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Original scientific paper

INTEGRATION OF LEAN PRINCIPLES AND AUTOMATION FOR DIGITAL TRANSFORMATION IN MANUFACTURING

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A b s t r a c t: Introducing automation in manufacturing can lead to increasing efficiency in the assembly process, reducing Lean production waste, and enhancing operator ergonomics. The purpose of combining automation and Lean is to bridge the gap between digital transformation and human-centric automation, ensuring technological evolution together with the operator's well-being while driving industrial optimization, innovation, and efficiency. According to the review, synergy is required; however, challenges remain in effectively aligning automation with Lean principles. This paper aims to analyze the possibilities for integrating automation and Lean management according to literature, exploring similarities and the implementation practices to achieve sustainable and competitive manufacturing.

Key words: Lean; automation; manufacturing; Industry 5.0

ИНТЕГРАЦИЈА НА LEAN-ПРИНЦИПИТЕ И АВТОМАТИЗАЦИЈАТА ЗА ДИГИТАЛНА ТРАНСФОРМАЦИЈА ВО ПРОИЗВОДСТВОТО

А п с т р а к т: Воведувањето автоматизација во производството може да доведе до зголемување на ефикасноста во процесот на склопување, намалување на Lean-загубите и подобрување на ергономијата на операторот. Целта на комбинирањето на автоматизацијата и Lean е да се премости јазот помеѓу дигиталната трансформација и автоматизацијата ориентирана кон човекот, обезбедувајќи еволуција на производниот систем заедно со благосостојбата на операторот, а наедно поттикнувајќи оптимизација, иновации и ефикасност. Според прегледот, потребна е синергија; сепак, остануваат предизвици во ефикасното усогласување на автоматизацијата со принципите на Lean. Овој труд има за цел да ги анализира можностите за интегрирање на автоматизацијата и Lean според литературата, истражувајќи ги сличностите и практиките за имплементација за да се постигне одржливо и конкурентно производство.

Клучни зборови: Lean; автоматизација; производство; Индустрија 5.0

1. INTRODUCTION

Lean manufacturing (LM) and automation represent two complementary yet sometimes conflicting approaches to improving production efficiency. LM aims to eliminate waste, enhance flexibility, and empower workers by focusing on continuous improvement and value-driven processes [1]. On the other hand, automation integrates technology to streamline operations, reduce human error, and improve overall performance. While lean automation offers significant advantages – such as minimizing process inefficiencies and optimizing workflow – it also presents challenges, including high implementation costs, reduced process flexibility, and increased reliance on technology over human expertise [2]. A balanced approach to digital technologies and ultimately automation is essential to keep it simple, cost-effective, and aligned with lean principles. Too much automation can make systems overly complex, reduce operator engagement, and limit flexibility in production. To ensure efficiency without compromising lean benefits, automation should be strategically planned.

The motivation for this paper comes from the need to implement digital technologies for processing automation, efficiency improvement, and enhanced ergonomics within the Smart Learning Factory – Skopje. These needs were identified during the initiation of the TEAM 5.0 scientific research project, led by the Faculty of Mechanical Engineering – Skopje, and supported by Ss. Cyril and Methodius University in Skopje and the Smart Learning Factory – Skopje. This paper builds on these efforts by exploring the relationship between Lean principles and automation to optimize manufacturing processes. The introduction should briefly place the study in a broad context and define the purpose of the work and its significance. In the first part of the paper, Lean Automation concept will be reviewed through several relevant papers. In the second part, Automation in manufacturing as a subject will be covered to establish a connection with the mentioned project where an improvement is needed in the assembly process, preferably done with a Pick-by-Light (PbL) system on the existing manual workstation. The third part includes discussion on the relationship between Lean and Automation providing synergy between the familiar Lean principles and main automation & control benefits.

2. LEAN AUTOMATION

In [3] authors discuss the synergy between LM and automation, emphasizing that Lean principles are a prerequisite for successful automation. The study highlights that while automation alone increases productivity from 27% to 61%, incorporating Lean tools such as inline quality control (IQC) before automation raises productivity further to 74%. This indicates that optimizing processes with Lean principles before automation maximizes efficiency, making automation more effective. The findings reinforce that digitalization and Industry 4.0 require Lean foundations to ensure smart, flexible, and responsive manufacturing. This is also discussed in [4], where the author highlights the positive correlation between I4.0 and Lean while noting the challenge of digital waste, urging its integration into value stream mapping. Limited to Swedish SMEs and select Lean practices, the study calls for further research on digital waste in areas like supplier development, employee digital engagement, and smart maintenance beyond Sweden. In [5] the authors explore the relationship between LM and Automation, focusing on the importance of finding the right balance between them to enhance manufacturing competitiveness. As industries face rising labor costs and a competitive market, automation is increasingly adopted to improve efficiency. However, without careful integration, automation may not align with Lean principles, leading to inefficiencies. The study highlights key factors for successful Lean automation, including a holistic approach, strategic planning, flexible solutions, ergonomics, waste reduction, and process simplification. It concludes that fully automated systems are not always necessary or feasible; instead, Lean tools can guide manufacturers toward simpler, cost-effective automation options. Sources [6] and [7] consistently show that combining Lean practices with Industry 4.0 technologies results in higher operational performance than applying either approach alone. Lean supports companies in adopting digital tools more effectively, while I4.0 technologies (such as IoT, AI, and cyber-physical systems) help address challenges like product customization and process complexity. Papers [8] and [9] acknowledge the fact that Industry 4.0 offers many new opportunities for automation of the traditional manufacturing processes and offers Lean-related solutions including technologies such as Automatically Guided Vehicles (AGVs), IoT, 5G and CPS.

A very important point is made in [10], where the authors explore the application of Lean Management principles beyond manufacturing, particularly in the banking and financial services sector, where automation and digitalization dominate. While this is not a priority for this paper, an interesting conclusion emerges – "Lean first, then Automate".

Finally, an integration of Lean Automation (LA), Lean Production (LP) and Industry 4.0 technologies is presented in [11]. Authors empirically test the link between LA and operational performance using data from over 200 firms. The findings reveal two key LA components: one focused on operational stability and supplier efficiency, and another on streamlining processes for improved delivery. The study confirms a positive correlation between LA and performance improvements, emphasizing the need for structured integration strategies.

Table 1

Overview of the literature review on Lean automation

Ref.	Main points
[3]	Lean as a prerequisite for automation, showing that IQC boosts productivity from 27% to 74%. Industry 4.0 relies on Lean to ensure smart, flexible manufacturing.
[4]	Industry 4.0's impact on Lean automation is examined, emphasizing digital tech adoption in SMEs, digital waste issues, and the need for further research on automation strategies.
[5]	The balance between Lean and automation for competitiveness is explored, highlighting strategic planning, waste reduction, and Kaizen for cost-effective and efficient automation.
[6]	Lean & Industry 4.0 integration, showing a strong correlation. Combining both boosts performance beyond individual effects, making Lean key to digital transformation.
[7]	Lean and Industry 4.0 enhance flexibility and efficiency in modern manufacturing. A structured model is suggested to align Lean with digital transformation.
[8]	An action plan for integrating Industry 4.0 in Lean is presented via design, integration, and continuous improvement. AI, AGVs, and 5G help minimize waste and boost efficiency.
[9]	Lean-Industry 4.0 synergy is discussed, using CPS and digital tools for automation. However, gaps exist in frameworks for flexible, automated workstations in Lean environments.
[10]	Lean is applied to banking, introducing 'Lean first, then Automate,' ensuring process optimization before digitization. The model solves sequencing issues in automation adoption.
[11]	Lean Automation (LA) as the integration of Lean Production (LP) and Industry 4.0 (I4.0) technologies, showing a positive impact on operational performance. It highlights the need for a structured approach to integrating these paradigms.

The papers summarized in Table 1 consistently highlight that Lean principles serve as a foundation for successful automation and digital transformation in manufacturing. While automation and Industry 4.0 technologies enhance productivity and flexibility, their effectiveness is maximized when preceded by Lean practices such as waste reduction, process simplification, and quality control.

Another concept that is widely known in literature is the Automation pyramid which represents the hierarchical structure of industrial automation systems [12]. The control level (PLCs, DCS) automates processes, while the supervisory level (SCADA) enables monitoring. The MES level optimizes production, bridging automation with business operations, and the enterprise level (ERP) handles planning and resource management. With Industry 4.0, this rigid hierarchy is evolving into a more interconnected, data-driven system. Considering the evidence from Table 1, authors suggest modification of this pyramid (Figure 1) by adding a base that is related to the Lean practices that are essential for smoother implementation of the following layers. Continuous improvement along the pyramid layers is also present to sustain the Lean aspects during the work.

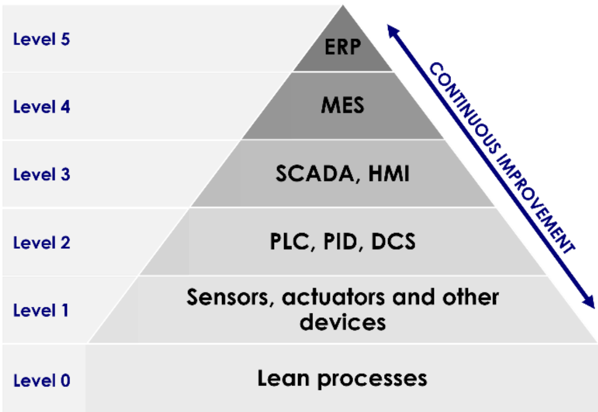

Fig. 1. Modified automation pyramid

3. AUTOMATION IN MANUFACTURING

This part of the paper focuses on reviewing scientific papers in the field of automation in manufacturing, especially in the assembly process. Nowadays, some product assembly processes still include manual activities that contribute to the Lean waste such as waiting, motion, over-processing, defects, inventory, unused talent, and more [13]. Implementing automation should replace the manual assembly process. As required in Industry 5.0, human satisfaction and well-being must be in collaboration with smart technologies and digital transformation for maintaining a suitable working environment. Including automation in the digitalization of some manual processes can raise the operator's productivity and self-esteem. Sometimes operators find process automatization stressful due to losing their job position or working with machines, following sequences, but it can help them increase their productivity or possibilities of doing more intelligent jobs.

In manufacturing, especially in Poka-Yoke-related solutions, the assembly process is led with the pick-by-light (PbL) method to prevent the process from making unexpected mistakes. It is considered an effective method to ensure detection and prevention while assembling. So, according to [14], 31 participants have been involved in assembly material order picking using both pick-by-paper (PbP) and PbL methods. In this paper operator's situation awareness (SA) has been measured through the Situation Awareness Global Assessment Technique (SAGAT) methodology. According to the results presented, no significant differences in SA levels between the two methods have been noticed. This finding suggests that PbL systems do not enhance or reduce a worker's ability to understand and respond to their surroundings during order picking. Evaluating the operator's physical stress while performing tasks, the heart rate has been monitored. The results represented that PbL led to increased physiological strain, but reduced subjective workload compared to PbP methods. Providing a smart manufacturing environment, in [15] is represented Poka-Yoke principles with PbL providing higher operational efficiency with error minimization. This paper presents an improved PbL configuration, combining hardware and software to guide operators with visual cues, boosting productivity, quality, and flexibility. The system includes a control unit, visual indicators (LEDs or displays), input devices (barcode readers, optical sensors), and communication interfaces. Sensors detect operator presence and item selection, while barcode readers track inventory movement. A central processing unit (CPU) processes signals, manages PbL operations, and ensures seamless communication with MES or ERP systems via wired or wireless networks for real-time updates. To enhancing product assembly assistance and avoid errors during it, the authors in [16] developed a PbL system based on computer vision technology. The product was developed using an ESP-32 microcontroller, a USB camera with a computer vision algorithm, LED indicators, TCP/IP communication protocol, and a router for data transfer. The camera is used for object detection based on a machine learning (ML) or deep learning (DL) approach. A few studies [7–21] reveal that PbL is a much more effective approach for efficient product assembly than alternatives such as augmented reality (AR).

In [22], the authors proposed the system that dynamically adjusts its automation level in response to varying production demands and conditions, providing flexibility and efficiency in manufacturing processes. According to adaptive automation, there is represented integration of cyber-physical systems (CPS) and the Internet of Things (IoT) to enable real-time monitoring and control of the picking sequences. This paper focuses more on the software part, including advanced human-machine interfaces (HMIs) to enable smooth operator interaction and system adaptability. Also, the embedded large network of CPS enables real-time data exchange between physical components and digital control systems, while the IoT devices collect and transmit the data from the actions in the picking station. The author's approach is more inclined to Industry 4.0 by promoting interoperability, information transparency, and decentralization of decision-making in assembly systems.

Despite PbL, PbP, pick-by-display (PbD), pick-by-projection (PbD) [23] is a method that introduces innovative prototype assistance designed to enable the manual order-picking process by projecting visual cues directly onto storage locations, guiding operators in real time. This approach utilizes projection technology by displaying picking information directly onto storage racks/shelves. The setup involves projectors mounted in the picking area to ensure clear and accurate visual guidance. Further improvement of the system is implementing sensors for the operator's action detection and correct item selection confirmation. PbP according to the authors, could be found as a promising tool that provides efficiency and accuracy while picking sequences and could be a very inclusive method by incorporating those with cognitive impairments. Most of the papers focus on software development instead of hardware improvement of the manufacturing system. In [24] is represented integration of Advanced planning and scheduling (APS) software in the traditional zero-defect manufacturing (ZDM) architecture where the main point is to enhance production efficiency and sustainability by reducing costs, energy consumption, and material waste, improving lead times and production planning. According to [25] is presented standard, semi-automated PbL Poka-Yoke working station where the operator picks the item according to the light and then activates the button to confirm that the item is picked from the container. A display visualizes the remaining number of parts in the container. According to the Lean principles, the assembly time for one item is 15 minutes. Improving the PbL system with additional hardware (sensors and other devices) and software, implementing CPS or IoT, there is a possibility that assembly time could drop below 15 minutes in the meantime rising the operator's satisfaction at the workplace. Digitization and interconnection of industrial processes through technologies like IoT, CPS, and big data analytics are a baseline of Industry 4.0 principles. It serves as the foundation for developing more sophisticated automation solutions in production and warehousing. Nowadays, one of the important factors is not only having the smartest manufacturing or assembly process but the evolution towards human-centric collaboration is the key factor leading to a smart, efficient, and successful environment [26].

PLCs, as one of the crucial devices in the control systems, continue to play an important role in industrial automation, but their functionalities are evolving to meet new requirements such as making the software more user-friendly and adaptable to changing manufacturing needs. Such improvements align with the human-centric focus of Industry 5.0 [27]. Table 2 summarizes these insights.

T a b l e 2

Overview of the literature review on automation in manufacturing

Ref.	Main points
[14]	Comparison of PbL and PbP methods in assembly order picking. 31 participants were tested using SAGAT methodology. No significant differences in SA were found. PbL increased physiological strain but reduced subjective workload.
[15]	PbL enhances operational efficiency and error minimization in Poka-Yoke systems. New PbL architecture integrates hardware (sensors, controllers, barcode readers) and software for guiding operators via visual cues. Data is transferred via MES/ERP for real-time updates.
[16]	Development of a PbL system using computer vision with ESP-32 microcontroller, USB camera, machine learning (ML)/deep learning (DL) for object detection, LED indicators, and TCP/IP communication. More effective than AR-based solutions.
[17], [18], [19], [20], [21]	Studies highlight that PbL is more efficient than AR for product assembly assistance, reducing cognitive load and improving accuracy.
[22] [18]	Adaptive automation in PbL integrates Cyber-Physical Systems (CPS) and IoT for real-time monitoring and flexible automation. Advanced Human-Machine Interfaces (HMI) improve user experience and system adaptability.
[23]	Pick-by-Projection (PbD) introduces a method where projectors display picking instructions on storage locations, enhancing accuracy and accessibility. Future improvements include sensors for detecting operator actions.
[24]	Integration of Advanced Planning and Scheduling (APS) software into Zero-Defect Manufacturing (ZDM). Focus on software improvements, reducing costs, energy consumption etc. Industrial Internet of Things (IIoT) is used for data transfer.
[25]	PbL Poka-Yoke workstation requires manual confirmation by pressing a button. Upgrading with additional sensors and CPS/IoT could reduce assembly time while improving operator satisfaction. Lean principles suggest reducing assembly time by 15 minutes.
[26]	Industry 4.0 focuses on digitization, IoT, CPS, and big data analytics for smart manufacturing and automation. However, Industry 5.0 shifts towards human-centric collaboration and sustainability.
[27]	Programmable Logic Controllers (PLCs) remain crucial in automation but are evolving to be more user-friendly and adaptable. This aligns with Industry 5.0 principles of human-centric design.

