré plots of athletes after training

V. CONCLUSIONS

In recent years, heart rate variability has been the subject of extensive scientific research and has found applications in

clinical and sports medicine. New technologies and mathematical methods for analysing HRV contribute to a better understanding of its role in both diagnostics and sports.

HRV plays an essential role in sports medicine, providing valuable information about the health status and training of athletes. It helps to optimize training programs and sports results. In addition, it can be used as an indicator of the adaptation of the cardiovascular system to training loads and to assess the level of physical exertion.

The application of mathematical methods for visual analysis, such as the Poincaré method, provides additional information about the physical condition of athletes. This method facilitates the personalization of training programs and load management in order to improve sports performance, prevent overloads and reduce the risk of injuries.

The advantage of the Poincaré method is that it allows for easy visualization of the dynamics of the heart rhythm. It allows all RR intervals to be seen on the graph, which allows for the rapid identification of deviations related to cardiovascular diseases or overload during training.

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Human-Robot Interaction in Educational and Healthcare Service Robots

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Abstract — *The paper presents an approach to the design of collaborative service robots in education and healthcare, based on the ability of the service robot to predict the positive or negative effects on the people they interact with at the systems design stage, rather than after their ad hoc implementation. The design focuses on 2 main functional characteristics, which represent communication functionalities - human-robot verbal dialogue and detection by the robot of negative/ambiguous emotional reactions of the human. Some aspects of the future implementation are outlined in the paper.*

Service robots, Collaborative robots, Cyber-physical nurse, Functional characteristics, Compassionate presence of the robot

I. INTRODUCTION

The idea of the feasibility of the so-called "cyber-physical nurse", which is a technical system (service robot) used not only in a medical, but also in a social context to help "alleviate suffering through compassionate presence" [1] (p. 6) is further developed in the present paper towards its main communication functionalities like human-robot verbal dialogue, on the one hand, and detection by the robot of negative/ambiguous emotional reactions of the human, on the other.

The adopted approach emphasizes the ability of the collaborative service robot to predict the positive or negative effects on the people they interact with at the systems design stage [2, 3], rather than after their ad hoc implementation. In the present paper the commonalities of some recent implementations of dialogue and mood detection in educational and healthcare service robots are outlined and discussed.

Two distinct, yet overlapping, cases of situations, demanding "compassionate presence" on behalf of the robot are outlined. The first one is the situation of special education when children are involved in learning activities with multiple repetitions and attempts to keep focused attention. It is very difficult to maintain positive emotionality during these rehearsals by the child. Social robots have revealed their potential to entertain the child and help implicitly learn new knowledge by preserving the cognitive resource of the child [4, 5, 6]. One cyber-physical system of the kind is presented in [4, 5], where learning is mediated by the mini robot BeBot, which supports the teacher and maintains the attractiveness of

the learning situation in the class. The potential of BeBot for entertaining patients in hospitals is discussed in [4].

Section II outlines the main features of an educational scenario for helping the child learn mathematics. The implementation of an inclusive class with robots, performing diverse tasks like detection of attention shift of the child, or expressed negative emotion, is depicted in figure 1.



Fig. 1. *Cyber-Physical Classroom Concept (generated with the help of SORA AI [7]).*

The second situation is a rehabilitation setting where a person has to communicate information about their condition, feelings of discomfort or current need. The main tool for this is the ability of the service robot to understand the utterances of the patient in a safe manner in order to provide an efficient support. Examples are reporting thirst, discomfort, attempts to attract attention, reporting a negative emotion, etc.

Section III presents a voice interaction architecture for a collaborative robot in relation to the verbal communication and activation of some immediate actions towards the patient.

Section IV covers a concept of the described voice human interaction architecture in a healthcare scenario. The Conclusion section outlines possible future research.

II. LEARNING MEDIATED BY THE MINI ROBOT BeBOT

The concept of “compassionate presence” in learning was piloted in an educational experiment carried in the Day center for children and youth with disabilities “Sveta Nedelya” (Sandanski, Bulgaria) [4, 5]. Figure 1 represents the concept of a classroom where teachers and robots pay attention to each individual child to support their learning need.



Fig. 2. Robot-Assisted Education - Learning Basic Math.

The robot used in this scenario - BeBot - has the following capabilities:

- ✓ to do precise movements and rotations of the mobile base;
- ✓ to speak using a TTS engine that supports 127 languages;
- ✓ to project images and videos on the wall (the robot head is a high resolution DLP projector);
- ✓ to express different emotions using specially designed emoticon images and the head-projector.

The robot programming and choreography are done using the software framework, called ERICS part of the OPERA platform.

The educational experiment in general is a robot assisted math lesson, where the children can be taught to sum the numbers from 1 to 10. The robot projects a movie with the lesson, speaks and makes funny moves. The teacher guides the entire process and gives confidence to the student so that the acquired knowledge is retained. The BeBot robot with its projection capabilities captures the interest of the child and makes the teaching process much easier. The teacher has the main and leading role in the teaching process and the robot is assisting the process, greatly improving the attention focus of the child on the educational topic. According to the teachers, involved in the pilot of this scenario, the proposed robot-assistive education enhances the learning of concepts of the child, their attention span and positive mood during the lesson. The received feedback from the children, participating in the study, was strongly positive.

III. REHABILITATION SETTING FOR COMMUNICATION INFORMATION ABOUT HEALTH CONDITION

The core system architecture for voice human-robot interaction (VHRI) in service robots comprises a voice interface pipeline coupled with an emotion detection module. Figure 3 presents an overview of the voice recognition and emotion detection pipeline. The audio input from the user is processed in order to understand what is being said (speech content and intent) and how it is being said (emotional tone), enabling the robot to decide on an appropriate response or action. The software framework is modular, allowing components to be improved or replaced as needed (for instance, swapping in a new speech recognizer or emotion classifier without overhauling the entire system).

