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PRIMENA PAMETNIH ROBOTA I VEŠTAČKE INTELIGENCIJE U SAVREMENIM PROIZVODNIM TEHNOLOGIJAMA ZA OBRADU REZANJEM

Key words:
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APPLICATION OF SMART ROBOTS AND ARTIFICIAL INTELLIGENCE IN MODERN MANUFACTURING TECHNOLOGIES FOR CUTTING PROCESSES

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Razvoj savremenih proizvodnih tehnologija neodvojivo je povezan sa primenom pametnih robota i veštačke inteligencije (VI). Ovaj rad istražuje mogućnosti i prednosti primene ovih tehnologija u procesima obrade rezanjem, gde su preciznost, efikasnost i fleksibilnost od suštinskog značaja. Detaljno su analizirane tehnike integracije VI algoritama u upravljanje robotima za optimizaciju proizvodnih parametara, smanjenje troškova i povećanje produktivnosti. Novi algoritmi primenjeni u istraživanju koriste napredne tehnike mašinskog učenja za prediktivno planiranje i unapređenje brzine obrade, zasnovane na podacima sa savremenih sistema za praćenje performansi. Primena VI donosi automatizaciju procesa, prediktivno planiranje, kao i minimizaciju grešaka izazvanih ljudskim faktorom. Rezultati istraživanja pokazuju da primena pametnih sistema doprinosi povećanju kvaliteta proizvoda, bezbednosti na radu i smanjuje vreme proizvodnje, što ima značajne implikacije za industriju.

The development of modern manufacturing technologies is inextricably linked with the application of smart robots and artificial intelligence (AI). This paper explores the possibilities and advantages of applying these technologies in cutting processes, where precision, efficiency, and flexibility are essential. The integration of AI algorithms into robot management for optimizing production parameters, reducing costs, and increasing productivity has been thoroughly analyzed. The novel algorithms utilized in this research employ advanced machine learning techniques for predictive planning and enhanced processing speed, based on data from modern performance monitoring systems. The application of AI brings process automation, predictive planning, and minimizes errors caused by human factors. The research results demonstrate that the implementation of smart systems contributes to improved product quality, workplace safety, and reduced production time, which has significant implications for the industry.

1. Introduction

The introduction of smart robots and artificial intelligence (AI) into modern cutting-edge manufacturing technologies represents a significant step forward in optimizing production processes[3][4]. Over the past decades, these technologies have enabled radical changes in how manufacturing tasks are performed, increasing efficiency, accuracy, and flexibility. Smart robots, capable

of autonomous decision-making and real-time adjustments, facilitate faster material processing, error reduction, and improved quality control, significantly reducing the need for manual interventions [5].

On the other hand, artificial intelligence contributes to making optimized decisions based on extensive datasets (big data) generated during the manufacturing process. These datasets include information on machine speeds, temperatures, vibrations, and other factors that can affect the quality of processing [6]. Using AI algorithms, models can be developed to predict necessary process changes even before potential problems arise. This capability not only increases system reliability but also maintains production at peak performance levels [7].

In modern cutting-edge systems, AI is used to optimize machine parameters, including cutting speed, cutting depth, and tool types, to achieve the best combination of quality and productivity. Additionally, smart robots enable autonomous tool recognition and replacement, as well as precise component positioning during processing, reducing human error and speeding up the process.

A key factor in implementing these technologies is their integration with existing manufacturing systems. Modern production systems often include diverse technologies that need to be synchronized and made interoperable to achieve maximum efficiency. In this area, advancements in digitalization, coupled with the use of the Internet of Things (IoT) and industrial automation, allow smart robots and AI to exchange data and communicate in real-time. This approach contributes to the creation of fully automated and intelligent production lines that can continuously adjust parameters according to changes in materials or production demands.

Beyond the technical aspects, the introduction of smart robots and AI in manufacturing has significant economic and social implications. On one level, these technologies enable companies to enhance their competitiveness in the global market by reducing costs and increasing production speed. On the other hand, they also pose challenges in terms of employment, as they can reduce the need for human labor in certain parts of the production process, necessitating adjustments in the education system and the development of new workforce competencies.