4. RELATION OF LEAN AND AUTOMATION

As a starting point for any Lean discussion are always the Lean principles as set by Womack [1]. Table 3 summarizes the Lean principles and the Automation & Control aspects that commonly C these principles.

If we review the Toyota House of Lean, also known as the House of Toyota Production System (TPS) [28], it does not explicitly include automation as one of its core pillars. However, automation is indirectly incorporated through the concept of Jidoka and continuous improvement.

One of the main pillars of the House of Lean is Jidoka, which refers to "automation with a human touch." It means that machines and processes are designed to detect abnormalities and stop automatically when a problem occurs. This concept is a form of smart automation that ensures quality at the source while allowing human intervention when needed. In modern applications, Jidoka has evolved to include IoT, AI-driven quality control, and predictive maintenance, making automation a key enabler of Lean principles [29].

The House of Lean emphasizes Kaizen, or continuous improvement. While traditional Kaizen focuses on incremental changes through human-driven problem-solving, modern Lean systems integrate automation to enhance efficiency and accuracy. Digital tools, real-time data, and Industry 4.0 technologies now support Lean improvements, such as automated data collection, machine learning for process optimization, and robotic process automation for repetitive tasks [30], [31].

The Just-in-Time (JIT) pillar of the Toyota House of Lean focuses on eliminating waste by delivering exactly what is needed, when it is needed, and in the right quantity. Automation supports JIT through automated material handling (AGVs), real-time inventory tracking, and digital Kanban systems, reducing lead times and improving production flow.

Table 3

Relationship between Lean principles and Automation & Control

Lean principle	Definition	Relations to Automation & Control
Define value	Focus on what customers consider valuable and eliminate anything that does not add value.	Optimization – automation and control are implemented to enhance efficiency and eliminate non-value-added processes through digital technology.
Map the value stream	Identify waste and inefficiencies in the process flow and remove bottlenecks.	Data and analytics – Automation systems collect and analyze real-time data to identify inefficiencies using technologies such as IoT, SCADA etc.
Create flow	Ensure a smooth production process with minimal delays, interruptions, or inefficiencies.	Operational stability – Automated feedback systems ensure steady operations and flow between (automated) systems.
Establish pull	Produce only what is needed, when it is needed, to reduce inventory and waste.	Adaptability - Automated scheduling, demand forecasting, and smart inventory management optimize production without overproduction or excess stock.
Seek perfection	Commit to constant optimization and refinement.	Continuous improvement – AI and machine learning continuously refine system performance, while predictive maintenance prevents downtime and inefficiencies.

5. CONCLUSIONS

Automation in manufacturing is crucial for efficiency, operator ergonomics improvement, and error reduction. However, prior process optimization and a certain level of leanness are essential for successful implementation. This paper reviewed Lean automation and manufacturing automation, exploring their synergy and mutual benefits. While automation is not a core pillar of the Toyota House of Lean, it plays a key role through Jidoka (automation with a human touch), continuous improvement (Kaizen), and Just-in-Time (JIT). Industry 4.0 technologies, such as IoT, AI-driven quality control, and predictive maintenance, enhance these Lean principles by improving responsiveness and waste reduction. However, automation must be strategically integrated to prevent inefficiencies, reinforcing the need for Lean foundations before digital transformation. Future research should focus on structured approaches to merging Lean and automation for optimized, sustainable manufacturing.

Future research in the beforementioned TEAM 5.0 project will include practical implementation of these findings and providing experimental evidence of the synergy between Lean and automation in manufacturing.

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Original scientific paper

DETERMINING THE DEGREE OF ACCEPTABILITY OF THE WORKING BODY POSTURE OF WELDERS THROUGH THE APPLICATION OF THE RULA METHOD

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A b s t r a c t: The purpose of this research is the determination of the degree of ergonomic acceptance of the working body posture of welders in a production plant from the metal processing industry in North Macedonia. The ergonomic analysis is done through the implementation of the Rapid Upper Limb Assessment (RULA) method. The quantitative score of the angles of the joints and working body postures is determined, with added additional scores for overload and muscle activity. Final scores for each welder are compared to four action levels showing the degree of acceptability of the working posture, the level of needed intervention, and a time frame for commencing risk control. The results indicate that welders are exposed to high risk work-related upper extremity musculoskeletal disorders (MSDs). Therefore, proposals for reducing the degree of risk from MSDs are given aimed at adjustments and adaptation of the equipment to the anthropometric characteristics of the individual welders.

Key words: welding; working posture; ergonomics; RULA; musculoskeletal disorders

ОДРЕДУВАЊЕ СТЕПЕН НА ПРИФАТЛИВОСТ НА ПОЛОЖБАТА НА ТЕЛОТО НА ЗАВАРУВАЧОТ ПРЕКУ ПРИМЕНА НА МЕТОДОТ RULA

А п с т р а к т: Целта на ова истражување е да се утврди степенот на ергономско прифаќање на држењето на телото при работа на заварувачите во производствен погон од металопреработувачката индустрија во Северна Македонија. Ергономската анализа е извршена преку имплементација на методот за брза процена на оптоварувањето на горните екстремитети (RULA). Одреден е квантитативниот резултат на аглите на зглобовите и држењето на телото при работа, со додадени дополнителни резултати за преоптоварување и мускулна активност. Конечните резултати за секој заварувач се споредени со четири нивоа на дејствување што го покажуваат степенот на прифатливоста на држењето на телото при работа, нивото на потребна интервенција и временска рамка за започнување со контрола на ризикот. Резултатите покажуваат дека заварувачите се изложени на мускулно-скелетни нарушувања (МСН) на горните екстремитети произлезени од работата со висок ризик. Дадени се предлози за намалување на степенот на ризик од МСН, насочени кон приспособување и адаптирање на опремата според антропометриските карактеристики на поединечните заварувачи.

Клучни зборови: заварување; работна положба; ергономија; RULA; мускул-скелетни нарушувања

1. INTRODUCTION

Ergonomics, formally defined, is a scientific discipline that is dedicated to understanding the interactions between people and the various elements of a system. Through the application of theory, principles, data and methods, it ensures the optimization of the human's well-being and the system performance.

A system is a set of interconnected elements that, through symbiosis, aim to achieve certain goals, and work is a set of interconnected activities, tasks, people, tools, resources, and processes combined to achieve a common goal, in order to produce a physical product or provide a service [1]. The goal of applying ergonomics in a production system is to create a proactively designed workplace in order to celiminate the risks of injury, pain, discomfort, and demotivation [2] and to create an environment that is designed in compatibility with human needs [3]. Ergonomics is aimed at better integrating the person into the system [4]. The successful adaptation of a work task to the worker depends on the degree to which certain important criteria are met, such as functional efficiency and productivity, comfort, health and safety of the worker, and quality of life outside the work environment [5]. In short, almost any aspect of work where a person is involved in performing a work activity and task can be the subject of ergonomic analysis [2].

Every person who has a managerial position in a production system wants the constituent units as subcomponents to function in symbiosis with the greatest possible ease and efficiency. However, in the case when a part of that system is a person in the role of a worker, the performance and results of the system as a whole can vary and differ depending on the current and daily physical fitness of the worker. Although people have great potential to bring flexibility, innovation and skills to solve various production problems, they are also exposed to the risk of developing work-related musculoskeletal disorders (MSDs) that arise from performing physical activity that overloads the human body. The first signs of such overload include discomfort, physical pain and repetitive injuries. Work-related MSDs include injuries and illnesses that are caused by harsh working conditions [6] and are usually not caused by acute events but develop slowly over time due to repeated use of the same body part group or microtrauma [7] and can be prevented or delayed [6]. Many of these disorders are caused by static postures, sometimes accompanied by intense exertion or repetitive movements that need to be maintained intensively for most of the working day [8]. Incorrect body posture can lead to local mechanical stress on muscles, ligaments and joints [9] and permanent damage to body tissues [10]. Extreme or uncomfortable postures are recognized as one of the main risk factors for the occurrence of MSDs [8]. MSDs of the back, upper and lower extremities are a cause for serious concern, as they are the most common cause of work-related absenteeism and represent an industrial problem [8], but the application of ergonomic principles reduces the possibility of MSDs [7]. Correct body postures at work significantly decreases the risk of MSDs and has a positive effect on the efficiency and effectiveness of the worker.

Therefore, manufacturing systems and their management should focus on applying the required methods and tools for ensuring the workers are healthy and efficient. The approach that a manufacturing system takes to addressing ergonomic aspects of work can depend on many things, such as the size and shape of the organization itself, past experience, and the level of knowledge of ergonomic methods and tools. Incorporating ergonomic knowledge early in the planning process and understanding ergonomics as a way to reduce costs by maintaining a healthy workforce are characteristics of a proactive approach. A reactive approach is characterized by not addressing problems and risks until the consequences of unergonomic work begin to appear, such as pain and injury among workers, resulting in absenteeism [2]. There are several methods that can be applied for ergonomic evaluations in the workplace, among which is RULA (Rapid Upper Limb Assessment).

This research focuses on the application of the RULA method in an ergonomic study of the working posture of welders in a specific production facility in the metalworking industry in the Republic of North Macedonia. The RULA method was chosen to help provide guidance for the middle and senior management to eliminate ergonomic entropy as an irregularity in the functioning of the work system and avoid the possible incorrect use of ergonomic principles that lead to fatigue, reduced productivity, and sometimes injury at the workplace.

2. BACKGROUND AND MOTIVATION FOR STUDY

In order to expand knowledge on the chosen topic, a research and study of relevant scientific literature in the field of ergonomics and specific case studies where the application of the RULA method is encountered was conducted. The research was focused on case studies in the field of production, conducted in various countries around the world from 2010 to the present. Many examples were reviewed and a part of them, related with welders, are analyzed in this section. The goal was to review possible applications of RULA, and search for applications in companies in North Macedonia.

Many of the reviewed researches were associated with assembly line tasks, focusing on identifying occupational risks and worker safety in the manufacturing industry through interviews, observations, video recordings and the application of the RULA method, highlighting the significant risks faced by workers, which require urgent changes, and investigating work-related MSDs among workers [11, 12, 13, 14]. Ergonomic evaluation tools are mostly applied where repetitive working postures occur to estimate the musculoskeletal load and risk of MSDs [15, 16, 17, 18]. The application of the RULA method was found in many other cases to evaluate and improve the ergonomics of various production processes, exploring the key role of ergonomics in improving productivity and quality and the relationship between work methods and workstations [19, 20, 21, 22].

More precisely, in the field of welding-related tasks, one study assesses the risk of musculoskeletal injuries in steel welding through field observation and research on welders' movements while performing different work tasks. Using the RULA method, the aim was to identify the factors that contribute to the occurrence of MSDs. The analyses highlight that these disorders are the result of incorrect working postures. Elements of the workplace, welding method and work environment factors determine the degree of disorders, with less skilled welders being found to be at higher risk of developing MSDs. The study suggests the implemention of periodic ergonomic reviews of facilities, workstation design and work practices, while emphasizing the importance of proper training of welders, in order to recognize and report symptoms of MSDs early, and the need for proper ergonomic design adapted to different welding positions [23].

Another study focuses on improving the ergonomic conditions of welders on assemblies in the automotive industry. Using the RULA method and computer-aided design software, an analysis of the existing welding process was performed, critical ergonomic problems were identified, and an ergonomic intervention was created by designing a hand support for the workers. The implementation of the support resulted in improved results and a change in the risk level from high to medium, indicating increased well-being among the welders. The analyses highlight the successful reduction of ergonomic risks obtained through the implementation of the optimized device, which was designed based on feedback from the workers [24].

One more research aims to assess and analyze the working posture of workers in a small manufacturing company, focusing on various work tasks such as material handling, cutting, drilling, welding and grinding. A questionnaire on musculoskeletal discomfort was administered workers, and it was found that the most prominent body areas with musculoskeletal discomfort were the lower back, upper back, shoulder and neck. Ergonomic risks were assessed using tools such as RULA and other methods, with the results of the RULA method showing that most workers (33.33%) needed additional ergonomic investigation and changes in their working posture, and 24.07% needed urgent ergonomic intervention and immediate changes. The results of the study prove that workers predominantly perform work tasks in an incorrect body posture, primarily due to a lack of ergonomic awareness. The study recommends changes in body posture and work-rest cycles, implementation of ergonomic interventions and appropriately designed workstations to mitigate risks [25].

The results of the review of the scientific literature and specific case studies in the field of production where ergonomic research has been applied, indicated that the application of the RULA method provides quick, simple and visual indications of the level of risk and the need for action [26]. The method does not require special equipment to provide an assessment of body postures along with muscle functions and external loads experienced by the body. This allows to perform assessments without additional costs. Since it is an observational analysis, the assessments from the method can be made at different workplaces without disrupting the work process and workers. Researchers using this method do not need previous skills in observation and ergonomic assessment [27].

More importantly, the review revealed a lack of application of the considered method in ergonomic research in companies from the manufacturing industry in our country, North Macedonia. Unfortunately, the reality is that in our country there is a lack of such, or similar, ergonomic research in other industries and systems. This lack means that systems take a reactive approach to work that is characterized by not solving problems and risks until the consequences of non-ergonomic work begin to appear, such as pain and injuries in the workforce that can result in absences. This is something that needs to change, i.e., at every organizational level, those responsible should have knowcledge of ergonomics and encourage its correct application in the direction of continuous improvement and correct business practice in which the value of a healthy workforce is proactively supported. Their knowledge of the needs and abilities of workers should result in feasible changes to the elements of the system that should reduce or eliminate risks.

Such shortcomings arising from insufficient ergonomic research, are a motivation for conducting research using the ergonomic method for rapid assessment of the upper extremities in order to identify and assess the risks arising from the incorrect implementation of ergonomic elements. The independent analysis of the current state of the workplaces in the company is additionally motivated by their own understanding of the economic benefits of the correct integration of the workforce into the system. An additional motivating factor for the application of the ergonomic method is the education of all involved in the system and the encouragement of thinking about the importance of ergonomics and its impact.

3. MATERIALS AND METHODS

This research was done in a part of a production plant in a specific company from the metal processing industry in North Macedonia. The TIG welding operation was chosen as the subject of ergonomic research, in which, through several years of work experience in the company and observation of the process, incorrect body postures of the welders were often observed. During observation, it was established that the TIG welding operation was performed in a sitting position 75% of the time, and the remaining 25% of the time was filled with occasional movement or standing of the welders. Therefore, the method for rapid assessment of the upper extremities (RULA) was chosen to be used as a tool for assessment of the risks arising from the working posture that was present when welding the joints of the assemblies.

The RULA method [27] was developed by ergonomists Lynn McAtamney and Nigel E. Corlett in 1993 [26], then members of the Institute of Occupational Ergonomics at the University of Nottingham, England [7]. The method is a type of observational tool [3] that can be used as part of an ergonomic assessment of workplaces [26] to examine workers' exposure to the risk of work-related MSDs of the upper limbs [28]. The method was developed to provide an analysis where the work places physical demands on the trunk, neck and upper limbs [26]. The focus of the method is to analyze the working posture of the person [7] and is used in work tasks that are characterized and defined as sedentary [27] in which the upper body is heavily engaged [26], and the worker performs work tasks in a sitting position for 75% of the time (6 hours out of an 8-hour working day), and the remaining 25% (2 hours out of an 8-hour working day) is in occasional movement or standing. During the analysis, using diagrams of different body positions, a quantitative assessment of the angles of the joints and the body posture is made, with additional assessments of the load and muscle activity [26]. By recording the observational elements, a final assessment is obtained, i.e., the risk is calculated in a score from 1 (low) to 7 (high) [27]. These ratings are compared to four action levels that indicate the level of intervention needed to reduce MSDs [3] and provide an indication of the time frame within which it is reasonable to expect risk control to begin [27].