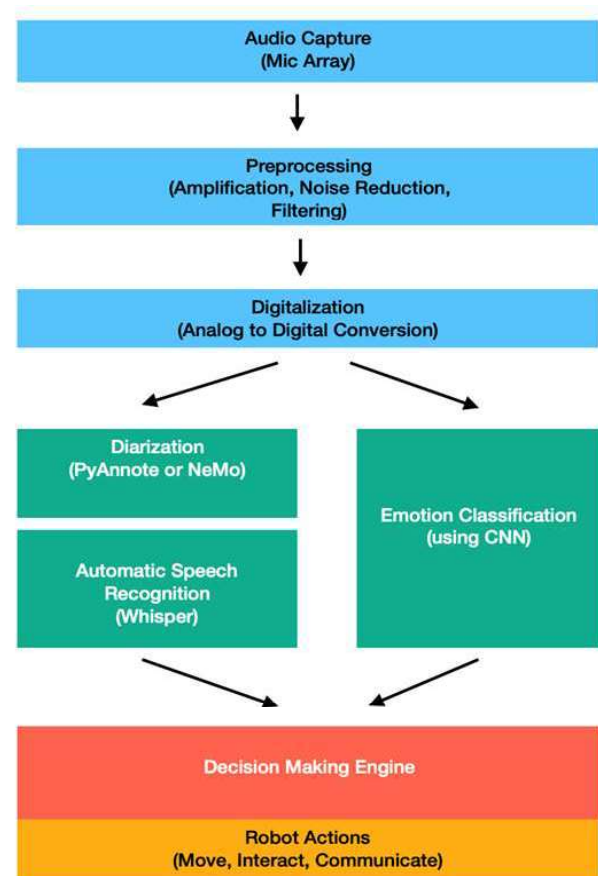


Fig. 3. Human-Robot Voice Interaction Architecture.

The key components of the architecture include:

Audio Capture and Preprocessing: Sound from the human is captured via the robot’s microphone array. The raw audio signal first undergoes preprocessing steps such as amplification, voice activity detection (to detect when a person is speaking), normalization of volume levels, and noise reduction to filter out background noise. These steps ensure that the subsequent analysis receives a clear and consistent audio input. Techniques like spectral subtraction or adaptive filtering may also be beneficial to suppress ambient noise, which is especially important in busy environments like classrooms or hospitals.

Automatic Speech Recognition (ASR) and Diarization: The cleaned audio is fed into a speech recognition (ASR)

engine to transcribe spoken words into text. In our current setup, this is handled by OpenAI's Whisper model, running locally on Mac Silicon hardware [8]. Whisper is a state-of-the-art transformer-based ASR model with relatively good accuracy even in noisy conditions. Trained on 680,000 hours of multilingual data, Whisper can transcribe speech even in challenging acoustic environments and across multiple languages [8, 9]. This multilingual ability is beneficial in both education and healthcare contexts (e.g., a robot that can understand English, Bulgarian, Spanish, etc., out of the box). Alongside transcription, the system can perform speaker diarization – determining “who spoke when” in the audio (currently for English Language only). Diarization (i.e. creating a diary) is important if multiple people (e.g., a patient and a nurse) are speaking near the robot, so that the robot can attribute statements or requests to the correct individual.

We have experimented with an open-source diarization tool - PyAnnote [10]. PyAnnote provides neural models for speaker segmentation and clustering, effectively separating different speakers in an audio stream. In practice, the audio pipeline uses PyAnnote to label segments by speaker ID, and Whisper then transcribes each segment. The combination yields transcripts with speaker tags, so the robot knows, for example, that Person A said “Where is my medication?” and Person B said “It's on the table.” This information can be crucial for context in decision-making. Alternatively NVIDIA's NeMo Framework can be used for diarization. NeMo is a scalable and cloud-native generative AI framework built for researchers [11].

Natural Language Understanding and Decision Module: The transcribed text (along with speaker information and optionally punctuation or sentiment cues from the ASR) is passed to the robot's dialogue and action management module. This module interprets the user's intent and decides on the robot's response. Two approaches can be used here: a rule-based dialogue manager or a large language model (LLM). In simple command-and-control scenarios (especially in healthcare routines), a rule-based system might map specific phrases or keywords to actions – for example, if the text contains “Bring water!” the robot will execute a fetch-water routine. However, for more flexible and natural interaction, the system can leverage an LLM-based AI agent. Modern LLMs (like GPT-style models) can take the user's transcribed input and generate contextually appropriate responses or action plans. For instance, the robot could use an LLM to parse a complex request (“I'm feeling cold, could you close the window and maybe tell me a joke?”) into actionable sub-tasks (adjust environment; engage in small talk). The combination of STT→LLM (and subsequently TTS for replying) is a growing trend in voice AI, enabling systems to listen, reason, and respond conversationally. The decision module may also incorporate additional logic to ensure safety and reliability – e.g., critical commands might require confirmation, and any ambiguous input might trigger a clarification question from the robot. The output of this module is a high-level decision: it could be a verbal response, a physical action, or a combination of both.