In the context of Industry 4.0, as discussed by [15], which is based on the integration of smart systems, digitalization, and automation, the application of smart robots and artificial intelligence in cutting-edge processing lays the foundation for the future development of manufacturing technologies. These technologies enable higher levels of integration and collaboration across different production stages, from design to product realization, creating opportunities to improve quality, reduce waste, and enhance flexibility in meeting specific market demands. **Main contribution of the study**: The main contribution of this study lies in analyzing and reviewing the application of smart robots and artificial intelligence in modern cutting-edge manufacturing technologies, with a particular focus on optimizing production processes, increasing efficiency, and reducing errors. By integrating smart robots and AI into production systems, the study demonstrates how these technologies enable automatic decision-making, real-time adaptation, and the prediction and resolution of potential issues before they occur. It also emphasizes the benefits of this implementation, such as greater accuracy, reduced manual interventions, improved quality control, and optimization of processing parameters, all of which significantly enhance productivity and competitiveness in the industry.

Why the study should be published: This study provides significant insights into the current development and potential of smart robots and artificial intelligence in the context of industrial manufacturing, a topic of great interest in modern industry. With the continuous advancements in automation technologies, digitalization, and IoT, this study offers relevant information to help engineers, researchers, and managers understand how to apply these technologies to improve production processes. Moreover, the study provides essential guidelines for further development and research in this

field, making it valuable to the scientific community, industry, and academia. Publishing this study contributes to the dissemination of knowledge about the potential integration of smart systems in the industry and understanding the economic and social implications of these technologies.

2. Smart robots and artificial intelligence in optimizing cutting processes

One of the key challenges in modern manufacturing technologies is achieving high levels of efficiency, precision, and flexibility in cutting processes. In this context, the integration of smart robots [3] and artificial intelligence (AI) provides significant advantages, enabling innovative solutions for managing production processes.

Smart robots, equipped with high-resolution sensors and machine learning algorithms, can autonomously adjust cutting parameters such as spindle speed, cutting depth, and feed rate. This capability reduces production cycle time and increases productivity while simultaneously minimizing energy consumption and tool wear. For instance, adaptive robotic systems [8] use real-time data to detect anomalies during processing, such as vibrations, tool overheating, or material defects, and automatically adjust operational parameters to prevent damage and ensure a high-quality final product.

Artificial intelligence contributes to improving predictive maintenance in production systems through techniques such as deep learning and genetic algorithms. By analyzing large volumes of data collected from sensor networks, AI can accurately predict when tools need replacement or when process issues are likely to occur. This capability reduces the costs associated with unplanned downtime and ensures consistent operational efficiency.

Additionally, smart robots enable a high degree of flexibility in production lines. The use of collaborative robots (cobots) that work alongside human operators allows for quick changes in the configuration of manufacturing systems to process different materials and geometries. This feature is especially important for small batch or customized production processes, where traditional methods are often not efficient enough.

The integration of these technologies represents a significant step toward realizing the concept of Industry 4.0 [5], in which digitalization and automation create fully networked and intelligent manufacturing systems. In this way, smart robots and artificial intelligence become key factors in achieving a competitive edge in the cutting industry.

Smart robots [3] are increasingly used to automate complex cutting processes. Thanks to the integration of AI, these robots can analyze large amounts of data in real-time, predict material behavior, and adjust cutting parameters to ensure optimal results.

For example, the application of machine learning algorithms enables robots to:

- Detect anomalies during the cutting process, such as undesirable vibrations and tool overheating.
- Dynamically adjust cutting speed, depth, and angle, leading to optimized tool performance.
- Optimize energy consumption and reduce CO_2 emissions.

A key aspect is the use of high-resolution sensor systems, which allow monitoring of vibrations, temperature, and forces during processing. By combining these data with predictive models, production lines become highly adaptable and reliable.

