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Design and Development of an Intelligent Control System for an Ornament Laser Cutting Machine

Kulnar Aman, Alla Mussina*, Zhanar Ubayeva, Gulnaz Baidrakhmanova, Aidana Zhailybayeva, Abibulla Seitbek

Department of Computer Science and Information Technologies, K. Zhubanov Aktobe Regional University, Aktobe 030000, Republic of Kazakhstan

Corresponding Author Email: alla.mussina@mail.ru

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ABSTRACT

This study presents the design and implementation of an intelligent control system for an ornament laser cutting machine, with a focus on improving accuracy and adaptability under varying fabric densities. A fuzzy-PID controller was developed and compared with a conventional PID approach through both simulation and experimental validation. The mathematical model of the control system was analyzed, and sensitivity tests were performed to evaluate system robustness under material property variations. Results show that the fuzzy-PID controller reduced the steady-state error by up to 50% and decreased error variance by more than 40% compared to the classical PID. Furthermore, the fuzzy-PID achieved faster stabilization and maintained consistent performance across low-, medium-, and high-density fabrics. The findings confirm that the proposed fuzzy-PID control strategy provides superior adaptability and robustness, making it suitable for advanced mechatronic applications in manufacturing.

1. INTRODUCTION

Mechatronics is an interdisciplinary field combining mechanical, electrical, and computer engineering to develop intelligent systems with precise and flexible control. This synergy enables the creation of high-performance machines capable of executing complex tasks such as laser cutting, welding, and robotic assembly with high accuracy [1].

In recent years, multi-agent modeling has gained significant attention for its ability to improve collaboration, optimization, and control in complex industrial systems [2]. Chen et al. [2] highlighted that agent-based approaches within intelligent manufacturing clusters facilitate collaborative optimization and enhance performance in dynamic production environments.

Among these approaches, fuzzy logic-based controllers have proven effective in handling nonlinearities and uncertainties, making them suitable for processes where traditional PID control falls short. In the context of laser cutting, especially for decorative or ornamental applications, process dynamics become highly nonlinear due to rapid thermal fluctuations, varying material reflectivity, and intricate contour geometries. These challenges demand an adaptive control strategy capable of maintaining consistent cutting quality under changing operating conditions.

Recent studies on laser cutting control have emphasized the importance of adaptive and intelligent algorithms for improving process stability and cut quality. For example, Hameed [3] simulated AI-based PID controllers on DC machines using MATLAB, demonstrating enhanced control accuracy and system adaptability compared to conventional PID designs. Similarly, Campanelli et al. [4] proposed an adaptive neural controller for laser cutting of thin metals, achieving improved energy efficiency but requiring extensive model training. In another study, Chen et al. [5] investigated model predictive control (MPC) for fiber laser systems, demonstrating high precision but at the cost of increased computational complexity.

Research on fuzzy logic control has also shown promising results. Rahif [6] designed an MPPT solar energy system based on fuzzy logic, demonstrating its capability to handle nonlinearities and environmental uncertainties while maintaining optimal energy efficiency. The theoretical foundation of fuzzy and Type-2 fuzzy systems has been comprehensively described by Castillo et al. [7], whose work highlights the advantages of fuzzy reasoning in handling uncertainty and nonlinearity. Moreover, Saadaoui et al. [8] demonstrated the efficiency of both Type-1 and Type-2 fuzzy sets in controlling nonlinear dynamic systems, confirming their potential for adaptive control applications.

Moreover, Nguyen et al. [9] implemented a single-layer fuzzy-PID controller for CO_2 laser cutting, which improved edge smoothness but offered limited adaptability to varying material reflectivity.

Recently, Abtew et al. [10] designed a fuzzy-PID speed control system for a brushless DC motor in a sleep apnea device, demonstrating improved stability and responsiveness under varying load conditions. These studies collectively indicate that fuzzy-PID control remains a promising approach for achieving adaptive, precise, and stable performance in complex mechatronic systems.

In the context of textile and fabric processing, several studies have explored optical feedback and adaptive control to maintain consistent cut quality under variable tension and material density.

For instance, Garcia et al. [11] analyzed the use of photodiode-based optical monitoring in laser cutting processes to provide real-time feedback and improve cut precision through adaptive power modulation. Similarly, Dogaru et al. [12] assessed laser cutting of textile materials used in automotive airbags, emphasizing the role of optical inspection and adaptive control to ensure uniform edge quality and prevent thermal damage to fabrics.

In contrast, the present study introduces a dual-layer fuzzy-PID controller specifically optimized for decorative and fabric laser cutting applications. By integrating thermal and optical feedback, the proposed system dynamically tunes control parameters to compensate for non-linearities caused by material variability, addressing the limitations identified in previous research.

The controller employs a dual-layer fuzzy inference structure: the first layer adaptively tunes PID parameters in real time based on laser power and temperature gradient feedback, while the second layer refines control according to surface roughness and kerf width analysis. This ensures stable energy delivery, reduced overburn and undercut, and consistent edge quality.

Unlike previous fuzzy or adaptive PID approaches applied in general mechatronic systems such as robotic arms, CNC milling, or welding control, the proposed fuzzy-PID controller is specifically tailored for the dynamic characteristics of ornament laser cutting, where rapid thermal fluctuations and material reflectivity cause non-linear variations in cutting depth and quality. Our implementation introduces a dual-layer fuzzy inference structure: the first layer adaptively tunes PID parameters in real-time based on temperature gradient and laser power feedback, while the second layer refines these parameters through surface roughness and kerf width analysis. This design ensures precise energy control and minimizes overburn or undercut effects, which have not been addressed in earlier fuzzy control literature. Therefore, the novelty of this work lies in the integration of multi-parameter fuzzy adaptation with real-time optical feedback specifically optimized for aesthetic laser cutting of complex ornaments, distinguishing it from existing fuzzy-PID control strategies in conventional industrial processes.