Emotion Detection Module: In parallel with speech-to-text processing, the architecture includes an emotion recognition pipeline operating on the user's voice. The same audio input (after preprocessing) is analyzed to infer the speaker's emotional state. This module produces an emotion label (such as “happy,” “calm,” “anxious,” “confused,” etc.) based on context and vocal intonation and other acoustic

features. The emotion detection system can use machine learning models that have been trained on labeled emotional speech data. Generally this involves extracting features from the audio using Mel-Frequency Cepstral Coefficients (MFCCs) or learned representations from a neural network to classify the emotion. The resulting emotion information is fed into the decision module, providing important context for the robot's response. For example, if a patient's words say they are feeling “okay”, but the emotion recognizer detects sadness or strain in the tone of voice, the robot can interpret that the patient might actually need help or comfort, prompting a more considerate response. It is a good approach if the emotion detection runs concurrently with speech recognition to minimize latency, and the decision module waits a short moment to receive both the transcribed content and the emotional cues before formulating a response.

Robot Response Generation: Finally, based on the decision module's output, the robot carries out the response. This can involve physical actions (moving, fetching an item, gesturing, etc.) and/or social actions like speaking to the user and expressing an emotion. For spoken responses, the system uses a TTS (text-to-speech) engine to synthesize the reply in a natural-sounding voice.

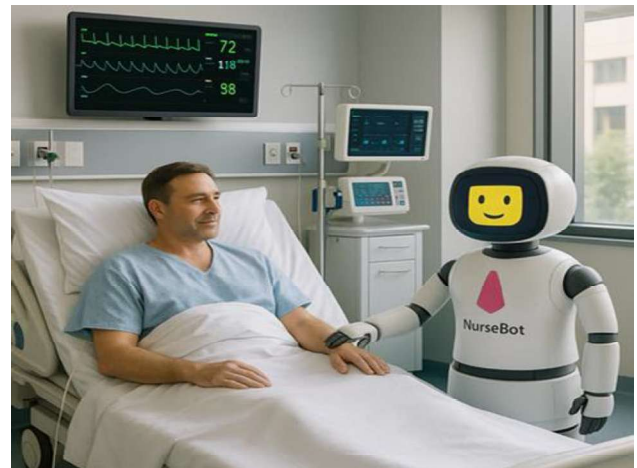


Fig. 4. Cyber-Physical Nurse Concept (generated with the help of SORA AI [7]).

In the future, if an improved speech engine is used, the robot might be able to modulate its tone or choose more gentle wording if it detects the user is upset, aligning with a more compassionate bedside manner. The closed-loop system then awaits further input, continually listening for voice commands or dialogue from humans.

In summary, the system architecture enables the robot to listen to what a user says, understand both the content and the emotional subtext, and act appropriately. This creates a more natural interaction flow, much like human conversation, where tone and words together inform how we respond. All the components such as Whisper ASR, PyAnnote diarization and emotion classifier can communicate asynchronously. The modular design allows swapping components - for example, updating the emotion model, without altering the rest of the system, and facilitates debugging.

Example of Emotion Extraction From Audio Data: CNN Classifier Trained on RAVDESS - The Ryerson Audio-Visual Database of Emotional Speech and Song (RAVDESS)

is a popular dataset, containing recordings of actors speaking sentences with various emotions (neutral, calm, happy, sad, angry, fearful, surprise, disgust) [12]. Using this dataset, a convolutional neural network classifies audio into one of these emotion categories. The approach involves converting the audio input into a suitable representation (Mel-spectrogram or a MFCC¹ matrix) and then feeding it into a CNN that learns to discriminate the emotion-related patterns in the voice. CNNs have been widely used in SER (Speech Emotion Recognition) because they can capture spectral-temporal features of audio effectively. In our case, the CNN model has a few convolutional layers for feature extraction followed by dense layers for classification. It achieves high accuracy on the RAVDESS test set - on the order of 70-80% classification accuracy, depending on the emotion, which is comparable to other research results [13]. Such performance is quite good considering human listeners also have trouble distinguishing certain emotions. The advantages of this CNN approach are its simplicity and speed: the model is relatively lightweight and can run in real time on the robot's onboard computer without requiring a GPU. It processes short audio chunks (e.g., 2-3 seconds of speech) and outputs an emotion label almost instantly, which is ideal for responsive interaction. Moreover, training on RAVDESS means the model is tuned for English speech with acted expressions – it recognizes exaggerated cues well (like a very angry tone or a very sad tone). However, there are limitations: since RAVDESS is acted, the model might not generalize perfectly to natural, subtle emotions in real conversations. It might misclassify emotions that are less pronounced or mixed. Also, because it's trained on English phrases, we must be cautious when dealing with other languages or cultural differences in emotional expression (though acoustic features of emotions tend to transfer across languages to some extent). If we needed the robot to detect emotions in another language, we'd ideally retrain or fine-tune the model on data in that language, or at least ensure non-language-specific features (tone, pitch) dominate the classification. Despite these caveats, this CNN (convolutional neural network) approach provides a solid baseline: it's easy to integrate and fast enough for continuous monitoring even on a Raspberry Pi 5 single board computer [13].

IV. A ROBOT-ASSISTED HEALTHCARE SCENARIO

Hospital with Cyber-Physical Nurse Robots: NurseBot (the cyber-physical nurse robot) operates in a hospital ward, assisting human nurses in routine tasks and providing companionship to patients (figure 5).

Let's think about a scene during the morning round as depicted in figure 4: NurseBot enters a patient's room to check on them and greets him, "Good morning, how are you feeling today?" using a pleasant, gentle voice (the robot's TTS is configured to a calm tone appropriate for a healthcare setting). The patient responds, "I'm okay, I guess... just a bit sore." The voice recognition module transcribes this. At the same time, the emotion detector notes a strain in the patient's voice that correlates with discomfort or sadness.