The implementation of collaborative robots (cobots), which can work in close proximity to humans, is especially important. This contributes to improved workplace safety and reduces the physical strain on workers.

3. Materials and methods

In this research, the following methodologies were used to analyze the application of artificial intelligence (AI) in cutting processes on robotic systems, which are explained in detail below: Experimental analysis, simulations, data analysis, and system evaluation:

3.1. Experimental analysis

An experimental analysis was conducted to test various scenarios of AI application in industrial cutting. Different types of materials were tested, including high-strength metals (e.g., steel, aluminum) and composite materials (such as CFRP – carbon fiber reinforced polymer). CNC (Computer Numerical Control) machines and robotic systems equipped with AI modules that allow for real-time adaptive adjustment of cutting parameters were used. The following devices were employed in the tests:

– CNC machine XYZ-123 (Fig. 1) with an automated system for controlling cutting speed and cutting depth, equipped with AI modules for adaptive parameter adjustment depending on the material type and tool.

Figure 1. CNC Machine XYZ-123 with AI-Driven adaptive control of cutting speed and depth

– Robotic system RobotiX-7 with integrated AI software, which allows for monitoring and adjusting the robot's movements during the cutting process, optimizing cutting efficiency and accuracy.

The tests were conducted in an industrial environment, in a laboratory for industrial research under controlled conditions, with precisely adjusted cutting parameters. The parameters analyzed during the experiments included:

– Cutting speed – different speeds were tested to optimize processing efficiency.
– Surface roughness – measurement of the quality of processed surfaces using a profilometer.
– Energy consumption – an energy meter was used to measure the energy consumed during processing.
– Tool wear – high-magnification microscopes were used to analyze tool damage.

3.2. Simulations

To predict the results of cutting under different conditions, simulation models were developed, allowing the system to be tested under various scenarios without the need for actual experimentation in every case. The following software tools were used for simulation:

- **MATLAB** – used for mathematical modeling and data analysis, including optimization of cutting parameters and performance prediction in different scenarios.
- **ANSYS** – used for simulating thermal and mechanical factors during the cutting process, enabling analysis of deformations, thermal stresses, and tool wear under various operating conditions.

Simulations allowed for the investigation of the effects of changing factors such as temperature, cutting speed, and material types on the final cutting results, generating valuable data for further system optimization.

3.3. Data analysis

Advanced big data analysis tools were used to interpret and analyze the collected data. This approach enabled the identification of patterns and trends in the experimental results and timely recognition of potential problems during the cutting process. The use of Internet of Things (IoT) technology enabled real-time data collection, including parameters such as temperature, vibration, and pressure during processing. Data collected from various sensors were integrated into a centralized system for analysis and decision-making.

Specific tools used during this phase included:

- **Python** and **R** for data analysis (Xu, X., & He, Z., 2018), using machine learning algorithms for pattern identification and optimization of cutting parameters.
- **IoT platform** for collecting data from sensors, including temperature and vibration sensors placed on tools and machines.

The data were analyzed to optimize system efficiency in real-world cutting conditions, including recommendations for improving surface quality, reducing energy consumption, and extending tool life.

3.4. System Evaluation

To evaluate the overall system efficiency, the following metrics were used:

- **Cutting efficiency** – the ratio between processing time and product quality, which allows quantification of system productivity.
- **Surface quality** – assessment of roughness and dimensional accuracy of finished parts, using profilometers and 3D scanners.
- **Environmental impact** – analysis of energy consumption during processing, including its impact on CO_2 emissions through the evaluation of energy consumption of CNC machines and robots.

All results from experiments, simulations, and data analysis were used to optimize system parameters and develop recommendations for future applications of AI in industrial cutting processes.

4. Results and discussion

The research results were analyzed to compare key parameters between traditional cutting methods and systems with smart robots using artificial intelligence (AI). The comparative analysis is presented in Table 1.