Participants

Before the ergonomic research began, the welders were introduced to the objectives and application procedures of the RULA method. All 5 welders currently present in the company gave an oral consent, which was then expressed in writing by completing individual consent statements. The respondents were informed about the details of the research and provided written consent.

In addition, a questionnaire on MSD symptoms was completed by each welder, from which data on the welders and certain anthropometric measures were extracted (Table 1). The standard working hours for all welders are 40 hours per week.

Table 1

Data for the study participants – welders

ID number in the company	Gender	Age (years)	Height (cm)	Weight (kg)	Work experience in the company
101	M	49	172	120	24 years and 5 months
102	M	49	180	105	6 years and 3 months
103	M	27	173	75	4 years and 7 months
104	M	22	173	65	2 years and 8 months
105	M	23	170	61	1 year and 7 months

The welders' identification (ID) numbers assigned upon their employment in the company were, accordingly, used as identification numbers in the ergonomic research (a welder with identification number in the company 101 corresponds to welder 101 in the research).

Environment

The design of the workplaces of the welders consists of a chair, a workbench and a vice (Table 2). Some of the work elements (the welding device, electrodes, additional materials and work orders) are usually placed on the workbench. The vice, which is a clamping device, is attached to the workbench with two sides between which the assembly/product is clamped during welding. The chairs and workbenches are static without the possibility of adjustment, and the vices are movable and can rotate around their own axis. The workplaces are safely and appropriately separated by partitions.

T a b l e 2

Data on the design elements of welders' workplaces

Work place	Height from floor (cm)		
	Chair	Table	Vice
Welder 101	600	840	1080
Welder 102	620	840	1070
Welder 103	600	840	1090
Welder 104	610	840	1060
Welder 105	600	860	1085

Procedure

The whole procedure was based on the steps according to the RULA method:

- Observation and selection of the working position and posture for further assessment;
- Assessment of the working posture;
- Determining the final score for the working posture; and
- Determining the level of action required.

Observation and selection of the working position and posture for further assessment

Before starting the methodological procedure, an initial preparation for the assessment was done by talking to the workers being assessed in order to gain knowledge about the work operation and understand the work tasks associated with it. The assessment using the method focuses on a single moment in the work cycle [27], which was done in this research conducting observations of movements and working postures over several work cycles before selecting the posture to be assessed. The goal was to observe postures that are adopted and persist throughout the entire cycle of the work task or postures that are present for a significant period of the work cycle, as recommended [27]. The most risky and critical posture of the body, was chosen as the subject of analysis, and selected based on its duration and degree of deviation.

Assessment of the working posture

In order to achieve a higher level of efficiency, in the analysis of the working posture, according to the RULA method, the body was divided into segments that form two groups: A and B. Group A includes the upper arm and forearm together with the wrist, while group B includes the neck, trunk and legs. This division and approach ensure that the entire working posture of the body is documented, ensuring that the impact on the posture of the upper limbs of any uncomfortable or unnatural positions of the legs, trunk or neck are included in the assessment [28].

To assess the working postures according to RULA, the range of motion of the body parts was divided and appropriately labeled, with a value of 1 being assigned to the movement or working posture of the corresponding body segment where risk factors are minimally present. Higher numerical values were assigned to the parts of the range of motion that are characterized by a more extreme posture indicating an increased presence of factors that cause stress on the structure of the segment itself.

The analysis and giving values/scores of body parts from groups A and B, according to the motion ranges, for each individual worker, for the selected working posture, was entirely done according to the RULA method.

Determining the final score for the working posture

The individual scores C (score for posture A + value for muscle activity + value of the load on the parts of group A) and D (score for posture B + value for muscle activity + value of the load on the parts of group B) were entered into a table, in order to obtain the final score for the working posture of workers. The final score for the body's working posture is the value that lies at the intersection between the value/score C and the value/score D.

Determining the level of action required

In the end, the final score was compared to four action levels which indicate the level of intervention required to reduce MSDs [3] and provide an indication of the time frame within which it is reasonable to expect to start risk control [27]. The action level is used to indicate the urgency and priority of the need for a change in the way of working [7] and determines the degree of acceptability of the work attitude to the body.

4. RESULTS

The whole procedure and obtaining of scores are described in detail in this section where results are presented for each worker.

Observation, identification and selection of the working position

Before selecting the body posture for each welder individually, observations of the welders' movements and posture were conducted over several work cycles. The focus was on the postures adopted by the welders when welding joints where a significant degree of body misalignment was visually observed. Incorrect postures identified as the most risky and critical were selected for assessment. This selection was also supported by interviews with the welders, who highlighted the selected postures as the most unpleasant moments during the performance of the work task. For 4 welders, the right sides were selected for assessment, and for welder number 103, the left side of the body was selected.

The selected postures were documented by photographing them from the appropriate side (Figure 1). Additionally, photographs were taken from views parallel to the frontal plane (Figure 2) and views parallel to the position of palms (Figure 3).

Fig. 1. Selected working posture and side view of the body among welders 101 – 105

Fig. 2. View parallel to the frontal plane of the selected posture of welders 101 – 105

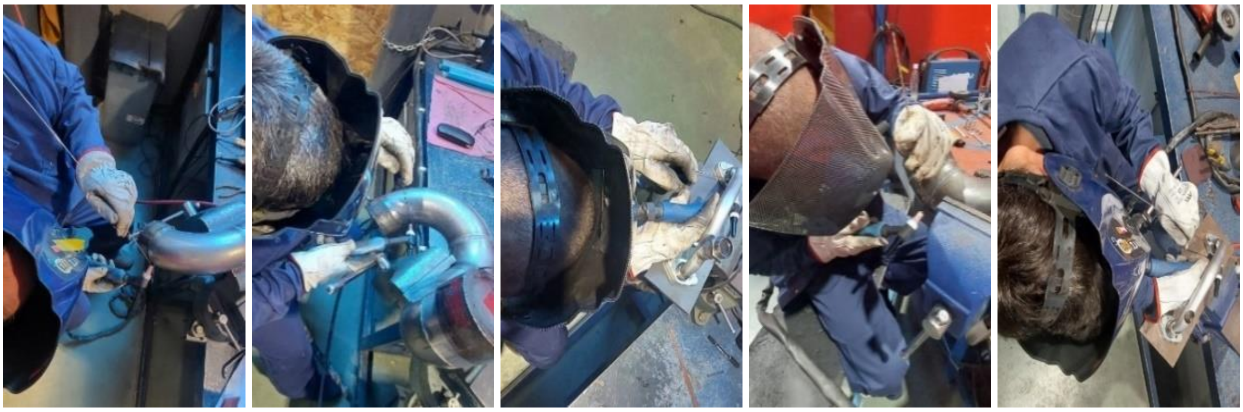

Fig. 3. View parallel to the palm placement in the selected posture of welders 101 – 105

Evaluation of the body postures and determining the acceptability

Before starting the assessment of the working posture of the body, the angles and positions of the individual parts of the body of the welders were determined. The scores were placed in appropriate tables from which scores for posture A and B were then obtained.

For example, for welder 101, the A score for the work posture is 5, and the B score is 8. The scores C and D for welder 101 are identical to the A and B scores of the working posture, accordingly, since no additional values are given for muscle activity and load value, because: the working posture of the body of the welder is not static for more than 1 minute; the working posture does not repeat more than 4 times a minute; and the load is less than 2 kg. Therefore, the final score for the assessed working posture of welder 101 is 7. This value corresponds to action level 4, indicating that the working posture is completely unacceptable, and conducting an additional research and implementing changes is needed immediately.

The same steps were repeated for welders 102, 103, 104, and 105 in order to obtain a final score for the working postures. The final score for the assessed working posture of welders 102 and 105 is 6. This value corresponds to action level 3, c that the working posture is partially acceptable, and conducting an additional research and implementing changes soon will be needed. For welders 103 and 104 the final score for the assessed working posture is 7. This value corresponds to action level 4, indicating that the working posture is completely unacceptable, and conducting an additional research and implementing changes is needed immediately.

Final results from the assessment

The results of the application of the RULA method (Table 3) indicated that welders were exposed to a probable and high risk of work-related MSDs of the upper limbs, without the presence of acceptable working postures of the welders. The questionnaire on manifested symptoms of MSDs noted that pain and discomfort were most prevalent in the neck area (60%) and the upper back (40%).

In the critical working postures that were the subject of the ergonomic research, the visually observed significant degree of misalignment of the body parts was confirmed by the high final scores that indicated the need to control risks, by initiating urgent corrective action to improve the workstations.

Table 3

Welder data and final scores from the application of the RULA method

Welder	Age (years)	Height (cm)	Weight (kg)	Work experience in the company	Final RULA scores
101	49	172	120	24 years and 5 months	7
102	49	180	105	6 years and 3 months	6
103	27	173	75	4 years and 7 months	7
104	22	173	65	2 years and 8 months	7
105	23	170	61	1 year and 7 months	6

5. DISCUSSION

The results showed that even though factors such as age, height, weight, and work experience in the company are important factors that can affect the efficiency and proper conducting of the working task, they are not the top factors that affect the level of exposure to the risk of MSD in this case. The main risk factor was identified as the current design of the workplace/station, whose elements, such as chairs and work tables, are static and do not have any possibilities for adjustment and alignment with the different anthropometric characteristics of welders. This conclusion corresponds to the results of analyzed studies applying the RULA method presented in the background section, where the working conditions with the highest adaptability showed the lowest ergonomic risk and the best performance, and workstations which were not adaptable and not complying with ergonomic standards revealed high risks for development of MSDs in various body parts. Moreover, studies aimed to redesign work stations, equipment and machines, to address ergonomic issues and uncomfortable body postures, found improved ergonomic scores with the redesigned adjustable solutions, decreasing health risks of workers.

However, on the other hand, this study also concluded that the practices of welders were not in accordance with ergonomic standards, with incorrect positions of body parts being adopted during work postures that were unconsciously practiced and were not caused by external factors. Such practices among welders reveal a lack of knowledge about ergonomics and awareness of the importance of the correct working posture of the body during work and its significance on the functionality of the body and well-being in and outside the work environment. This result was also found in analyzed literature examples where urgent changes were indicated and a lack of awareness of ergonomics in the industry, especially in the welding process, where workers adopt incorrect working postures, was found.

Therefore, the reduction of the final score, i.e., the reduction of the risk of MSD occurrence, can be achieved by creating a plan with guidelines for improvements. In this plan, initially, all welders should acquire basic knowledge in the field of ergonomics, while appropriate education should be carried out in order to reduce or eliminate the adopted incorrect body postures that are not caused by external factors. The top management of the company should be familiar with the actual situation and conditions, as well as the economic aspects of the performance of the production system. The engineers in the company should provide practical suggestions for changes, which depending on the investment plan, should be designs of new or redesigns of existing elements of the welders' worklaces, but also proposals for purchasing new elements.

In general, specific changes should be aimed at providing mobility options for chairs and work tables, allowing for adjustment and compliance with the different anthropometric characteristics of each welder. In addition, a design of a device that will be placed on the floor should be provided, where the welders' legs and feet are well supported when sitting, and the body weight is evenly balanced. In order to prevent the load on the upper parts of the body, hand supports should be provided, as well as vices that can automatically rotate a pedal.

6. CONCLUSION

This research revealed the ergonomic shortcomings of the current design of workplaces/stations in a specific company in the metalworking industry in the Republic of North Macedonia, through the application of the RULA method. The results of the application of the method indicated the exposure of welders to a probable and high risk of work-related MSDs of the upper extremities, without the observed presence of acceptable working postures of the welders' body. It was concluded the main risk factor is the current design of the workplace/station whose elements, are static and do not have the possibility of adjusting to the different anthropometric characteristics of the welders. On the other hand, the welders had incorrect body positions, which were unconsciously adopted without being caused by any external factor, thereby revealing a lack of knowledge about ergonomics. Based on this, suggestions are given for reducing the risk of MSDs by creating a plan with guidelines for improvements. The plan includes: education of the workers and management in the company to acquire basic knowledge in the field of ergonomics, providing practical suggestions for changes aimed at ensuring the adaptability of the work equipment, and design of additional working-aid devices.

In general, the initially established finding that there is limited application of ergonomic research in companies from the manufacturing industry in North Macedonia was confirmed. As expected, this study revealed issues which were not resolved previously in the specific company since no deeper analysis of the individuals work stations was done. However, this research confirmed that the RULA method is easy to apply. It provides a good indication of the degree of acceptability and the action levels that should be taken. The conducted research contributed to drawing conclusions that the middle and senior management in the company should take in order to improve working conditions and eliminate risks. All participants in the study gained knowledge and awareness of the importance of proper body posture and its impact on body function and well-being in and outside the work environment.

The limitation of this ergonomic study was that it did not include detailed information on finger position, which is a major limitation in the assessent of the welder's overall risk. However, since the observed risk factors are still high even without such inclusion, the relevance of finger position is considered, and it is proposed to fill the gaps by using other assessment tools as part of future, broader or more detailed ergonomic research.

The following step of this research is to optimize the working stations of the welders according to the proposed solutions and obtain the new RULA scores which will indicate if there is a significant connection between the specific redesigns and the welders working body postures. This process can then be finalized by proposing an ergonomic evaluation framework which can be easily applied in other companies from the industry, involving larger study groups, and covering more working operations. Such framework can provide significant data which will encourage the application of ergonomic studies in North Macedonia for reducing health risks in working systems.

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DESIGN AND PROTOTYPING OF AUTONOMOUS ROBOTIC VEHICLE FOR PATH FOLLOWING AND OBSTACLE AVOIDANCE

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A b s t r a c t: This paper presents the design and implementation of a compact robotic vehicle capable of autonomously following a predefined path through integrated sensor technologies. A Pixy2 camera detects and translates the path into vector data, enabling real-time tracking across straight and curved segments using differential steering. Motor control is achieved by modulating the speed of two DC motors via the L298N driver, guided by line position data. Communication between the camera and Arduino Uno is established through the SPI interface. An ultrasonic sensor enhances navigation by detecting and avoiding obstacles. The system halts safely at designated stop lines by setting motor PWM to zero. This project demonstrates effective hardware-software integration for autonomous navigation, combining sensor fusion, control logic, and real-time processing.

Key words: autonomous car; Pixy2; differential control; sensor integration; PID

ДИЗАЈН И ПРОТОТИПИЗИРАЊЕ НА АВТОНОМНО РОБОТСКО ВОЗИЛО ЗА СЛЕДЕЊЕ ПАТЕКА И ИЗБЕГНУВАЊЕ ПРЕЧКИ

А п с т р а к т: Овој труд се фокусира на развој на мало роботско возило способно да следи дефинирана патека користејќи интеграција на сензори. Камерата Pixy2 ја детектира линијата и ја претставува како вектор, овозможувајќи следење на патеката во реално време. Возилото е дизајнирано да следи патека што се состои од прави делови и кривини, користејќи диференцијално управување. Контролата на двата DC-мотора се постигнува со приспособување на нивните брзини, овозможувајќи прецизно управување врз основа на положбата на линијата. Камерата комуницира со Arduino Uno преку SPI интерфејсот, додека моторите се контролираат преку драјверот на моторот L298N. Дополнително се користи ултразвучен сензор за откривање и избегнување предмети на патеката. Системот е дизајниран да застане пред линијата за запирање со исклучување на моторите (PWM поставен на нула), овозможувајќи возилото безбедно да застане. Проектот ја истакнува синергијата на хардвер-софтвер, докажувајќи автономна навигација преку интеграција на сензори, алгоритми за контрола и обработка во реално време.

Клучни зборови: автономно возило; Pixy2; диференцијално управување; интеграција на сензори; PID

INTRODUCTION

This paper was developed to demonstrate a simple and cost-effective method for implementing autonomous navigation. Line-following robots are widely used in educational and research settings as they offer a practical platform for exploring control systems, sensor integration, and real-time decision-making. Additionally, they serve as foundational models for real-world applications in transportation and logistics. The primary objective of this work is to design a small robotic vehicle capable of following a predefined path using the Pixy2 camera and differential steering. The` research highlights how affordable and readily available components can be integrated to achieve effective autonomous mobility.