NurseBot's decision module interprets that the patient might be downplaying his pain or mood. Instead of just logging vitals, the robot decides to show concern. It replies, "I'm sorry to hear that you're feeling sore. Is there anything I can do to help ease your discomfort?" This empathetic response is made possible by the emotion-aware system

recognizing that "I'm okay" didn't sound genuinely okay. The patient might then admit, "Well, my back hurts quite a bit this morning." NurseBot can follow up with an offer: "Would you like me to alert the nurse to bring your pain medication, or perhaps adjust your pillows?" In this way, the robot facilitates communication between the patient and the healthcare staff, ensuring needs are met promptly



Fig. 5. A Nurse, Assisted by NurseBot, BeBot and NAO (generated with the help of SORA AI [7]).

Another scenario is during the robot's autonomous rounds: NurseBot moves through the hallway delivering items or doing room checks. It might encounter a nurse who calls out, "NurseBot, bring this file to Room 12 when you get a chance." Using voice recognition, it transcribes and confirms the task. If the nurse's tone has sounded urgent or stressed (perhaps it has detected urgency in the voice), NurseBot can prioritize that task sooner.

If the robot meets a patient who is anxious (imagine a patient in isolation who hasn't seen many people), and the patient engages it in conversation, the emotion detection subsystem might sense *loneliness* or *anxiety*. NurseBot could then spend a few extra minutes talking with that patient (within its permitted scope), offering comforting words or even playing soft music – acting as a *social companion*. In doing so, it provides not just medical assistance but also compassion and emotional support. This is crucial in healthcare, where emotional well-being significantly impacts recovery.

In a multi-person interaction, say if a doctor, a nurse, and a patient are discussing in the room while NurseBot is present, the robot uses diarization to follow the conversation. If the patient becomes confused about the medical information (detected via a hesitant or worried voice asking a question), NurseBot can later provide a simplified explanation or notify the nurse to clarify, ensuring the patient's understanding. All these interactions are made smoother by the robot's ability to understand natural language voice commands (no one has to fiddle with a touchscreen or a sophisticated user interface) and to detect unspoken cues of emotion. Nurses often say a kind word or show concern naturally; NurseBot, through its programming,

¹ Mel-frequency cepstral coefficients

may try to emulate some of that by detecting cues and responding with pre-programmed empathetic phrases or actions. It is by no means a replacement for human empathy, but it augments the care team by extending the reach of compassionate monitoring – for example, continuously listening for signs of patient distress when nurses are not immediately present. If it detects a patient crying or calling out with fear in their voice at night, it can automatically alert staff and go to that room to say “Help is on the way” thereby comforting the patient until a nurse arrives. These scenarios show that voice and emotion recognition significantly enhance the robot’s *compassionate presence*.

In education, the robot becomes an engaging, responsive aide that can motivate and comfort students. In healthcare, the robot transforms from a simple delivery or measuring device into a pseudo-companion that can attend to patients’ emotional needs in between the busy schedules of human caregivers. Importantly, the robots perform these roles without needing complex interfaces – speech is the primary mode of interaction, which is the most natural human modality of communication [14].

The frequency of human-robot interaction can be modulated according to the preferences of the patient. In a study of the effect of a humanoid robot teacher on the degree of student confidence in class, two types of students were identified – socially-oriented and socially-indifferent [15]. The socially-oriented students preferred the presence of a human during the lesson performed by a humanoid robot NAO (as in figure 5), whereas the socially-indifferent students did not mind the presence of the robot only during the lesson (as in figure 4). Therefore, by accounting for the preferences of the patients, the frequency and distribution of human nurse and robot tasks can be optimized.

By adjusting its responses to the personality as well as to the emotional state of the human, the cyber-physical nurse NurseBot interacts in a way that feels more human-like, promoting trust and likability. This ensures long-term acceptance of such robots in everyday environments.

V. CONCLUSION

Human-robot interaction in the realms of education and healthcare will greatly benefit from advances in voice recognition and emotion detection. In this paper, we discuss how educational service robots (exemplified by the BeBot and OPERA platform) and the cyber-physical nurse robot concept (NurseBot) can engage in natural, intuitive interactions by understanding human speech and emotions. We presented a system architecture that integrates state-of-the-art speech-to-text transcription with speaker diarization and a decision-making engine. Parallely, an emotion recognition module analyzes vocal cues to provide the robot with awareness of the user’s emotional state. This combination enables the robot to not only hear the words being spoken, but also to feel the tone behind them, leading to richer and more context-aware responses. We also explored the importance of emotion recognition, highlighting that modern transformer models offer strong performance at the cost of higher complexity. By implementing these components, the robots are able to maintain an interactive, compassionate presence – BeBot supports teachers by engaging students with responsive dialogue and emotional feedback, while NurseBot assists

healthcare staff by communicating with patients in an understanding manner.

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Perspectives on High -Tech Assistive Technologies for Therapy of Communication Disorders: Findings from Delphi Studies

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Abstract—Recent advancements in high-tech Assistive Technologies (ATs), especially those driven by Artificial Intelligence (AI), have greatly improved the quality of life and of individuals with various neurodevelopmental disorders and communication disorders in particular, contributing to progress in education, employment, social participation and overall well-being. However, despite these improvements, considerable obstacles persist in the application of such technologies across different sectors, highlighting the need for further investigation into their future development. This study explores emerging trends and future directions in ATs, offering key insights from both national and international perspectives. A national Delphi study involving 66 experts from academia, disability-focused organizations and neurodevelopmental centers, along with an international study including 284 participants from 31 European countries, were conducted to evaluate future-oriented projections and gather insights into participants' attitudes toward ATs. The results of the national survey reflect a moderate consensus among Bulgarian experts, reveal a sense of cautious optimism regarding the use of ATs, particularly those powered by AI, for individuals with disabilities. On the other hand, the results of the international study show a similar trend but indicate a little stronger consensus among experts on the positive impact and desirability of ATs in promoting the social inclusion of individuals with neurodevelopmental disabilities.