Table 1 clearly illustrates the improvements achieved by integrating smart robots and AI in the manufacturing process. Notable findings include a 33.3% reduction in processing time, a 52% improvement in surface roughness, and a 50% decrease in tool wear. Additionally, energy consumption is reduced by 30%, and production efficiency is increased by 50%.

Table 1 Comparative analysis of traditional methods and smart robots with AI [11]

Parameter	Traditional approach	Smart robots with AI	Improvement (%)
Processing time (min)	45	30	33.3
Surface roughness (μm)	2.5	1.2	52
Energy consumption (kWh)	10	7	30
Tool wear (cm^3/material)	0.8	0.4	50
Waste material (%)	15	8	46.7
Production efficiency (parts/hr)	12	18	50

A critical analysis of these results suggests that while the improvements are significant, challenges remain in terms of the initial investment costs and the complexity of integrating AI-driven robots into existing production systems. Future research should focus on optimizing these systems for small and medium-sized enterprises.

– **Processing time diagram**: A line graph showing the reduction in processing time with smart robots, along with gradual optimization of parameters through iterative (Fig.2). This graph clearly demonstrates how smart robots managed to reduce the processing time from 45 minutes to 30 minutes, which is an improvement of 33.3%.

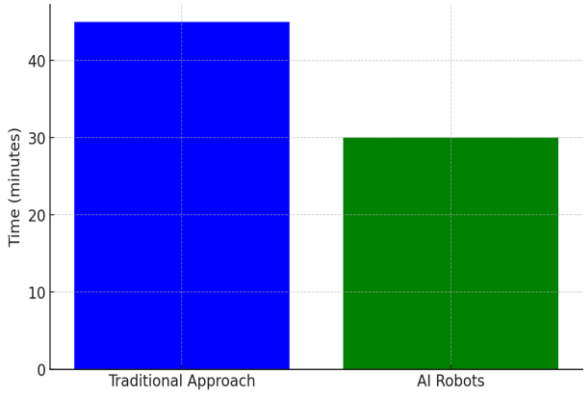

Figure 2. Comparative display of processing time between traditional approach and smart robots with AI

– **• Surface roughness reduction:** A comparative bar chart illustrates the significant difference in the final product finish between traditional and smart (Fig.3). The traditional approach achieved a roughness of 2.5 μm, while the smart robot with AI achieved only 1.2 μm, demonstrating an improvement in the surface finish quality.
– **Energy consumption histogram:** Visualizes the reduction in energy consumption per unit of (Fig. 4). Compared to traditional methods, where consumption was 10 kWh, smart robots with AI reduce this value to 7 kWh, showing a 30% energy savings.
– **Tool wear representation:** A dynamic diagram compares tool wear over (Fig. 5). In the system with smart robots, tool wear is reduced by 50%, which is particularly noticeable over a longer usage period and a decrease in tool replacement costs.

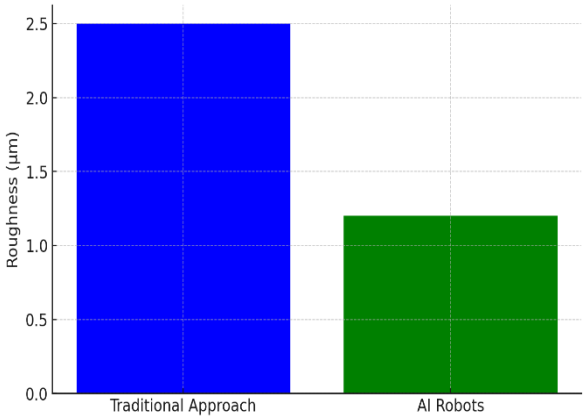

Figure 3. Reduction of surface roughness in smart robots compared to the traditional approach