To contextualize this study, it is essential to examine prior research on line-following robots and autonomous navigation systems. Recent advancements in mobile robotics have been driven by the rapid development of sensor technologies, microcontrollers, and sophisticated navigation and obstacle avoidance algorithms. The following literature review summarizes various approaches to the design and implementation of mobile robotic platforms with functionalities including line following, autonomous navigation, obstacle detection, and surveillance. These implementations utilize diverse platforms such as Arduino, Raspberry Pi, and an array of specialized sensors and modules. One early design utilizes an Arduino Nano microcontroller with three infrared (IR) sensors to detect a black line on a white surface. The robot employs four DC motors controlled by an L293D motor driver and is programmed to move when a white surface is detected and stop when encountering a black one [1]. In another project, a line-following robot is developed as a mobile surveillance system. This system uses an Arduino Uno for control, NI MyRIO for wireless communication, four pairs of IR sensors for navigation, and a webcam for visual monitoring [2].

A more complex platform combines a Raspberry Pi and Arduino Uno for steering control. The robot features a fixed four-wheel chassis and is equipped with multiple sensors and a robotic arm, enabling capabilities such as mapping, autonomous navigation, and object manipulation for transportation tasks [3]. Another project incorporates two ultrasonic and two IR sensors, enabling the robot to first identify the line to follow and then detect obstacles or edges during movement. The system continues to navigate the path only when no obstacles are detected and the line remains within sensor range [4]. An additional study describes an obstacle-avoidance robot that initially operates in manual mode through a Bluetooth connection with an Android smartphone. The robot transitions to autonomous mode using ultrasonic sensors to detect and avoid obstacles in real time [5]. Meanwhile, robotic vision is explored using the Pixy2 camera, programmed via the PixyMon application to track a dominant object based on color detection [6]. Another approach applies Dijkstra's algorithm to generate an optimal offline path. The robot pauses at each node to assess the environment for obstacles before continuing its movement [7]. This study also provides an overview of twelve positioning methods, categorized into radio-frequency techniques – such as IMU, VLC, IR, ultrasonic, geomagnetic, and LiDAR – and non-radio-frequency methods, including Wi-Fi, Bluetooth, ZigBee, and RFID [8].

Further development is seen in an autonomous vehicle designed to detect and avoid obstacles dynamically. This vehicle adjusts its speed based on the presence of obstructions, optimizing its path to reach a target destination more efficiently [9]. Finally, another project presents a multi-functional robot incorporating a control module, ultrasonic sensor, line sensor, IR sensor, and Bluetooth module. This robot is capable of both autonomous line following and remote control via infrared or Bluetooth communication with a mobile phone [10].

METHODOLOGY

The methodology describes the systematic process followed in the development of the robotic vehicle. The design was approached using a black box model as shown on Figure 1 to define the overall function of the system, which was then decomposed into subfunctions shown on Figure 2 representing sensing, control, actuation, and power supply. A morphological matrix shown on Table 1 was created to evaluate alternative solutions for each subfunction, allowing a structured comparison of possible design choices. Based on this analysis, the most suitable components and methods were selected to form the final solution.

Fig. 1. Black box for the autonomous vehicle

The black box model shows the robotic vehicle as a system where energy and sensor data are inputs, and the controlled movement and stopping actions are the outputs.

To better understand the internal structure of the system, the main functions of the robotic vehicle are broken down into distinct subfunctions. Each subfunction addresses a key aspect of operation, from sensing and control to actuation and movement. Figure 2 shows the main subfunctions of the robotic vehicle and their interactions.

A morphological matrix shown on Table 1 was created to compare alternative solutions for each subfunction, helping select the most suitable components for the system.

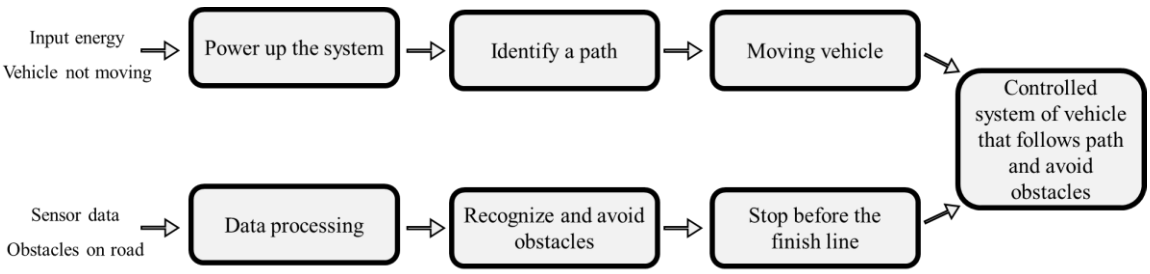

Fig. 2. Subfuntions of the system

T a b l e 1

Morphological matrix for choosing components

Subfunctions	Executors	
1. Power up the system	1.1. Lithium batteries 	1.2. Alkaline batteries 
2. Identify a path	2.1. IR sensor 	2.2. Camera 
3. The vehicle is moving	3.1. DC motor 	3.2. Stepper motor 
4. Data processing	4.1. Arduino 	4.2. Esp32 
5. Avoid obstacles	5.1. Camera 	5.2. Ultrasonic sensor 
6. Stops before the end line	6.1. Ultrasonic sensor 	6.2. Camera 

The final solution has chosen the lithium batteries (1.1) for powering the system, camera (2.2) for identifying a path, DC motor (3.1) for movement, Arduino (4.1) microcontroller, Ultrasonic sensor (5.2) for avoiding obstacles and camera (6.2) for stopping the vehicle. In this system, the vehicle operates by moving between the white lines using sensors to detect the line position. The vehicle is powered by lithium batteries and controlled via an Arduino microcontroller, using DC motors driven through a motor driver. The Pixy2 camera detects the black line in the center and guides the vehicle along the path. The Pixy2 detects the line by representing it as vectors defined by a start point (x_0, y_0) and an end point (x_1, y_1) within the camera's field of view. These vectors are extracted from the image and represent the direction and position of the line on the path. In the code, the robot uses the horizontal positions x_0 and x_1 of the first detected vector to calculate the central position of the line using the formula $(x_0 + x_1) / 2$. This value is then compared to the ideal center of the camera's field of view, which is 39 on the horizontal axis (since the Pixy2 has an effective horizontal resolution of 78 pixels). The difference between the detected line position and the center is treated as a tracking error. This error is fed into a PID controller, which calculates a correction value to adjust the PWM signals to the left and right motors, allowing the robot to accurately follow the line by steering toward the center of the path. The system also uses an ultrasonic sensor to detect and avoid obstacles along the path. When the Pixy2 no longer detects the central line, the Arduino interprets this as the stop line being near and stops the motors.

PROTOTYPING

The prototyping phase focuses on the practical implementation of the robotic vehicle, combining all hardware components into a functional system. This chapter presents the main components used, their assembly, and the wiring diagram, including assembly drawings and renders, to illustrate how the sensors, actuators, and control system are integrated to achieve autonomous line-following and obstacle avoidance.

Components and assembly

The main components used for prototyping of the vehicles are:

– **Arduino Uno** – central microcontroller for processing sensor data and controlling motor outputs;

– **Pixy2 camera** – detects and tracks the line on the path using vector representation;

– **HC-SR04 Ultrasonic sensor** – detects obstacles to enable avoidance;

– **DC motors** – provide driving force in a differential drive configuration;

– **L298N motor driver** – controls motor speed and direction via PWM signals from the Arduino;

– **Lithium battery** – supplies stable power to all components;

– **Chassis and wheels** – provide mechanical support and mobility.

Assembly drawing and CAD models were created to visualize the placement of components on the chassis and ensure correct mechanical assembly (Figure 3). Renders of the assembled vehicle show the final design and layout (Figure 4).

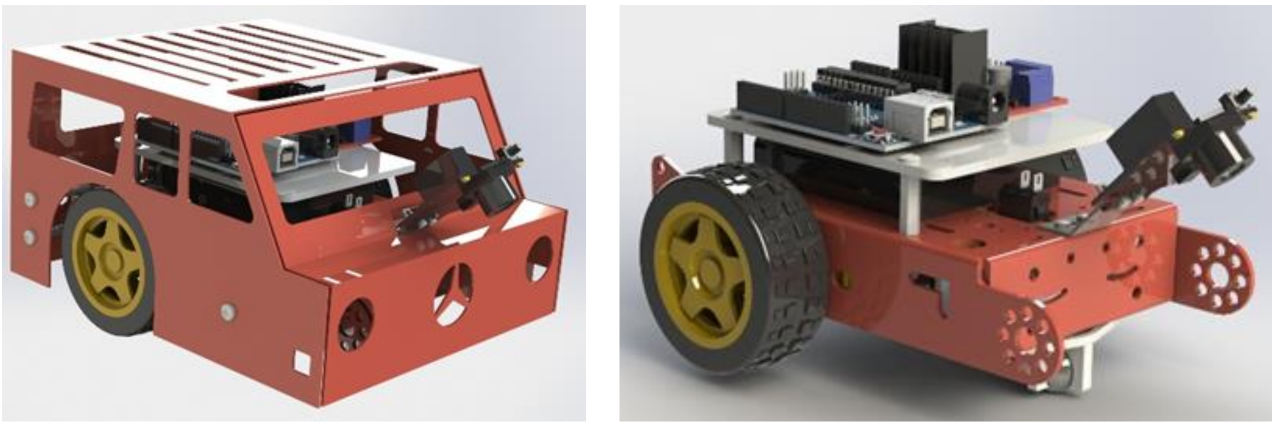

Fig. 3. Rendered photo of the vehicle design

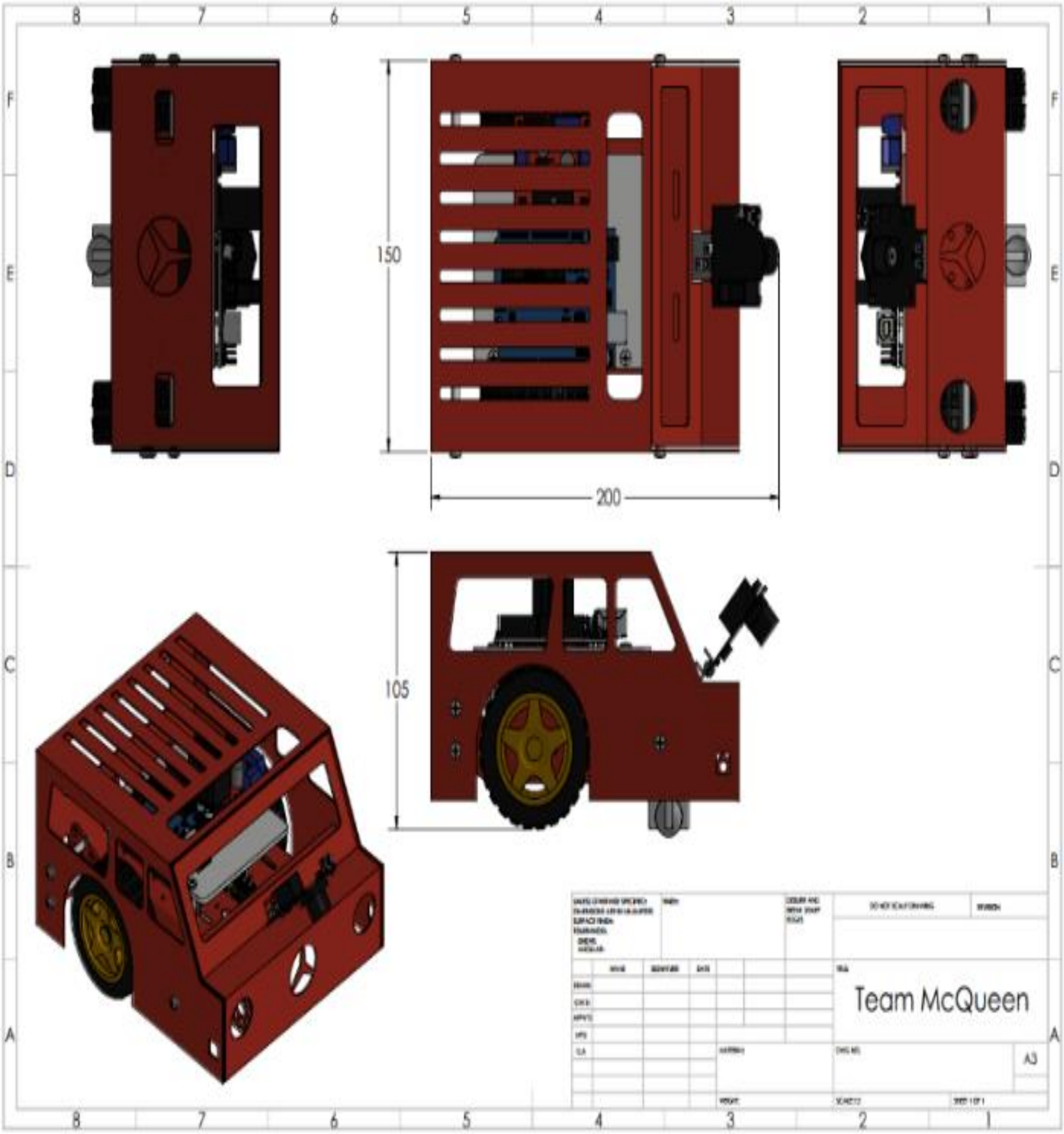

Fig. 4. Assembly drawing of the vehicle

Figure 5 illustrates the wiring diagram of the system. The Arduino Uno microcontroller serves as the central unit, coordinating signals between the sensors and the actuators. It receives input from the Pixy2 camera and the ultrasonic sensor, processes the data through the implemented code, and generates control signals for the motor driver. The motor driver regulates the power supplied from the lithium batteries to the DC motors, enabling smooth and precise motion control. This wiring setup ensures reliable communication between all components and provides the foundation for the system's programmed behaviour.

Figure 6 shows the prototype of the autonomous vehicle. The images present the overall design and assembly of the system, including the chassis, mounted sensors, wiring, and power supply. These visuals provide a clearer understanding of how the individual components are integrated into a functional unit.