Keywords—High-tech Assistive Technologies, AI, Neurodevelopmental Disorders, Communication Disorders, Delphi Studies, Expert Perspectives

I. INTRODUCTION

Assistive Technologies (ATs) refer to a broad range of products, services and systems designed to support individuals with disabilities in carrying out specific tasks. These technologies foster greater independence and enable access to education, employment, and full participation in society. The advancement of Artificial Intelligence (AI) has significantly enhanced ATs, leveraging algorithms and data-driven insights to make assistive tools more powerful and effective than ever before.

According to the World Health Organization (WHO), assistive technology refers to products that support or enhance an individual's functional abilities and independence, ultimately contributing to their overall well-being [1]. The Convention on the Rights of Persons with Disabilities (CRPD) explicitly outlines that States Parties have general

obligations to actively engage in or encourage research and development, as well as to promote the availability and use of new technologies—such as information and communication technologies, mobility aids, devices, and assistive technologies—that are appropriate and affordable for people with disabilities. Additionally, States are required to ensure that persons with disabilities have access to information about these mobility aids, devices, assistive technologies (including emerging technologies) and other forms of assistance, support services, and facilities [1]. MacLachlan et al. [2] highlight the significant role AT can play in enhancing access to education and employment, thereby improving overall well-being and fostering social inclusion.

Regarding education, the UNESCO-WEIDONG Group project titled “Leveraging ICT to Achieve Education 2030” highlights the importance of using Information and Communication Technologies to strengthen education systems, facilitate knowledge exchange, increase access to information, promote high-quality and effective learning, and improve the efficiency of service delivery [3]. Within this framework, ATs can be instrumental in facilitating communication and boosting the academic achievements of individuals with diverse disabilities. Additionally, AT can support the development of cognitive abilities and assist in managing challenging behaviors. It also holds the potential to increase self-confidence and foster stronger connections between teachers and students.

Over the past few decades, the field of ATs have experienced significant progress focused on improving quality of life and fostering independence for individuals with developmental conditions and communication disorders in particular. Currently, advanced Assistive Technologies, particularly Socially Assistive Robots (SARs), Virtual Reality (VR), and Conversational AI (Conv. AI), are regarded as highly effective tools in aiding professionals working in Speech and Language Therapy (SLT) for children with communication disorders.

Since there is a gap between the potential of ATs and their practical application in SLT, in the frame of ATLog project (<https://atlog.ir.bas.bg/en/>) a new software and ergonomic platform had to be created for seamless integration of ATs in SLT and intuitive design of interactive and engaging learning scenarios assisted by these high-tech technologies. The research objectives of this study are as follows: (1) to perform



Delphi studies with relevant statements concerning developments in ATs anticipated up to the year 2030, and (2) to evaluate the responses of participants, to draw future directions and to propose the foundational features of an ergonomic platform to streamline the integration of high-tech ATs in SLT. To achieve these objectives a national Delphi study involving 66 experts from academia, disability-focused organizations and neurodevelopmental centers, along with an international study including 284 participants from 31 European countries, were conducted to evaluate future-oriented projections and gather insights into participants' attitudes toward ATs.

II. CHARACTERISTICS OF THE DELPHI STUDY

In recent decades, the Delphi method has played an essential role in developing best practice recommendations via collective knowledge, particularly in scenarios where research is limited, logistical challenges arise or existing evidence is contradictory [4]. This methodological approach is particularly valuable for gathering perspectives on ATs in the field of communication disorders as it facilitates the collection of expert opinions and helps address challenges in this evolving field. The Delphi technique follows a structured process for forecasting by harnessing the collective expertise of a panel of specialists. It integrates both qualitative and quantitative aspects, offering a well-rounded perspective on the research problem [5]. The technique facilitates the coordination of expert discussions while ensuring compliance with four key principles: anonymity, controlled feedback, iteration and statistical group analysis [6]. The Delphi expert group is composed of members chosen primarily for their professional skills in the research subject.

III. RESULTS FROM THE DELPHI STUDIES

A. Results from the international Delphi study

Employing a two-round Delphi method, the authors in [7] carried out an international research study with a panel of 284 experts from 31 European countries, gathering both quantitative and qualitative data. The study explored perspectives on assistive technologies, incorporating ten future-oriented projections and covering five categories – politics, education, technology, employment and society. The authors established the end of 2030 as the timeframe for evaluating the potential realization of each projection and asked the specialists to assess the expected likelihood in 10% intervals. The expert panel included professionals from academia, industry, service providers and disability organizations. The main research question in the paper focused on the challenges experts recognize in the implementation and adoption of ATs for neurodevelopmental disorders with a particular focus on autism and intellectual disabilities. Figure 1 shows that the economic challenges are the most significant across the different projections, particularly in relation to technology forecasts. These challenges are associated with the development of multilingual/personalized devices using AI and the open-source hardware and software of ATs. This suggests that financial issues, such as high costs and funding challenges, are a key factor in the implementation and adoption of ATs. Technological challenges are the least significant across most projections, indicating that they are not the primary obstacles. Addressing economic and political barriers is crucial to the

successful development of assistive technology solutions in the field of neurodevelopmental disorders.