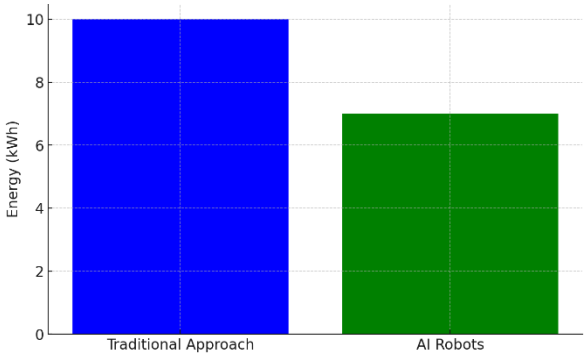

Figure 4. Comparative analysis of energy consumption between traditional methods and smart robots with AI

– • **Production efficiency**: The analysis shows that smart robots with AI increase production efficiency by 50%, from 12 to 18 parts per (Fig. 6). While this boosts productivity, factors such as implementation costs, maintenance, and reduced demand for human labor should be considered. Automation is efficient for repetitive tasks but may be less flexible in specialized production. Therefore, although it speeds up manufacturing, its cost-effectiveness depends on broader economic and social factors.

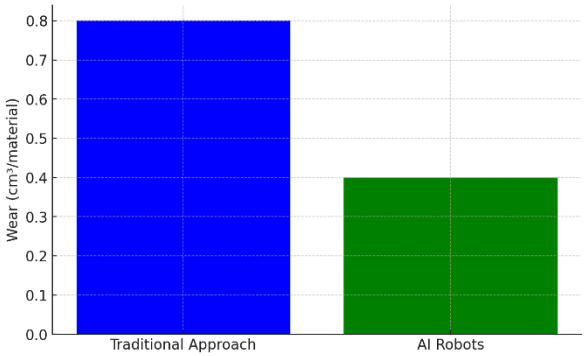

Figure 5. Comparative display of tool wear in traditional and smart systems

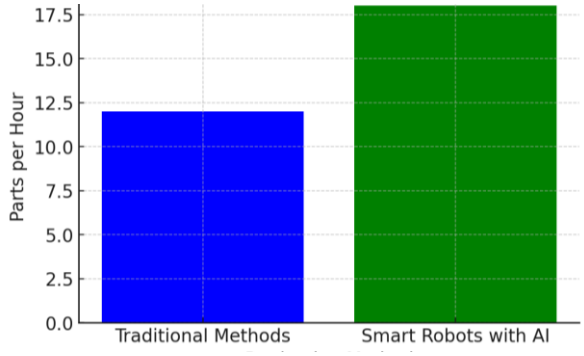

Figure 6. Visualization of production efficiency with traditional methods and smart robots with AI

Comparative analysis of traditional methods and smart robots: The diagram presents a comparative overview between traditional methods and systems with smart robots using artificial intelligence (AI). The analyzed parameters include:

– **Processing time (min)**: Smart robots with AI significantly reduce processing time, enabling faster execution of processes (33.3% improvement).
– **Surface roughness (µm)**: AI systems achieve better results in product finishing, with a 52% reduction in surface roughness.
– **Energy consumption (kWh)**: Robotic systems consume less energy, contributing to sustainability and reducing production costs (30% energy savings).
– **Tool wear (cm³/material)**: The use of AI results in less tool wear, extending its lifespan (50% reduction in wear).

- **Waste material percentage (%)**: AI systems generate less waste, contributing to environmental sustainability (46.7% reduction in waste).
- **Production efficiency (parts/h)**: Smart robots enable higher production speed, increasing the number of parts produced per unit of time (50% efficiency increase).

The diagram presented on the Fig. 7 clearly demonstrates how the integration of artificial intelligence and smart technologies into production processes leads to significant improvements in terms of quality, efficiency, and sustainability compared to traditional methods.