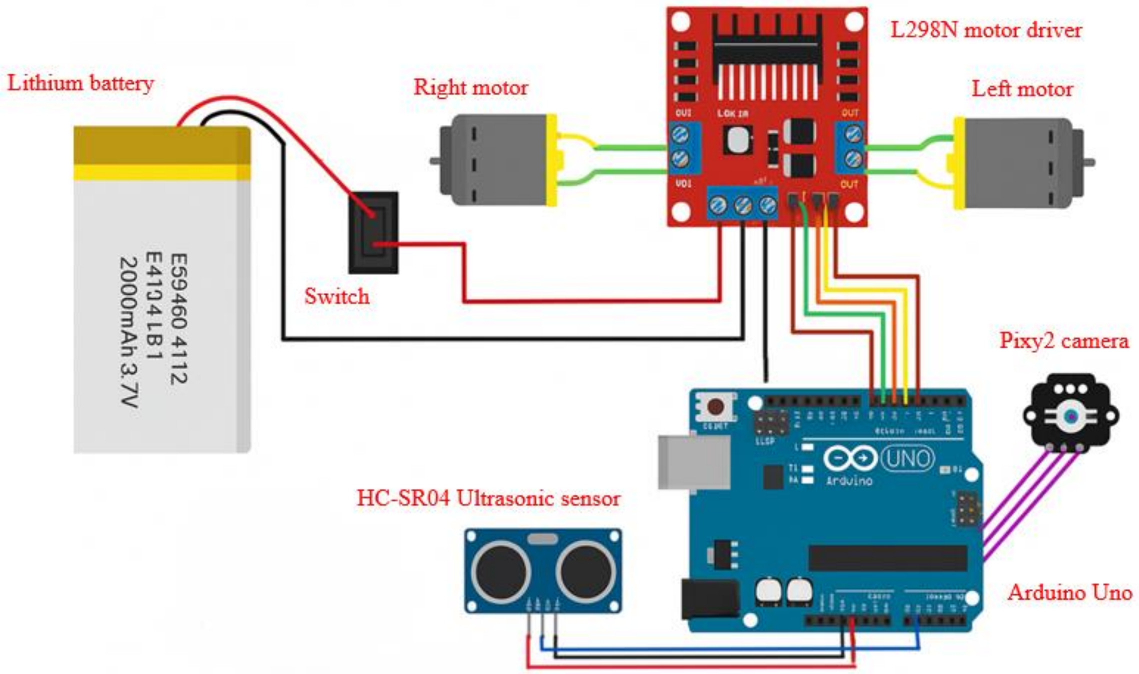

Fig. 5. System connection of the components

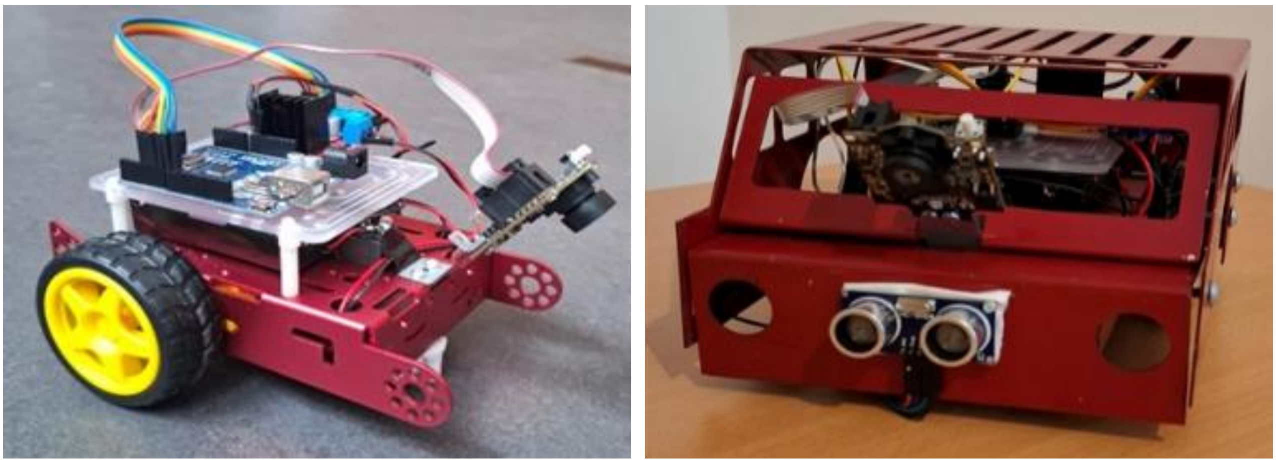

Fig. 6. Prototype of the vehicle

RESULTS

The expected results focus on assessing the robotic vehicle's functionality and stability under real-world conditions. It is anticipated that the vehicle will successfully follow a predefined line using the Pixy2 camera, which detects the black line in real time and represents it as a vector. The camera determines the vector's position and compares it to the center of its field of view (value 39). The deviation from the center generates an error value, which is used by a PID (Proportional–Integral–Derivative) controller to calculate a correction. This correction dynamically adjusts the speeds of the left and right DC motors, allowing the robot to maintain accurate and stable line tracking.

The PID controller uses three components – proportional, integral, and derivative – to respond to changes in the error signal. The proportional term responds to the current error, the integral accounts for accumulated past errors, and the derivative anticipates future trends based on the rate of error change. The controller is configured with the following gains: the proportional gain is 2, the integral gain is 0, while the derivative gain is 1.

Based on the correction value, the motor speeds are adjusted as follows: when turning left, the left motor slows down, and the right motor speeds up, while when turning right, the right motor slows down, and the left motor speeds up.

To regulate motor speed, the system uses Pulse Width Modulation (PWM), a technique that controls the effective power delivered to the motors by rapidly switching the voltage on and off. Arduino implements PWM with 8-bit resolution, meaning the PWM value can range from 0 to 255. This range represents the duty cycle, where a value of 0 equates to a 0% duty cycle (no power) and 255 equates to 100% (maximum power). For forward motion, both motors are set to a base PWM value of 150, corresponding to a duty cycle of approximately 58.82%.

The vehicle's turning and movement are achieved through **differential steering**. Depending on the correction value from the PID controller, one motor's speed increases while the other decreases, enabling smooth and precise directional changes. To ensure correct operation, PWM values are constrained within the valid range from 0 to 255.

In addition to line tracking, the system includes **obstacle detection** using an HC-SR04 ultrasonic sensor. This sensor emits ultrasonic pulses and measures the time it takes for the echo to return after hitting an object. The distance to an object is determined by measuring the time it takes for an ultrasonic pulse to travel to the object and reflect back to the sensor. Using the known speed of sound (approximately 343 meters per second), the system calculates how far the object is based on the duration of this round-trip. Based on the measured distance, the vehicle makes decisions accordingly:

If the object is more than 20 centimeters away (considered a safe distance), the vehicle continues following the line using the Pixy2 camera and PID control.

If the object is 20 centimeters away or closer, the vehicle stops line following and activates obstacle avoidance mode.

In obstacle avoidance mode, the vehicle first comes to a brief stop to ensure safety. It then performs a turning maneuver to change its direction. After turning, the ultrasonic sensor scans the new path to check for any obstacles. If the path is clear, the vehicle continues moving forward.

The observed results show that the vehicle successfully follows the predefined path with high precision, using real-time data from the Pixy2 camera and dynamic adjustments from the PID controller. When the line is centered, both motors receive equal PWM signals, and the robot moves straight. When the line deviates from center, the PID controller modifies the motor speeds, accordingly, allowing for smooth and accurate turns. The system handles both straight and curved segments effectively, without noticeable oscillations or delays.

When the Pixy2 camera can no longer detect the lines such as at the end of the track the system shuts off both motors by setting their PWM values to zero, ensuring a safe and controlled stop. Additionally, the HC-SR04 sensor reliably detects obstacles within 20 cm and enables the robot to avoid them, regardless of the object's shape, color, or transparency. This robustness makes the system suitable even in challenging environmental conditions like dust or fog.

Overall, the results validate the integration of the Pixy2 camera, PID-based motor control, and ultrasonic sensing as a reliable and stable solution for autonomous navigation. The combination of accurate line following and responsive obstacle avoidance demonstrates the system's successful both in terms of mechanical design and software functionality.

CONCLUSION

This project successfully demonstrated the development of a compact autonomous robotic vehicle capable of following a predefined path while avoiding obstacles. The integration of the Pixy2 camera with a PID control algorithm enabled precise, real-time line tracking, allowing smooth navigation through both straight and curved sections. The ultrasonic sensor provided reliable obstacle detection and avoidance, ensuring safe operation under dynamic conditions. Testing confirmed that the system responds quickly to changes in the line position, maintains stable operation, and stops accurately at the end of the path. Overall, the results highlight the effectiveness of combining sensor integration, control algorithms, and real-time data processing to achieve robust and precise autonomous navigation in a compact robotic platform.

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Original scientific paper

INTELLIGENT CONTROL OF KUKA ROBOTIC SYSTEMS BASED ON AI-DRIVEN HUMAN MOTION TRACKING

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A b s t r a c t: Industrial robot control, often restricted by proprietary systems like KUKA Robot Language, presents a challenge for advanced scientific research and intuitive programming. This paper introduces a novel, low-cost framework for Intelligent Control of KUKA Robotic Systems using AI-Driven Human Motion Tracking to facilitate kinesthetic teaching. The system integrates the MediaPipe Hands Deep Learning model for real-time 3D hand landmark tracking with a custom PyOpenShowVar/KUKAVARPROXY control middleware, enabling soft real-time command transmission to a KUKA KR 16-2. The framework achieved 97.3% accuracy for discrete gesture commands and used a Direct Landmark Differencing approach to provide intuitive, simultaneous control over 3D joint-space movement. While exhibiting 200 ms soft real-time overhead, the performance is highly suitable for path teaching and significantly lowers the technical barrier for human-robot collaboration and flexible manufacturing.

Key words: KUKA manipulator; computer vision; AI-driven control; deep learning; real-time control

КОНТРОЛА НА РОБОТСКИТЕ СИСТЕМИ KUKA ЗАСНОВАНА НА СЛЕДЕЊЕ НА ЧОВЕЧКОТО ДВИЖЕЊЕ СО ПРИМЕНА НА ВЕШТАЧКАТА ИНТЕЛИГЕНЦИЈА

А п с т р а к т: Контролата на индустриските роботи, која често е ограничена од сопствен програмски јазик како што е KUKA Robot Language, претставува сериозен предизвик за напредни научни истражувања и за развој на интуитивни методи на програмирање. Овој труд претставува иновативна и економична рамка за интелигентна контрола на роботските системи KUKA, која користи вештачка интелигенција и следење на човечко движење со цел да се овозможи кинестетичко учење. Развиениот систем го комбинира длабоконевронскиот модел MediaPipe Hands за следење на тридимензионални координати на движењата на раката во реално време, со сопствено развиен посреднички слој за комуникација PyOpenShowVar/KUKAVARPROXY, кој овозможува реалновременска размена на команди со роботот KUKA KR 16-2. Предложената рамка постигнува 97,3% точност при препознавање поединечни гест-команди, со што овозможува интуитивна и истовремена контрола на движењата во тридимензионален простор. Покрај регистрираното доцнење од околу 200 ms во реално време, постигнатите перформанси се целосно соодветни за учење на патеки и значително ја намалуваат техничката бариера за колаборацијата човек – робот и за флексибилно производство.

Клучни зборови: KUKA-манипулатор; компјутерска визија; контрола со вештачка интелигенција; контрола во реално време

1. INTRODUCTION

Industrial manipulators, such as those manufactured by KUKA, are the cornerstone of modern automation, characterized by their precision, robustness, and speed. However, their primary control architecture is designed for industrial efficiency and safety, often relying on proprietary, text-based languages like the KUKA Robot Language (KRL). While suitable for repetitive, pre-programmed manufacturing tasks, this closed-system design presents significant barriers to scientific research [1, 2]. Researchers often seek maximum control, low-level access to variables, and the ability to integrate advanced mathematics or third-party libraries-functionalities that KRL inherently limits. Consequently, fully exploiting the mechanical capabilities of high-performance industrial platforms in scientific and novel control contexts is often impossible.

To overcome the limitations imposed by inustrial controllers, the robotics research community utilizes various middleware and communication interfaces. This is crucial for implementing advanced control methodologies, such as complex Human-Robot Interaction (HRI) schemes or Learning from Demonstration (LfD). Specifically, our approach leverages an open communication interface that not only grants soft real-time access to robot state and control variables but also includes a Python class capable of generating KRL source files (.src) offline. This feature allows users to program complex robot paths in a flexible, high-level environment like Python, completely eliminating the need for specialized KRL knowledge and significantly reducing programming time.

Building on this flexible control foundation, this paper presents a novel framework for Intelligent Control of KUKA Robotic Systems Based on AI-Driven Human Motion Tracking. The core of the system utilizes Deep Learning techniques for robust Hand Gesture Recognition, capturing the operator's movements and translating them into intuitive trajectory commands. This AI-driven approach drastically simplifies the teaching process by translating intuitive human motion directly into executable robot code, saving considerable time and lowering the technical expertise barrier for operators. This research aims to achieve a viable and efficient method for kinesthetic teaching that allows non-expert users to program complex tasks. By seamlessly coupling cutting-edgeAI-based perception with an agile control interface, we demonstrate the potential of open control methods to enable flexible manufacturing and truly intuitive human-robot collaboration.

Prior research in robotics has addressed the challenges of flexible control through various approaches. Regarding industrial system accessibility, several works have proposed software interfaces and middleware to unlock low-level control of platforms like KUKA, attempting to bridge the gap between proprietary KRL and external programming environments [3, 4]. Crucially, traditional online communication with KUKA robots is fundamentally limited to additional packages like KUKA. RobotSensorInterface and KUKA. Ethernet KRL-XML, which restrict the I/O capacity and the complexity of the external control loop [5]. Concurrently, the HRI-field has advanced through Learning from Demonstration (LfD) [6], and more recently, Deep Learning (DL) techniques have demonstrated exceptional performance in real-time vision tasks for hand gesture and human pose estimation [, 8, 9]. While these three areas – open control interfaces, DL – based perception, and LfD – have been explored individually, a unified framework that integrate a high-fidelity, DL – driven gesture system with a flexible, soft real-time KUKA – control architecture remains a critical need.

The key contributions of this work are: (1) The successful integration of a DL-based hand gesture recognition system with an external control interface to realize a stable and responsive soft real-time control loop for the KUKA controller. (2) The development of a precise control and mapping strategy that translates gesture and pose data into safe and stable KUKA joint space trajectories. (3) Comprehensive experimental validation demonstrates the accuracy, low latency, and ease-of-use of the proposed intelligent control framework for complex collaborative tasks, enabled by our flexible, middleware-based architecture. The remainder of this paper is organized as follows: Section 2 details the system architecture, hardware components, software environments, and the connectivity setup. Section 3 presents the experimental setup. Section 4 discusses the results and performance evaluation. Finally, Section 5 offers the conclusion and future work.

2. SYSTEM ARCHITECTURE

System architecture overview

The proposed intelligent control system operates on a distributed architecture designed to facilitate intuitive human interaction with industrial robots. As illustrated in Figure 1, the framework comprises three primary interconnected layers: the human operator providing intuitive inputs, an external laptop/PC responsible for integrated perception and control logic, and the KUKA robot controller (KRC) with its attached KUKA KR 16-2 manipulator for physical task execution. The system uses DL techniques for robust hand gesture recognition and a custom middleware for flexible robot control and offline program generation.

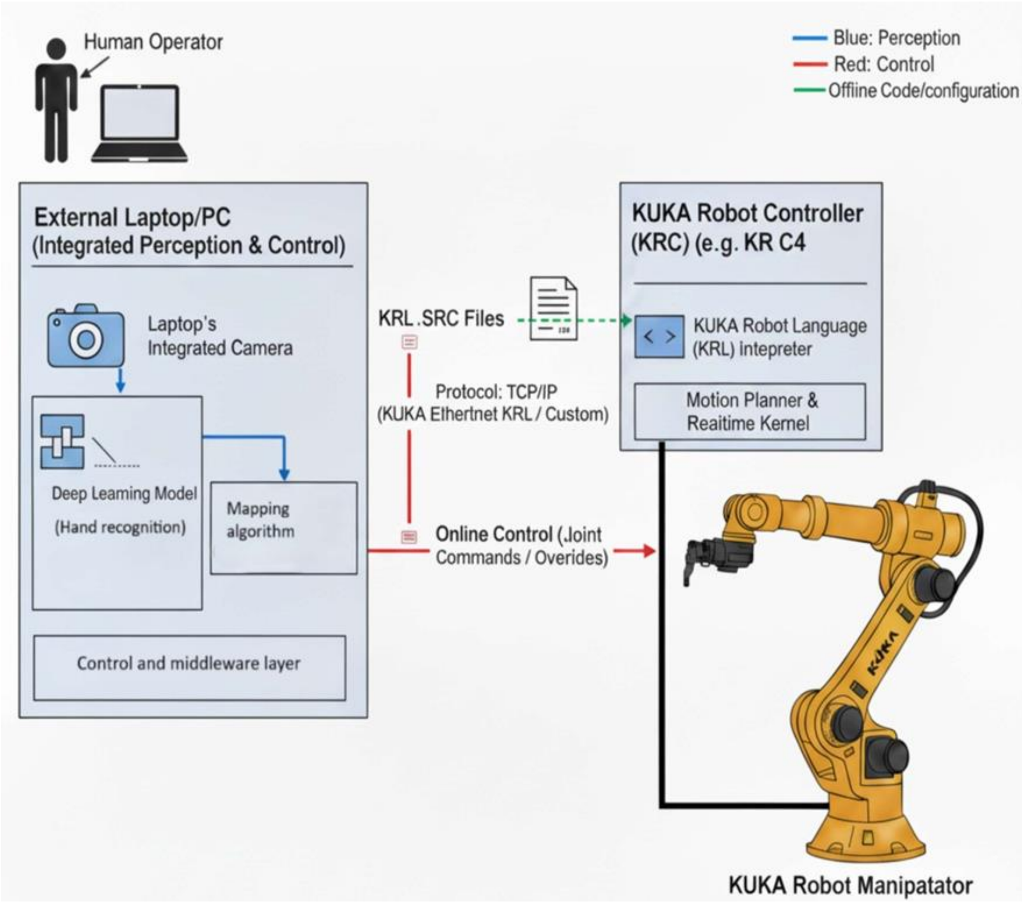

Fig 1. System architecture of AI-driven KUKA framework

Hardware components

The control framework utilizes three core hardware elements: the industrial manipulator, the robot controller, and the perception system.