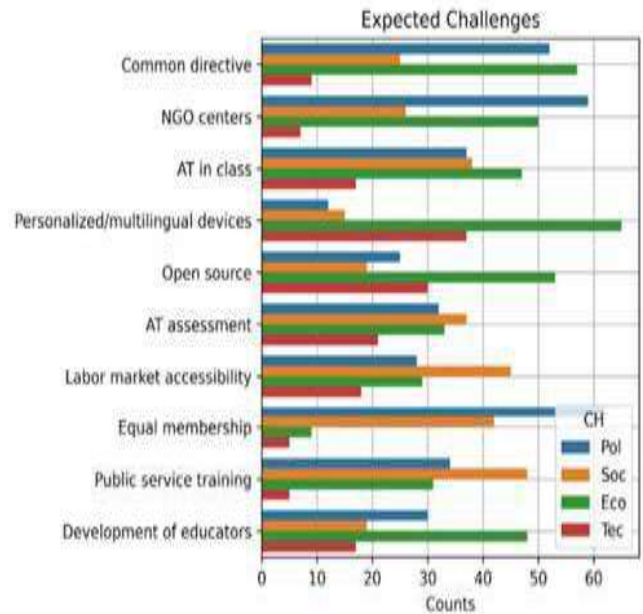


Fig. 1. A visual representation of the challenges anticipated by the experts in the study (N=284). Adapted from [7].

The essential aspects of the Delphi study included expected probability, desirability, and impact in case of occurrence of the proposed scenarios. The authors identified two clusters which are shown in Figure 2. Cluster 1 included four projections that scored higher across all three dimensions. These projections focused on personalized and multilingual devices, AT assessment, public service training, and educator development.

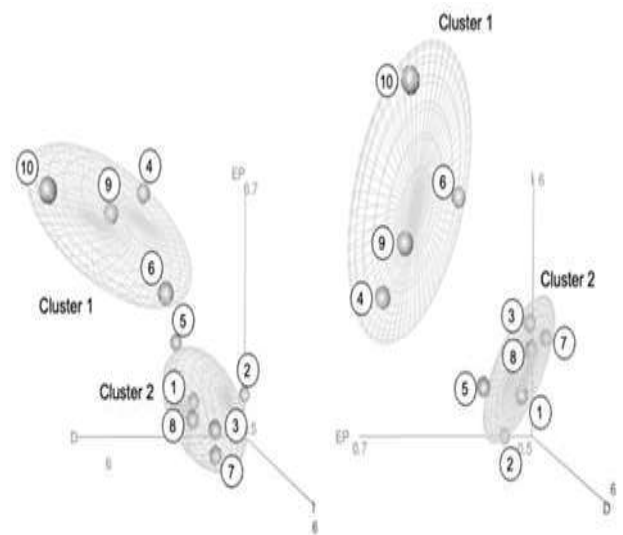


Fig. 2. Cluster-based representation of the evaluated projections. Axis definitions: EP-Expected Probability; D-Desirability; I-Impact. Adapted from [7].

Cluster 2 comprised six projections with generally lower scores, addressing a common directive: the establishment of NGO centers, the integration of ATs in education, adoption of open-source solutions, improved labor market accessibility and equal membership opportunities for individuals with intellectual disabilities and/or autistic individuals. As a whole, the results show that assistive technologies are expecting to

greatly enhancing accessibility for people with neurodevelopmental disabilities. The findings indicate a strong expert consensus on the positive impact and desirability of ATs in fostering social inclusion for individuals with neurodevelopmental disorders.

B. Results from the national Delphi study

Similarly, a national Delphi study (in Bulgaria) was conducted to further explore perspectives on AT-s in CD, involving 66 professionals from academia, disability organizations, and neurodevelopmental centers. The research experimental procedure, informed consent and protocols approved by the Ethics Committee have been uploaded to the OSF platform [8]. The study employed a two-round Delphi method to gather input on 11 forecasts covering politics, education, society, technology and employment, mirroring the categories used in

the international study. The findings aimed to ensure the relevance and effectiveness of the ATL or platform during its early development stage. One of the goals of the study was to understand the attitudes and preferences of experts regarding the use of AT-s in SLT on a national level. Additionally, the study aimed to reach a consensus among the specialists on the proposed scenarios as far as possible.

The findings show that most specialists are optimistic about the potential benefits of ATs for therapy of CD in the medium term. There is a moderate consensus among experts regarding the benefits and desirability of these technologies. The majority believe it is very or moderately likely that the proposed scenarios will become reality by 2030 and that is reflected in eight out of the eleven forecasts. Figure 3 shows the results for these 8 projections.