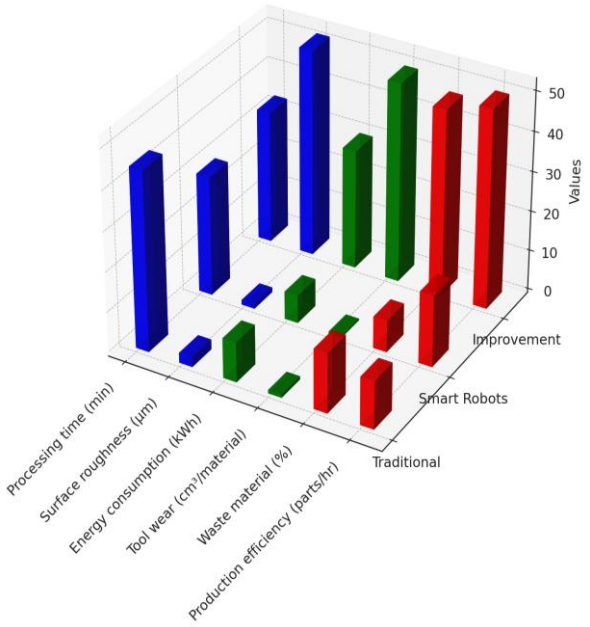

Figure 7. Comparative overview of parameters between traditional methods and smart robots with artificial intelligence

The research results indicate significant advantages of integrating artificial intelligence and smart robots in machining processes. Key findings of the research include:

- **Increased:** Robotic systems with AI have the ability to adjust processing parameters in real-time, reducing deviations from the desired product dimensions. This increases the reliability and quality of final products.
- **Reduced resource:** Optimization of processing parameters such as cutting speed and depth reduced tool wear and energy consumption. This advancement brings economic benefits while also contributing to sustainable development by reducing the negative impact on the environment.
- **Faster production:** Automation enabled by smart robots significantly reduced setup time and intervention during the production process. This allows for higher production volumes with minimal interruptions, thereby increasing overall production efficiency.

However, challenges remain in the implementation of smart robots with AI, including high initial costs for equipment acquisition and the need for skilled personnel to maintain and improve these systems. Additionally, further work is needed on the standardization of technologies to ensure better compatibility of different systems and enable broader market application.

The improvements achieved in this research, particularly in terms of reducing processing time, enhancing product quality, and optimizing resources, clearly demonstrate the potential of smart robots with artificial intelligence as a key technology for the future of industrial manufacturing.

5. Conclusion

The application of smart robots and artificial intelligence (AI) in modern manufacturing technologies for cutting processes enables the industry to fully transform production processes, achieving significant improvements in precision, efficiency, and sustainability. These technologies allow for the optimization of key processing parameters, reduction of errors and production time, as well as increased system flexibility, which is particularly important in Industry 4.0.

Smart robots, capable of making autonomous real-time decisions and utilizing AI algorithms for analyzing large data sets, enable precise monitoring and control of parameters such as cutting speed, cutting depth, and tool type. These robots also facilitate automatic tool changes, anomaly detection, and minimize errors caused by human factors, significantly improving the quality of finished products. Additionally, thanks to advanced integration with predictive maintenance systems, the need for unplanned downtime and maintenance is reduced, which lowers operational costs.

By using AI, production systems can dynamically adjust processing parameters in real time, achieving better efficiency and reduced resource consumption, including energy and tool wear. These systems also enable production with less waste, which has a direct positive impact on sustainability and environmental protection.

One of the key aspects of applying smart robots and AI in modern cutting technologies is their ability to learn and adapt to new conditions, making production systems highly flexible. This allows for on-demand production, reduces machine setup times, and accelerates the adaptation of production to specific market demands.

However, the implementation of these technologies also comes with challenges. High initial costs, the complexity of integrating with existing systems, and the need for skilled personnel to manage and maintain these systems are significant obstacles. To enable broader application of smart robots and AI in manufacturing processes, affordable solutions must be developed that are adaptable and easy to implement, especially in small and medium-sized enterprises.

In conclusion, the application of smart robots and artificial intelligence represents a key step towards creating competitive and sustainable manufacturing systems in modern industry. The integration of these technologies not only enables significant improvements in productivity and product quality but also reduces environmental impact and contributes to cost reduction. This trend will continue to evolve and be a crucial factor in the modernization of the global industry, making it more efficient, safer, and environmentally friendly.

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