KUKA KR 16-2 manipulator and controller

The core execution platform for this system is the KUKA KR 16-2 industrial robot, a 6-axis articulated manipulator known for its payload capacity (16 kg) and extensive reach (1610 mm). This model is representative of common industrial applications, providing a robust platform for testing the developed control middleware. The robot is managed by a KUKA robot controller (KRC), typically the KR C4 model, running the proprietary KUKA operating system with a soft real-time kernel. The KRC handles all kinematics, safety functions, and motion planning. External commands are directed to the controller via a dedicated network interface, bypassing the standard teach pendant programming flow to allow for external influence over joint movements and program execution.

Integrated perception system

The human-robot interaction is driven by an integrated visual perception system. This consists of the integrated camera on the external laptop/PC, which provides a live RGB video stream of the human operator's workspace. The camera's feed is processed directly by the external laptop/PC, which hosts the DL-models. This integrated setup offers a portable and cost-effective solution for motion capture, eliminating the need for dedicated, high-cost external depth sensors or specialized Vicon systems. The primary function of this hardware is to reliably deliver video data at a sufficient frame rate to the software layer, ensuring low-latency gesture recognition for the soft real-time control loop.

Software environment and middleware

The control and perception systems are established across three distinct software layers: the deep learning stack for perception, the custom Python middleware for control logic, and the KRL environment on the robot controller. Figure 2 shows the detailed data flow.

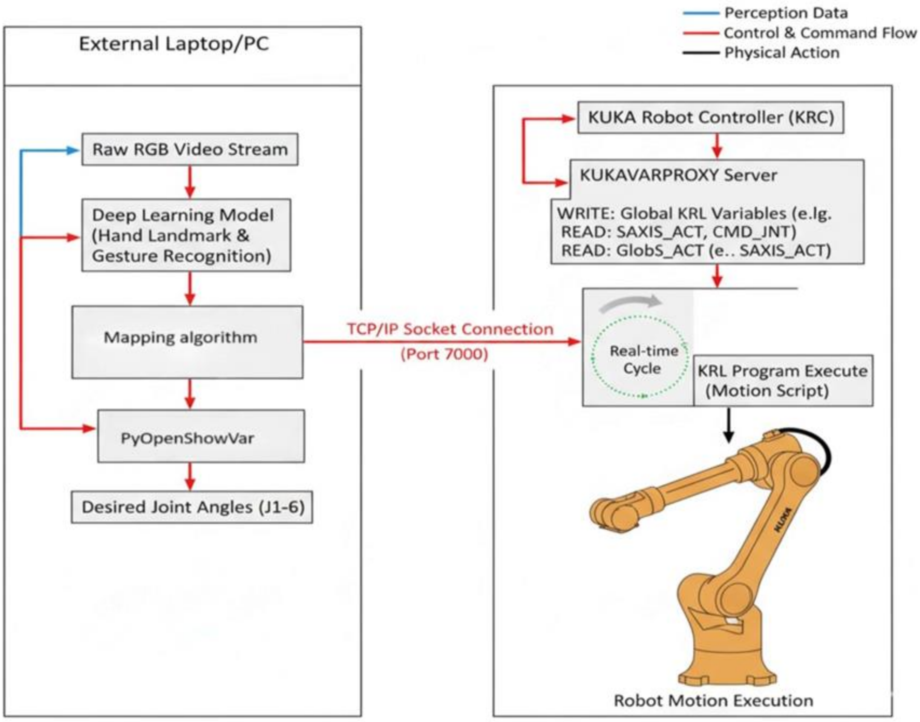

Fig 2. Detailed data flow

Control middleware: KUKAVARPROXY and PyOpenShowVar

The core of the system's external control capability relies on a client-server architecture designed to bypass the limitations of standard KRL programming. On the KUKA robot controller (KRC) side, the open-source KUKAVARPROXY acts as a server. This dedicated application runs on the KRC's Windows environment and establishes a TCP/IP socket connection, typically listening on Port 7000. Its fundamental role is to provide a channel for remote programs to read and write global KRL variables (such as $OV_PRO or dedicated position variables) by implementing the OpenShowVar protocol over the network.

On the external laptop/PC side, the communication client is the PyOpenShowVar library. This Python package handles the low-level network interface, translating the high-level control decisions from the gesture recognition system into the specific messaging format required by the OpenShowVar protocol.

The use of this client-server coupling is essential for achieving soft real-time control and is specifically leveraged for:

– Real-time Joint Overrides: The Python script uses PyOpenShowVar to repeatedly write calculated joint angle increments into pre-declared global KRL variables. A parallel KRL program running on the KRC continuously reads these variables to modify its current motion cycle, effectively enabling the external PC to directly influence the robot's trajectory based on human input.

– State Feedback: The library is used to read back system variables, such as the actual joint position ($AXIS_ACT), closing the control loop and allowing the Python middleware to maintain an accurate model of the robot's state.

– Programmatic Control: PyOpenShowVar allows for remote manipulation of program flow flags and system variables, enabling the user to start, stop, or reset the main KRL execution program based on a recognized hand gesture.

This implementation allows the Python middleware to exert granular control over the robot's motion through variable manipulation, which is the foundational element enabling the AI-driven kinesthetic teaching framework.

3. EXPERIMENTAL SETUP

Description of experimental environment

The experimental validation of the AI-driven control framework was conducted using a KUKA KR 16-2 industrial manipulator controlled by a KRC4 controller. The robot was secured to a standard industrial floor mount within a defined safety cage area.

The perception system utilized the integrated camera on the external laptop/PC, which was positioned approximately 1 meter from the human operator. This arrangement ensured the camera maintained a full-frame view of the operators dominant hand, covering the entire operational range used for gesture control. The robot's primary workspace was configured to be within a safe collaborative zone, and the KRC4 controller and the external laptop/PC were connected via a dedicated Ethernet cable using a static IP configuration for the stable TCP/IP connection.

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Case study I: Discrete position selection

The first case study focuses on validating the discrete gesture recognition capability for fast, programmatic robot control. The system was tasked with recognizing the number of fingers the operator held up (one, two, or three). Based on the recognized count, the robot was commanded to move to a corresponding, pre-determined target position. For example, holding up one finger triggered movement to Position One, two fingers to Position Two, and three fingers to Position Three. This test evaluates the overall latency and reliability of the perception-to-program execution sequence.

Case study II: Continuous control with tracking

The second, more complex case study validates the continuous control and mapping capability. This involved recognizing two primary operational states:

1. Open hand (Continuous control): When the hand was open, the system activated the proportional control mapping, allowing the robot's joints to follow the hand's movements. An open hand moving left, for instance, resulted in the appropriate joint movements toward the left.

2. Depth control: The system also utilized the distance of the hand from the camera (depth, z-axis) to control the robot. Moving the open hand toward or backward from the camera translated into corresponding movements along the robot's principal axis, enabling three-dimensional control over the manipulator's End-Effector or specific joints.

AI model for hand motion tracking

The core of the perception system is a robust, low-latency Deep Learning model responsible for tracking the operator's hand motion in real-time, detecting gestures, and extracting both fine-grained landmarks and categorical gesture IDs.

Dataset and preprocessing

The system utilizes the MediaPipe Hands framework, which employs a highly optimized, pretrained model for real-time hand detection and tracking. The input video stream from the integrated camera is preprocessed by MediaPipe to the first identify the hand's Region of Interest (ROI) and then predict 21 3D hand landmarks (normalized Px, Py and Pz coordinates). The z coordinate provides relative depth information crucial for Case study II. The classification of the discrete gestures (0, 1, 2, or 3 fingers) for Case study I was handled by a lightweight classifier built on top of the raw landmark data, which relied on geometric features such as the distance and relative position between fingertip and joint landmarks.

Model selection and training process

Model selection: The system leverages the pretrained, pipeline-based model from MediaPipe Hands. This architecture was chosen for its optimal balance between accuracy and extremely high inference speed, which is a non-negotiable requirement for soft real-time robot control. The pipeline consists of a lightweight Palm Detector followed by a dedicated Hand Landmark Model. This design allows the system to achieve an average processing rate of approximately 30 Frames Per Second (FPS) on the external PC, minimizing overall system latency.

Training process: The underlying hand detection and landmark models are pre-trained. The necessary "training" effort focused on system calibration – empirically tuning the proportional scaling factor k and the coordinate mapping boundaries – and on the lightweight gesture classifier, which was trained using a small, self-collected dataset to validate the geometric thresholds used for the finger-counting task (Case study I).

Evaluation metrics

The validation of the AI perception system was quantified using two primary performance metrics:

1. Gesture Classification Accuracy (ACC gestures). This metric specifically validates the reliability of Case study I: Discrete position selection. It was measured as the percentage of correctly identified discrete gestures across a diverse test set.

2. Detection latency. Reported as the achieved Frames Per Second (FPS). Consistent, high throughput (30 FPS) is crucial because minimizing the perception delay ensures that the overall control loop remains responsive enough for smooth, intuitive guidance as validated in Case study II.

Real-time data acquisition from hand tracking

The Python middleware acts as the central hub, continuously acquiring and translating data from the AI Perception system. This process is executed at approximately 30 FPS. The control strategy implements a Direct Landmark Differencing approach, leveraging the structured output of Media-Pipe to ensure low-latency control. The wrist position vector, $P_{\text{human}}(t)$, is extracted directly from the Media-Pipe output, consisting of the normalized x, y, and z coordinates of the wrist landmark. The kinematic mapping algorithm calculates the required change in robot joint angles $\Delta\Theta_{\text{robot}}$ using the proportional control law based on the change in the raw, filtered landmark position:

$$\Delta\Theta_{\text{robot}} = k * (P_{\text{human}}(t) - P_{\text{human}}(t-1)).$$

This Direct Landmark Differencing method is superior as it uses the inherent normalized 3D information from Media-Pipe to control the robot along the *x, y*, and *z* axes simultaneously. The continuous control loop is active when the "Open Palm" gesture is detected $k = 0.15$.

Data transmission to KUKA robot controller

The calculated commands (either the program flag or the $\Delta\Theta_{\text{robot}}$) are immediately prepared for network transmission to the KRC via the established TCP/IP link. The transmission process utilizes the specialized client-server architecture:

– Client encoding: The PyOpenShowVar library formats the data into the OpenShowVar protocol string.

– TCP/IP transmission: The message is sent over the dedicated Ethernet link to the KUKA-VARPROXY server on the KRC.

– Server execution: Upon receipt, KUKA-VARPROXY instantly writes the data to the predefined global KRL variables, enabling the following control states:

- Discrete position select (Case study I): An integer variable is updated, causing the main KRL program to execute a pre-programmed PTP motion to position 1, 2, or 3.
- Continuous control (Cases study II): The calculated $\Delta\Theta_{\text{robot}}$ values are written to variables that are continuously read by a loop in the KRL program to incrementally adjust the robot's ongoing motion every cycle, achieving soft real-time guidance.
  - Stop / Pause (Closed fist): Sets $$\Delta\Theta_{\text{robot}} = 0,$$ halting all joint velocity.
- Teach / Key-frame save (Four fingers): An instruction flag is sent to the KRL program to record the robot's current joint angles ($AXIS_ACT) to a file for offline program generation.

4. RESULTS AND DISCUSSION

Results from Case study I: Discrete position selection

Case study I validated the system's ability to reliably translate discrete hand gestures into fixed program commands, with the primary metric being Gesture Classification Accuracy. The system's reliability for programmatic command execution was measured across 50 trials for each of the three finger-count gestures (1, 2, and 3 fingers up). The geometric classifier implemented using Media-Pipe landmarks proved highly effective and robust. Table 1 shows the results from testing data for the hand recognition model.

T a b l e 1

Results from testing data for the hand recognition model

Gesture (target)	Number of trials	Correctly classified	Accuracy %
One fingers (Pos 1)	50	49	98
Two fingers (Pos 2)	50	49	98
Three fingers (Pos 3)	50	48	96
Overall	150	146	97.3

The high average accuracy of 97.3% confirms the robustness of the geometric thresholding approach for converting visual input into reliable, discrete operational states.

The total time from the gesture being recognized to the robot initiating its PTP movement was measured to assess the pipeline's overall efficiency. The 200 ms difference represents the combined overhead introduced by the perception system (Media-Pipe frame processing) and the Python middleware's control logic execution. This establishes that the system is suitable for non-critical programmatic moves but highlights the latency component contributed by the soft real-timeAI framework.

Results from Case study II: Continuous kinesthetic control

The system successfully achieved a continuous control loop rate tied to the perception system's throughput of approximately 30 FPS, as shown on Table 2.

T a b l e 2

Perception value and implication for control

Metric	Measured value	Implication for control
Perception	30 FPS	Loop cycle time of ~33 ms (ideal minimum latency).
Proportional scaling factor (k)	0.15	Empirically tuned for safe and intuitive joint velocity.

Qualitatively, the robot's motion was perceived as smooth and responsive for slow-to-moderate hand movements, validating the choice of $k = 0.15$. High-frequency hand movements resulted in noticeable lag and jerkiness, confirming the limitations inherent in the soft real-time communication (TCP/IP) and the KRC's KRL execution cycle.

The proportional control successfully mapped the x and y screen coordinates to the appropriate robot joint movements. Crucially, the z-coordinate (relative depth) provided by MediaPipe was utilized to control axial movement. The result was moving the hand closer to the camera (decreasing z) consistently caused the robot's end-effector to move along its direction of extension and retraction, enabling intuitive forward and backward control. This demonstrates the successful exploitation of MediaPipe's 3D landmark data for control beyond planar movement.

Discussion of system performance

The system's overall control rate is constrained by the 30 FPS perception throughput and network overhead, placing it firmly in the domain of soft real-time control. The achieved fidelity allows operators to effectively "teach" spatial points and paths by walking the robot through the desired trajectory. For kinesthetic teaching, where intuitiveness and safety are prioritized over microsecond precision, this performance is adequate.

Acritical consideration for the Direct Landmark Differencing approach is the risk of driving the manipulator into kinematic singularities. To ensure robustness and safety, coding solutions were implemented within the KRL program on the KRC:

1. Maximum delta value limit: The program enforced a maximum magnitude on the incremental joint commands ($\Delta\Theta_{robot}$) received from the PC. This prevents excessive acceleration near singularity zones, capping the maximum velocity command for any single axis.

2. Singularity region detection: The KRL code includes logic to monitor the robot's current joint configuration. If the robot enters a predefined proximity to known singularities (e.g., wrist or shoulder singularities), the KRL program automatically reduces the proportional gain (k) to zero or switches to a position-hold mode. The external PC is then notified with a status message (e.g., "Cannot reach this target, possible singularity").

The implementation of the Direct Landmark Differencing approach proved highly intuitive. Operators did not need to perform complex mental mapping; a change in the hand's position in space directly resulted in a proportional change in the robot's joint velocity. This method:

1. Eliminated system overhead: By avoiding complex inverse kinematics and external OS calls, the control was streamlined.

2. Enabled 3D control: The direct use of MediaPipe's coordinate offers a low-cost, effective method for controlling the third dimension (depth), a significant enhancement over planar 2D vision systems.

The combined results confirm that the low-cost, vision-based framework is a viable and highly accessible alternative for developing natural, kinesthetic teaching interfaces for industrial manipulators.

5. CONCLUSIONS AND FUTURE WORK

This work developed a low-cost, intuitive, and soft real-time kinesthetic teaching interface for industrial manipulators using AI-based vision. The system successfully integrated the MediaPipe Hands model for gesture-based perception and used PyOpenShowVar/KUKAVARPROXY middleware for TCP/IP communication with the KUKA KR 16-2 robot.

Experimental results confirmed the system's effectiveness:

High reliability: The gesture classification system achieved 97.3% accuracy, demonstrating the robustness of the geometric gesture recognition approach.

Intuitive 3D control: The Direct Landmark Differencing method effectively utilized 3D depth data from MediaPipe, enabling natural control of depth (Pz axis).

Precision: During continuous motion, the system maintained end-effector accuracy within one decimal point of the target, meeting typical industrial tolerances.

Soft real-time performance: Despite a 200 ms overhead from AI processing and TCP/IP communication, the system proved suitable for non-time-critical kinesthetic teaching and path recording tasks.