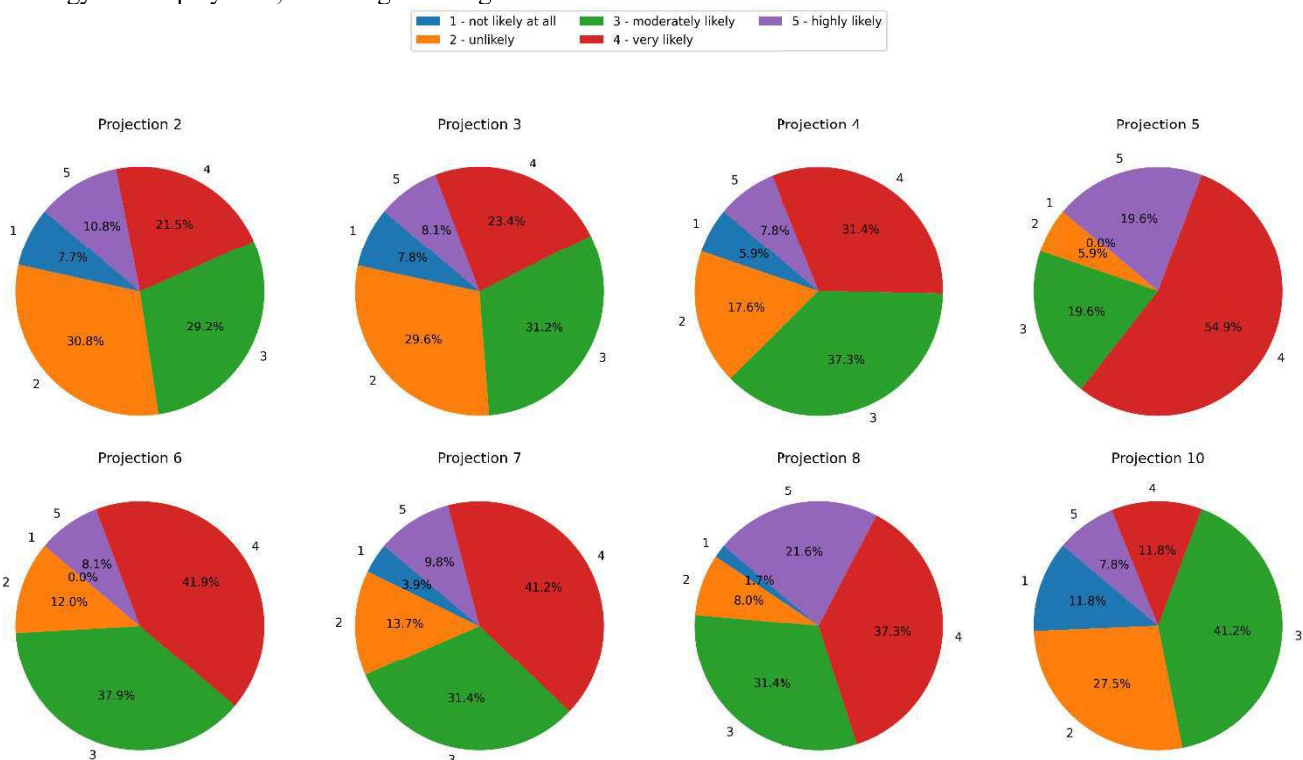


Fig. 3. Results from chosen projections: ATs in classroom (Projection 2), adoption of SARs (Projection 3), VR applications (Projection 4), integration with Bg GPT chat (Projection 5), open-source solutions (Projection 6), parent training programs (Projection 7), practitioner implementation (Projection 8), and investments in speech and language centers (Projection 10).

According to the results of the study, the most optimistic statements are for: AT-s integrated with Bg GPT chat (Projection 5), open-source hardware and software (Projection 6) and training programs for parents (Projection 7). Regarding Projection 5, experts tend to believe that it is very likely that the AI chatbot developed in Bulgarian, Bg GPT, will become very popular in interactions with people with communication disorders. The reason for this is likely the widespread use of the general Chat GPT chat bot and its expansion into more areas of public life. The chatbot's features, such as accessibility, the ability to understand and respond to a wide range of natural language queries, and customization according to specific needs and preferences, contribute to its popularity and trust. In combination with its services developed in Bulgarian, the chatbot becomes a very valuable attribute of assistive technologies in interactions with people with communication problems. For the open-source solutions

(Projection 6), experts believe that it is very likely that ATs will be based on open-source software. They are hopeful that this will become a reality by 2030, so the software will be accessible to everyone working with children and adolescents — users, parents, and professionals. Given the rapid technological progress, it is entirely feasible for ATs to become more accessible and personalized in the near future. Another most optimistic statement by experts is related to training programs for parents (Projection 7), according to which there will be regular trainings on how to use various ATs by 2030. This scenario is very likely for the participants to become reality. The use of ATs is rapidly increasing due to their improvement and the growing awareness of their benefits. As more children and adolescents use these devices, the need for parents to understand and support their use will also grow.

On the other hand, the specialists are most pessimistic about the use of ATs in the classroom (Projection 2), where the most

frequent response is “unlikely”. This reflects the experts' lack of trust that every school in the country will have developed a methodology for using ATs, likely due to the uneven distribution of resources in schools in Bulgaria and the lack of sufficient equipment in many of them. As a result: there is a large discrepancy between those, who have the opportunity to integrate ATs and those who do not. Experts are pessimistic only a little regarding the adoption of SARs (Projection 3), with the response “unlikely” ranking second, following “moderately likely”.

C. Discussion

The international research employing the Delphi method outlined two likely scenarios for the future evolution of ATs. The first scenario points toward a path of greater technological sophistication, broader integration, and improved accessibility, fueled by fast-paced innovation and a rising societal focus on inclusivity. Key aspects of this trajectory include the development of personalized and multilingual devices (4), advancements in ATs assessment methods (6), enhanced training for public service professionals (9), and expanded professional development for educators (10). The findings emphasize the need for strong collaboration among key stakeholders — especially between industry, policymakers, and practitioners—to overcome existing obstacles and unlock the full benefits of ATs, ideally by 2030 as projected in the study. According to a diverse group of European stakeholders, achieving this vision will require sustained investment in personalized, multilingual technologies, professional training for educators, and the expansion of public service programs.