Overall, the proposed framework provides a viable and accessible alternative to expensive commercial solutions, showing that consumer-grade vision systems and open-source middleware can enable natural, expressive robot programming interfaces.

Building on the success and current limitations of the system, several future improvements are proposed:

– Reduce latency with hard real-time control: Migrating from soft real-time TCP/IP to KUKA. RSI (Robot Sensor Interface) with UDP communication could reduce latency and significantly improve motion smoothness.

– Enable Cartesian-space control: Implementing a direct inverse kinematics (IK) solver would allow intuitive control of the robot's end-effector in x, y, z space, overcoming the non-linear behavior of joint-space control.

– Incorporate predictive AI models: To mitigate perception delays, methods like Kalman filtering or RNNs could predict hand positions a few frames ahead, allowing proactive motion and improved responsiveness.

– Develop a full teaching platform: A graphical user interface (GUI) could be added to allow editing, saving, and replaying taught paths, along with features like speed profiles and tool state control – transforming the system into an end-to-end prototyping tool.

– Enhance safety: Expanding the middleware's safety logic to include collision prediction based on 3D workspace mapping (e.g., using RGB-D data) would improve operational safety.

– Expand gesture vocabulary: Adding dynamic gestures for more complex commands (e.g., grip/release, speed control, or mode switching) would allow operators to execute more advanced tasks without using the physical SmartPAD.

These directions aim to refine the system into a robust, flexible, and user-friendly tool for advanced human-robot collaboration and intuitive robot programming.

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Original scientific paper

FAILURE MODE AND EFFECT ANALYSIS-BASED RISK ASSESSMENT OF A BRIDGE CRANE MAIN GIRDER

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A b s t r a c t: This paper presents an integrated approach for evaluating the condition and failure risks of the main girder in a bridge crane. The study uses numerical simulations performed in Ansys. The critical stress zones for various trolley positions and dynamically amplified loads are identified using numerical analyses. In the following phase, the results from the numerical analysis are used as input for the Failure Mode and Effect Analysis - FMEA method. Based on the generated FMEA, the data are further utilized to develop a MATLAB algorithm that integrates the FMEA parameters and provides an assessment of the structural condition and failure risks. The suggested methodology enables an improved approach to crane inspection and maintenance planning.

Key words: bridge cranes; main girder; FMEA

ПРОЦЕНА НА РИЗИК ЗАСНОВАНА НА АНАЛИЗАТА НА МОЖНИ НЕИСПРАВНОСТИ И ПОСЛЕДИЦИ НА ГЛАВНИОТ НОСАЧ НА МОСТОВСКА ДИГАЛКА

А п с т р а к т: Овој труд претставува интегриран пристап за оценување на состојбата и ризиците од отказ на главниот носач кај мостовска дигалка. Преку нумеричките анализи во Ansys се идентификувани критичните зони на напрегања за различни положби на количката, како и при динамички зголемени оптоварувања. Во следната фаза, резултатите од нумеричката анализа се користат како влезни податоци за методот Анализа на можните неисправности и последици (анг. *FMEA*). Добиената *FMEA* се имплементира во алгоритамот *MATLAB* кој ги интегрира параметрите на *FMEA* и овозможува процена на структурната состојба и ризиците од отказ. Предложената методологија овозможува подобрен пристап кон инспекцијата и планирањето на одржувањето на дигалките.

Клучни зборови: мостовски дигалки; главен носач; анализа на можни неисправности и последици

1. INTRODUCTION

One of the most important and critical elements in the construction of bridge cranes is the main girder, therefore, its condition largely determines the safety of crane operation [1, 2]. The need for such research is supported by a review of earlier studies in the fields of crane engineering, reliability assessment, maintenance, and crane inspection [3, 4, 5, 6]. The research [7] focuses on safety regulations, identifying inconsistencies within national standards and suggesting more precise and unified guidelines to reduce crane-related accidents. In [8], traditional FMEA is enhanced with multicriteria decision-making tools to better assess failure modes in renewable energy systems, while [9] examines the impact of human factors, such as noise and mental exhaustion, using a virtual reality crane simulator. Industry 4.0 applications are addressed in [10], where machine-vision methods in conjunction with PFMEA and DFMEA enhance production quality control. Studies [11] and [12] examine real operational issues in crawler cranes and crane guiding structures, using experimental data and FMEA to identify causes of failures and excessive wear. Methodological developments of FMEA appear in [13], which introduces Z-numbers and clustering algorithms, and in [14], where fault trees, Bayesian networks, and Markov chains are integrated to evaluate crane reliability. Broader safety factors in construction environments are explored in [15]. Risk-assessment improvements are further presented in [16] using Z-numbers and set-pair analysis, and in [17], where human error risks are prioritised through cumulative prospect theory. Lastly, [18] combines Fishbone, Pareto, and FMEA analyses to identify dominant failure causes in crawler cranes, showing mechanical issues to be the most important. Overall, the literature indicates a shift towards integrated analytical models, sophisticated monitoring technologies, and stronger emphasis on human and operational factors to increase crane reliability and safety. Based on the conducted research, it is evident that accurately assessing the condition of the main girder requires a combined approach involving analytical calculations and modern numerical methods. As a result, the primary objective of this study is to identify the most critical parameters during crane operation. The focus of this research was to collect data and develop an algorithm for assessing the most critical element of the main girder. By generating and implementing a MATLAB code, this study aims to effectively support both crane inspection and maintenance. This research paper helps solve current and important challenges in scientific and professional studies related to crane maintenance and inspection.

2. METHODOLOGY

The methodological approach in this paper is based on applying earlier obtained analytical and numerical results into the FMEA method and implementing the outcomes in MATLAB. The analytical and numerical results used in this study originate from the author's unpublished structural analyses of the crane girder. These results were obtained as part of a broader research effort and are solely used here as structural indicators for identifying critical regions and supporting the FMEA procedure. The phases of the research are presented in Figure 1.

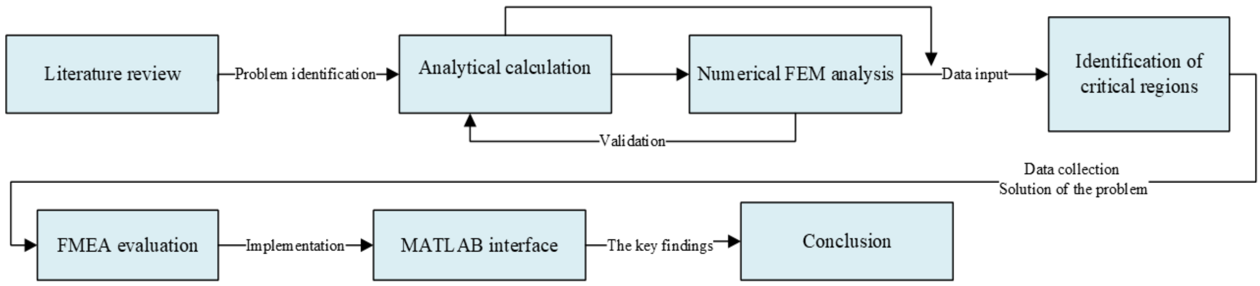


Fig. 1. Research methodology

3. STRUCTURAL ASSESSMENT RESULTS OF THE MAIN GIRDER

The main girder examined in this study belongs to a real bridge crane located at Institute of Earthquake Engineering and Engineering Seismology - IZIIS. A CAD model of the crane created in SolidWorks is shown in Figure 2.

a) *Analytical analysis of the main girder*

First, the main girder was calculated analytically. The main girder of the bridge crane is a welded box profile, whose geometry and material properties are derived from the crane documentation (Table 1) [19]. The analytical analysis is performed according to the classical beam theory, where the girder is modelled as a simply supported beam subjected to a uniformly distributed load q and a concentrated load Q with two variable positions, depending on the trolley location: at mid-span (L/2) and in an end position (e) [1, 2, 3]. The results indicates that the girder operates in the elastic range under the applied loading. The analytical results serve as a basis for verification with numerical analysis.

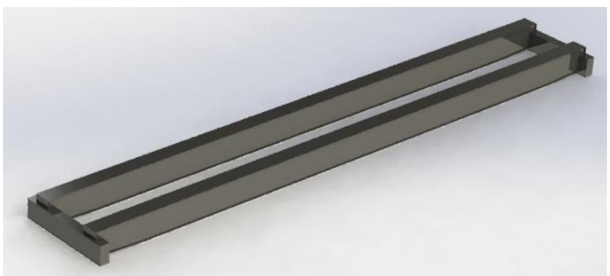


Fig. 2. CAD model of the main girder

Table 1

Geometrical characteristics and exploitation parameters of the main girder

Characteristics / Parameters	Symbol	Value
Height of the girder	H	700 mm
Width of the girder	B	450 mm
Thickness of top/bottom plate	T	8 mm
Thickness of side plates	S1, S2	6 mm
Moment of inertia	Ix	145284 cm^4
Section modulus	Wy	1513 cm^3
Lifting capacity	Q	10 t
Span	L	16.24 m
Lifting height	H	9 m
Wheelbase of the trolley	LM	1450 mm
Number of trolley wheels	–	4, divided 2 per side
Driving class coefficient	γ	1.05
Dynamic coefficient (for speed up to 15 m/min)	ψ	1.15
Bridge acceleration coefficient	ka	0.15
Trolley acceleration coefficient	Kam	0.15
Skewing coefficient	λ	0.17
Material		S235JR
Material parameters		
Elastic modulus	E	2.10 × 10^{11} Pa
Poisson's ratio	ν	0.30
Density	ρ	7850 kg/m^3
Yield strength	fy	235 MPa
Stress$_{allow}$	σ_{allow}	≈ 0.6·fy = 141 MPa

b) *Numerical analysis of the main girder*

The CAD model created in SolidWorks was transferred into ANSYS Workbench [21, 22], and discretized using higher-order quadratic three-dimensional solid elements (SOLID186). The girder is modelled in the numerical simulation as a simply supported beam, with one end vertically fixed and the other axially movable. Cases with the load at mid-span and in the end position were analysed, under nominal and dynamically increased loading (ψ = 1.05; 1.10 and 1.15) [14]. The adopted dynamic coefficients reflect the dynamic effects of load lifting and trolley motion under normal operating conditions. The mesh is denser in the areas where stress concentration is expected, around the supports and the trolley path, as well as coarser in the remaining parts. The model contains 98,786 nodes and 46,504 elements (Figure 3). A mesh density check was performed, where further refinement did not produce stress variations greater than σ < 3%. This confirms that the selected mesh is appropriate. Table 2 shows the stresses and deformations obtained from the static simulations in Ansys.

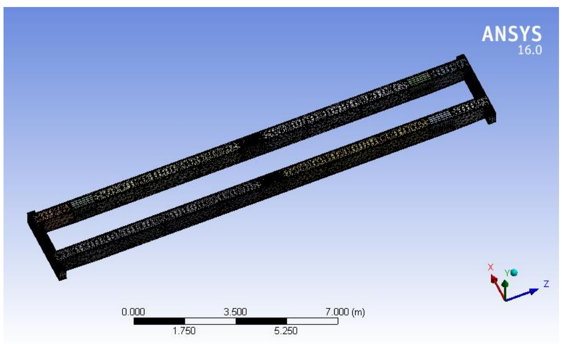


Fig. 3. Mesh

Table 2

Results of the static analysis: stresses and deformations

Case No.	Position of the trolley	Dynamic coefficient	Max stress	Max deformation
1	In the middle	1	155.59 MPa	4.42 mm
2	In the end position	1	117.98 MPa	2.29 mm
3	In the middle	1.05	160.48 MPa	4.57 mm
4	In the end position	1.05	114.34 MPa	2.287 mm
5	In the middle	1.10	180.04 MPa	8.22 mm
6	In the end position	1.10	119.34 MPa	2.36 mm
7	In the middle	1.15	282.73 MPa	8.22 mm
8	In the end position	1.15	125.12 MPa	2.44 mm

4. FAILURE MODE AND EFFECT ANALYSIS – FMEA

The FMEA method is presented in a table [21, 22]. Table 3 contains all elements that are necessary for identifying and evaluating the potential failures of the main girder of the bridge crane. The table is split into two sections, the first section being descriptive and including: identification of the components, the manner in which the component fails, and the main consequence of the failure. With ID, the numbering and decomposition of the potential failures are performed.

The failure mode clarifies how the failure might happen, i.e., what precisely may be the defect in each of the listed components. The following are listed as failure modes:

- *Local yielding at midspan.* – This failure mode is chosen because, based on the analytical and numerical analysis, the midspan is the location where the largest bending moment occurs, and therefore the highest stresses appear [23, 24, 25]. This failure mode is critical because any local yielding directly reduces the girder's ability to support load.
- *Stress concentration near end support.* – In the area of the end supports, according to the Ansys simulations it is noticeable that local high stresses appear, especially due to [26, 27]:

  – eccentric positioning of the trolley,

  – presence of welded joints and diaphragms.

  These effects create local concentrations which often indicate possible crack locations.
- *Excessive vertical deflection.* – Deformations are a key factor in the occurrence of failures. Excessive deformation may lead to [27, 28]:

  – difficulties in the movement of the trolley,

  – occurrence of vibrations,

  – increased fatigue of the structure.

  This mode is included because it does not necessarily cause a direct failure, but it critically affects functionality and safe operation. Results for the deformations that emerge are derived from the numerical simulations.
- *Effects of dynamic amplification*. – Cranes operate under real conditions where the load is never perfectly static. Accelerations, start/stop motions, micro-impacts and oscillations create a dynamic factor $\psi > 1$ [29]. The dynamic effects can significantly increase the stresses, as observed in the results from the numerical simulations.
- *Fatigue crack initiation.* – Bridge cranes operate with a large number of loading cycles. Repeated stresses, even if they are below the yield limit, can eventually initiate fatigue cracks, especially in areas with stress concentration (welds, diaphragms, end connections [30, 31]). Fatigue is one of the most common mechanisms of long-term failure in steel structures.

Main causes. – The factors or conditions that could lead to failure are listed, or the question of why that failure occurred is addressed.

- *High bending stress; dynamic load factor.* – As a cause for the occurrence of local yielding at midspan, it is the maximum bending moment that arises as well as the dynamic factors that additionally increase the stresses in that area [24, 25].
- *Eccentric trolley load; weld geometry*. – As a result of the different positions of the trolley, an uneven distribution of stresses appears. Stress

concentration may occur in areas where welds and geometric changes are present.

- *High service load; insufficient stiffness*. – Lifting larger loads and the structure's lack of stiffness may be the reasons for the main girder's deformations and tilt [28].
- *Sudden trolley movement; impact loads*. – Sudden accelerations, braking, and impact loads create short-duration but very high dynamic stresses. These conditions often lead to extreme structural responses [29].
- *Repeated load cycles; stress concentrations*. – This cause is typical for fatigue damage, because repeated loading cycles initiate cracks in areas with stress concentrations [30, 31].
- *Main consequences*. – This section lists the consequences that appear after the failure, i.e., how the failure affects the further operation and safety of the crane.
- *Loss of stiffness; local plasticity*. – This consequence is selected because local yielding directly leads to a reduction in stiffness and a decrease in the load-carrying capacity of the main girder [23, 24].
- *Local cracking; vibration issues*. – The stress concentration at the ends of the main girders most often results in local cracks and vibrations, which are common signs of early structural damage [26, 27].
- *Serviceability issues; trolley misalignment*. – Excessive deformation makes it difficult for the trolley to move, which directly interferes with safe operation [28].
- *Increased stresses; higher fatigue demand*. – The dynamic effects increase the stress C and accelerate fatigue damage, so this consequence is critical [29].
- *Crack growth; reduced load capacity*. – As loading cycles increase, fatigue-induced cracks grow, which reduces the load-carrying capacity of the entire girder and posesa serious risk of failure [30, 31].