As for the national Delphi study, it cannot be stated that professionals and other stakeholders hold a pessimistic view regarding the integration of Socially Assistive Robots (SARs), Conversational AI and Virtual Reality (VR) into their professional practice. On the contrary, many recognize the potential of these technologies to significantly enhance therapeutic and educational outcomes for individuals with communication and developmental disorders. However, there remains a degree of skepticism about the likelihood of these ATs becoming widely adopted and accessible across the country. This cautious outlook is primarily linked to the current high cost of technologies such as SAR's, which continues to pose a major barrier to broader implementation. Limited funding, lack of infrastructure and insufficient training opportunities may also contribute to concerns about the feasibility of integrating high-tech ATs into everyday practice, especially in resource-constrained settings. As such, while the professional community remains open to innovation, the full realization of ATs potential will likely depend on future advancements in affordability, policy support and access to training and resources.

IV. CONCLUSIONS

The combined insights from both the international and national Delphi studies, underline a shared recognition of the potential of high-tech Assistive Technologies (ATs) in improving the quality of life. For individuals with communication and neurodevelopmental disorders, and, in

particular, help draw future directions and propose the foundational features of an ergonomic platform to streamline the integration and application of high-tech ATs in such therapy. While international experts envision a promising trajectory marked by technological advancement, integration and inclusivity, driven by personalized solutions and stakeholder collaboration, the national perspective anticipates a more cautious optimism. Bulgarian professionals acknowledge the value of innovations such as Socially Assistive Robots, Conversational AI and Virtual and Augmented Reality, yet express concerns about the economic and infrastructural limitations that may hinder widespread adoption.

To bridge the gap between the potential of ATs and their practical implementation in the therapy of communication and development disorders, the ATLog project addresses the need for sustained investment, supportive policy frameworks and strong cross-sector partnerships. Based on the findings of both Delphi studies, ATLog actively advocates the position that achieving the full potential of ATs by 2030 will require concerted efforts to ensure these technologies are not only innovative but also affordable, accessible and supported by well-trained personnel.

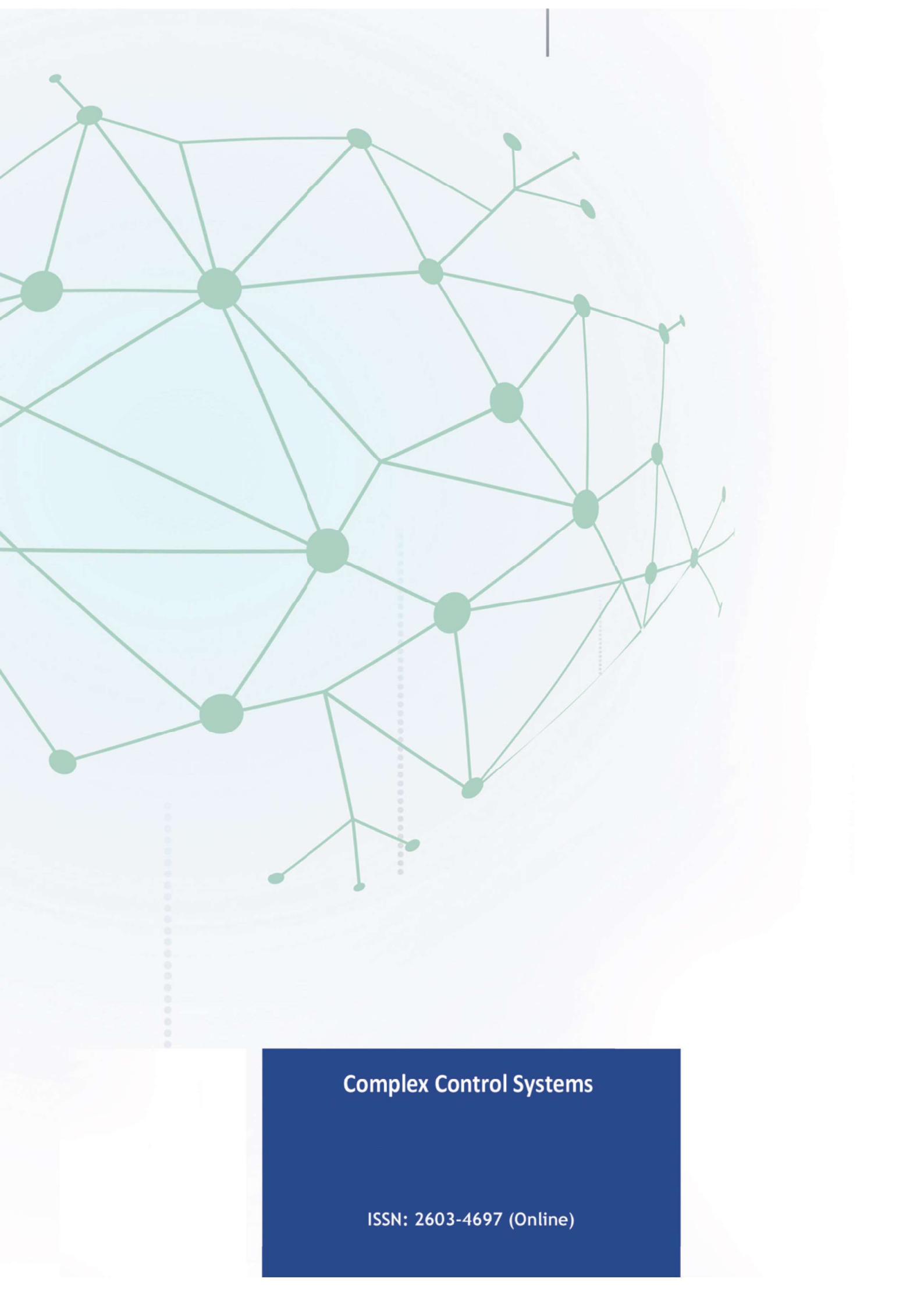
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