Table 3

Failure mode and effect analysis – FMEA, of the main girder

ID	Failure mode	Main causes	Main effects	S	O	D	RPN
FM1	Local yielding at midspan	High bending stress; dynamic load factor	Loss of stiffness; local plasticity	9	4	4	144
FM2	Stress concentration near end support	Eccentric trolley load; weld geometry	Local cracking; vibration issues	8	4	5	160
FM3	Excessive vertical deflection	High service load; insufficient stiffness	Serviceability issues; trolley misalignment	7	4	3	84
FM4	Dynamic amplification effects	Sudden trolley movement; impact loads	Increased stresses; higher fatigue demand	8	3	6	144
FM5	Fatigue crack initiation	Repeated load cycles; stress concentrations	Crack growth; reduced load capacity	8	3	5	120

In addition to the descriptive assessment, the FMEA also includes a numerical evaluation of each failure mode in order to obtain a quantitative estimation of the risk. For each failure mode, three parameters are assigned: severity (S), occurrence (O), and detectability (D). These parameters are typically ranked on a scale of 1 to 10. Severity represents the consequences of the failure, occurrence reflects the expected frequency of the failure, while detectability evaluates how easily the failure can be identified during inspection. The Risk Priority Number (RPN) is calculated as (1) [32]:

$$RPN = S \cdot O \cdot D \tag{1}$$

A higher RPN indicates a more critical failure mode that requires greater attention, more frequent inspections, or preventive maintenance.

For the crane that is the subject of this study, the S (Severity) consequences if the failure occurs are determined according to:

- how seriously the damage affects safety,
- whether it significantly reduces the load-carrying capacity,

- whether it disrupts serviceability.

According to this,

- S = 9 means very severe consequences (local yielding, loss of stiffness),
- S = 7 means moderately severe consequences (large deformation),
- S = 8 means severe, but not critical consequences (stress concentrations, dynamic effects, fatigue).

The values for Occurrence (O) show how often the failure is expected to appear in real operation.

It is determined based on:

- number of loading cycles (fatigue),
- frequency of dynamic effects,
- trolley position.

So,

- O = 4, moderate likelihood (statically and geometrically induced stresses),
- O = 3, lower likelihood (dynamic effects, fatigue, which occur occasionally but not constantly, which is justified because the crane has been in operation for more than 40 years, implying a high number of accumulated loading cycles.

Detection (D) – the values for Detection show how easily the failure can be identified with common inspection methods. It is determined according to:

- visibility of the damage (plasticity, crack, large deformation),
- accessibility for inspection,
- need for NDT methods.

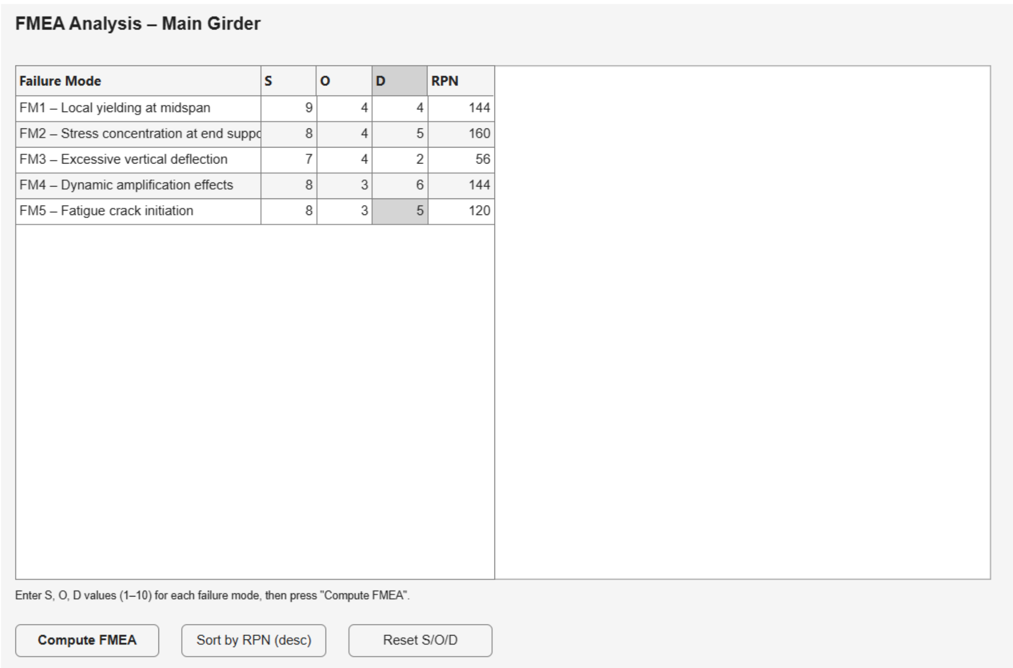
Specifically for this crane:

- D = 3–4 easily noticeable conditions (large deformation, plasticity),
- D = 5 harder to notice (stress concentrations, cracks around welded zones),
- D = 6 low detectability (dynamic effects that require measurement, not visually visible),

Through this approach, the FMEA serves as a link between the numerical analysis and the practical maintenance strategies, supporting informed decision-making aimed at improving reliability and safety during crane operation.

4.1. *Implementation of FMEA in MATLAB*

In the MATLAB implementation of the FMEA procedure, the user provides the three standard FMEA parameters for each identified failure mode: Severity (S), Occurrence (O), and Detection (D). These input values are assigned based on engineering judgement and on the structural indicators obtained from the numerical analyses, including maximum stresses, deformation levels, and the critical regions along the main girder (Figure 4).



Failure Mode	S	O	D	RPN
FM1 – Local yielding at midspan	9	4	4	144
FM2 – Stress concentration at end suppo	8	4	5	160
FM3 – Excessive vertical deflection	7	4	2	56
FM4 – Dynamic amplification effects	8	3	6	144
FM5 – Fatigue crack initiation	8	3	5	120

Fig. 4. MATLAB interface for the FMEA analysis of the main girder

Once the input values are defined, the MATLAB script automatically determines the RPN values for all failure modes and ranks them from the most to the least critical. The program then generates a results table that summarises each failure mode together with its S, O, D, and RPN ratings. In addition to the numerical output, a bar chart is created to visually compare the RPN values and to easily identify the dominant failure mechanisms (Figure 5). Through this automated workflow, the MATLAB tool enables fast, transparent and reproducible evaluation of the FMEA results. The result facilitates decision-making, by indicating the failures modes that call for priority inspection, preventative maintenance, or more structural evaluation.

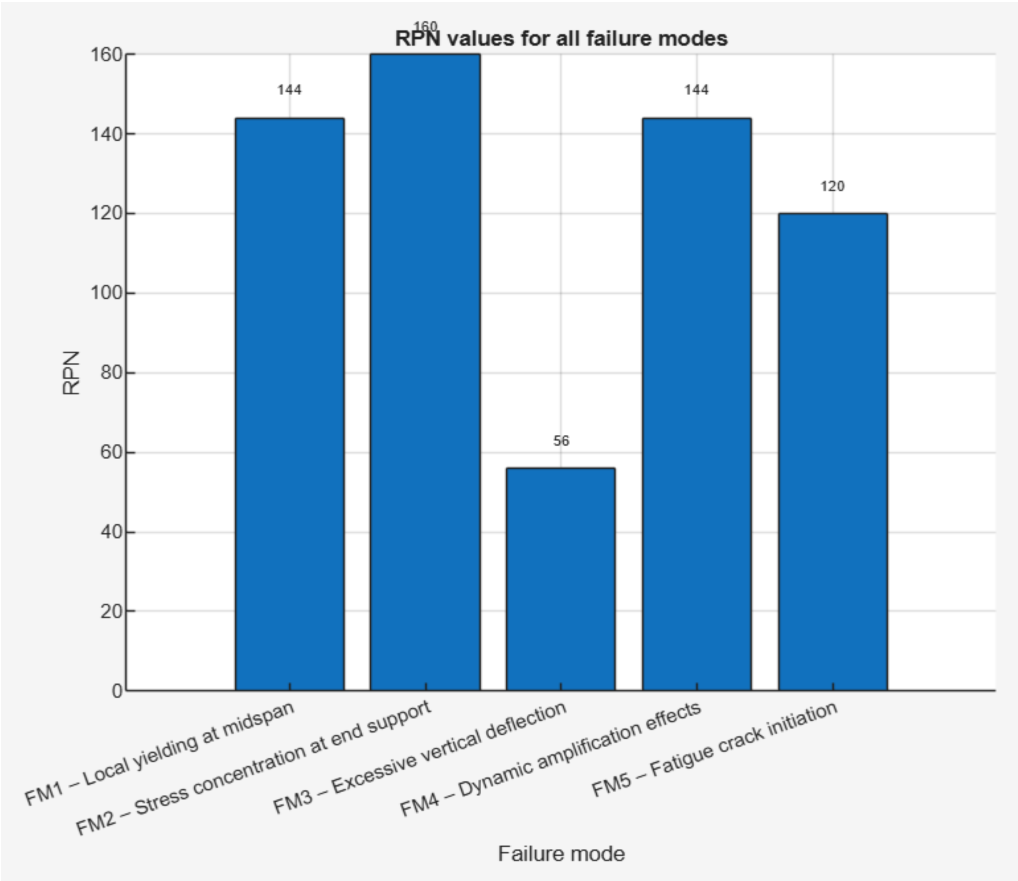


Fig. 5. Graphical representation of the computed RPN values

4. RESULTS AND DISCUSSION

Figure 4 shows the MATLAB interface developed for the FMEA of the crane main girder, where the user inputs the S, O and D ratings for the identified failure modes. Five failure modes were taken into consideration in the reference case: FM1 – local yielding at midspan, FM2 – stress concentration at the end support area, FM3 – excessive vertical deflection, FM4 – dynamic amplification effects, and FM5 – fatigue crack initiation. The initial ratings were assigned based on the numerical results and engineering judgement, considering the stress levels, deformation values, and the likelihood of detecting the damage during inspection. The calculated RPN values are summarized in the table within the interface and are shown graphically in Figure 5. The highest RPN value (RPN = 160) is obtained for FM2 – stress concentration near the end support, indicating that this area is the most critical in terms of severity, occurrence and detectability. This finding is consistent with the numerical simulations that revealed increased stresses and potential stress raisers around the end connections and welds. Local yielding at midspan (FM1) and the response under dynamic amplification effects (FM4) both result in RPN = 144, confirming that the midspan area under dynamic loading is also an important location that requires attention. Fatigue crack initiation (FM5) has a moderate RPN of 120. Although the fatigue life obtained from the numerical analysis is within acceptable limits, the possibility of crack initiation in highly stressed or welded areas should not be disregarded, particularly during long-term cyclic operation. In contrast, excessive vertical deflection (FM3) has the lowest RPN (RPN = 84), which reflects the fact that the calculated deflections remain well below the serviceability limits and can be easily identified by visual inspection or simple measurements.

Overall, the FMEA results indicate that the most relevant risks for the investigated crane girder are related to local stress concentrations and dynamically amplified loading, rather than global stiffness or deflection. The MATLAB tool provides a transparent and adaptable method to update the S, O and D ratings as new inspection data or improved numerical results become available. This facilitates the planning of targeted inspections, strengthening measures, or operational adjustments when necessary and makes it simple to reevaluate the risk ranking.

5. CONCLUSION

The FMEA conducted in this study shows that the most critical risks for the analyzed crane main girder arise from local stress concentrations and dynamically increased loading. This results from the input data acquired through the analytical and numerical analysis. The final FMEA evaluation is presented through a MATLAB tool, which provides a fast and transparent ranking of the failure modes and supports informed decisions regarding inspection and maintenance.

In conclusion, the results confirm that incorporating FEM indicators with the FMEA approach greatly enhances the reliability assessment and contributes to safer and more effective operation of bridge cranes. However, there is still room for improvement in this model. Future work may include the development of advanced MATLAB tools that automatically import FEM results, inspection data, and information from installed sensors. This would enable the parameters and risk level to be updated in real time. The same concept can also be applied to other components of the crane.

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Reviews are submitted at the invitation of the Editorial Board. They should be surveys of the investigations and knowledge of several authors in a given research area. The competency of the authors should be assured by their own published results.

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The article and annexes should be written on A4 paper with margins of 2.5 cm on each side with a standard font Times New Roman 11 points and should be named with the surname of the first author and then if more and numbered. It is strongly recommended that on MS Word 2003 or MS Word 2007 and on PDF files of the manuscript be sent by e-mail:

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A letter must accompany all submissions, clearly indicating the following: title, author(s), corresponding author's name, addres and e-mail addres(es), suggested category of the manuscript and a suggestion of five referees (their names, e-mail and affiliation).

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The papers should be written in the shortest possible way and without unnecessary repetition.

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Only SI (Système Internationale d'Unites) quantities and units are to be used.

Double subscripts and superscripts should be avoided whenever possible. Thus it is better to write $\nu_3(PO_4)$ than $\nu_{3_{PO_4}}$ or exp(–E/RT) than $e^{-E/RT}$. Strokes (/) should not be used instead of parentheses.

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Each paper should contain an **abstract** that should not exceed 150 words, and **3–5 key words**. The abstract should include the purpose of the research, the most important results and conclusions.

The **title**, **abstract** and **key words** should be translated in Macedonian language. The ones written by foreign authors will be translated by the Editorial Board.

In the **introduction** only the most important previous results related to the problem in hand should be briefly reviewed and the aim and importance of the research should be stated.

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Figures (photographs, diagrams and sketches) and **mathematical formulae** should be inserted in the correct place in the manuscript, being horizontally reduced to 8 or 16 cm. The size of the symbols for the physical quantities and units as well as the size of the numbers and letters used in the reduced figures should be comparable with the size of the letters in the main text of the paper. Diagrams and structural formulae should be drawn in such a way (e.g. black Indian ink on white or tracing paper) as to permit high quality reproduction. The use of photographs should be avoided. The tables and the figures should be numbered in Arabic numerals (e.g., Table 1, Figure 1). Tables and figures should be self-contained, i.e. should have captions making them legible without resort to the main text. The presentation of the same results in the form of tables and figures (diagrams) is not permitted. The use of equation editor (MS Word, Microsoft Equation, Math Type 6.0 Equation) for typesetting the equations is recommended. Strokes (/) should not be used instead of parentheses.

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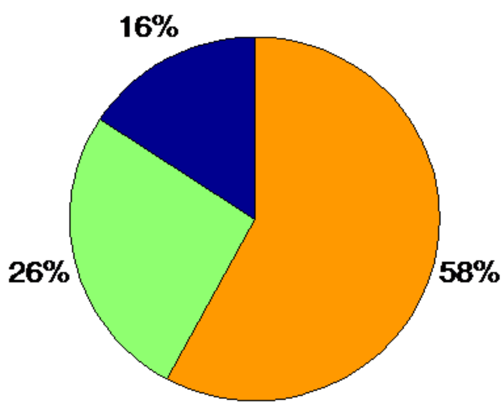

Fig. 1. Example of a graph and a single-line caption (colour)

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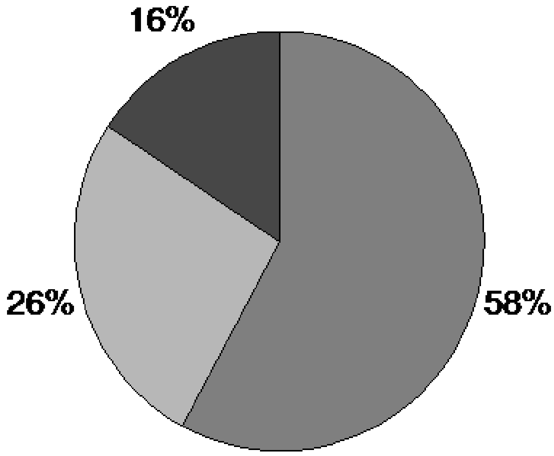

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REFERENCES

[1] Surname, N(ame).; Surname, N(ame). (Year): *Name of the Book*, Publisher.

[2] Surname, N(ame).; Surname, N(ame). (Year): *Name of the Book*, Name of the Series. Publisher, **vol.** XXX.

[3] Surname, N(ame).; Surname N(ame). (Year): Title of the article, *Name of the Journal*, **vol. XX,** No. XX, pp. XXX–XXX.

[4] Surname, N(ame).; Surname N(ame). (Year): Title of the article, *Proceedings of the Name of the Conference,* vol. **XX,** pp. XXX–XXX.

[5] Surname, N(ame).; Surname, N(ame).: *Name of the Patent*, Institution that issued the patent and Number of the patent (Date dd. mm. yyyy).

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[11] Surname, N(ame).: Surname, N(ame). (Year): *Title of the Report*, Organization that issued the report, number of the report.

[12] Institution that issued the standard (Year): *Name of the Standard* & Number of the standard.