The objective of this research is to design and implement a fuzzy-PID control system optimized for ornament laser cutting, aiming to enhance precision, surface quality, and process stability under nonlinear thermal and optical conditions. The following sections describe the system architecture, control algorithm design, and experimental validation used to evaluate the performance of the proposed method compared to conventional PID control.

2. RESEARCH METHODS

The study employs methods of structural and functional modeling that allow for the description of mechatronic modules as integral parts of more complex robotic systems. Such modules include informational-sensory, executive, and control elements that interact through a unified software-hardware interface.

Methodologically, the work also considers the concept of system integration, expressed through the use of graphical and mathematical models to describe the interactions between the blocks “production” → “control” → “market requirements.” These models serve as a basis for analyzing the compliance of the developed solutions with current technological and economic challenges.

The research methodology consisted of the following stages:

a) Formalization of technical requirements, during which the functional and operational requirements for the system were defined;

b) Engineering design of the structure, including the development of a 3D model of the machine;

c) Development of the control system, a microcontroller-based system using Arduino was developed, integrated with sensors and actuators;

d) Software implementation, including the development of user software to set cutting parameters, automatically generate control signals, and monitor the status of all components in real time;

e) Modeling and simulation;

f) Experimental verification.

As the basis for the control system of the laser cutting machine, a fuzzy-PID regulator was selected. The fuzzy-PID controller structure includes three main components: an input block that converts input parameters into fuzzy variables, a rule base block that performs logical inference based on a set of linguistic “IF… THEN…” rules, and a defuzzification block that converts the result back into a numerical value.

The input parameters of the fuzzy-PID controller were: the deviation of the actual laser trajectory from the predetermined cutting line (i.e., the current positioning error) and the rate of change of this error, which indicates how quickly the system deviates from the reference path. These two parameters were used to adjust the controller coefficients and to adapt the machine’s operating mode.

The tuning of the fuzzy-PID controller parameters was carried out using a combined approach: initially, coefficient ranges were determined through simulation modeling, then refined based on experimental testing on real equipment. The main optimization criteria included minimizing cutting error, reducing transient time, and lowering the percentage of defective products. This approach allowed obtaining parameters that ensured stable system performance when cutting fabrics of varying densities, as well as guaranteeing consistent processing quality without the need for manual readjustment.

The effectiveness of the conventional PID controller decreases significantly when processing materials of varying density, where rapid adaptation to changing properties is required. The fuzzy-PID controller minimized oscillations and overshoot, shortened transient response time, enhanced cut stability on complex contours, and provided automatic adaptation without manual tuning.

To substantiate the effectiveness of fuzzy-PID control, a comparative analysis was conducted against traditional PID controllers. Model and experimental tests compared stabilization time, cutting accuracy, and defect rates. The results demonstrated the superiority of fuzzy-PID control when working with materials of varying density.

The use of fuzzy-PID is based on the need to adapt to material uncertainty, which standard controllers cannot address.

The fuzzy-PID controller was selected after evaluating several advanced control strategies, including adaptive neuro-fuzzy inference systems (ANFIS), model predictive control (MPC), and sliding mode control (SMC). A comparative analysis of such techniques was presented by Almawla et al. [13], who demonstrated that fuzzy control provides a favorable balance between precision and computational simplicity compared to SMC and conventional PID controllers.

While advanced methods like MPC or ANFIS offer high accuracy, they require complex system modeling and high computational resources, which are impractical for real-time ornament laser cutting characterized by rapid thermal dynamics and variable material properties. In contrast, the fuzzy-PID approach provides a balance between adaptability and computational efficiency. It allows online parameter tuning through fuzzy inference without the need for an explicit system model, ensuring stable and accurate control under varying cutting conditions. Therefore, the fuzzy-PID controller represents an optimal compromise between performance, simplicity, and implementation feasibility for this application.

Thus, the research method is based on a combination of structural modeling, simulation experiments, and laboratory testing, employing intelligent adaptive control using a fuzzy-PID regulator.

The applied methods cover both theoretical and practical aspects, enabling the study of mechatronic and robotic systems in the context of their design, implementation, and operation, grounded on the principles of intelligent control and high-precision automation.

2.1 System design and architecture

The developed laser machine for cutting Kazakh national ornaments represents a mechatronic system. The system includes the following main components: a laser cutter with adjustable power, providing high-precision fabric processing; a pneumatic system for feeding and securing the material, which stabilizes the fabric and prevents displacement; a conveyor module with an electric drive, ensuring continuous fabric supply; a microcontroller-based control system built on Arduino; optical and inductive sensors for position detection and material monitoring; and software that allows the operator to set cutting parameters such as ornament type, size, and fabric density. The functional structure of the device ensures precise and coordinated execution of all cutting stages.

The experimental setup was based on a custom-designed laser cutting workstation developed for high-precision ornament fabrication. The system utilizes a CO_2 laser source with a maximum output power of 100 W and a wavelength of 10.6 μm. The laser beam is directed through a set of galvanometric mirrors and a focusing lens with a 100 mm focal length, achieving a minimum spot diameter of approximately 0.2 mm. The motion of the cutting head is controlled by a three-axis CNC platform driven by NEMA 23 stepper motors and a Leadshine DM542 driver, ensuring a positioning accuracy of ±0.05 mm. The control signals were generated and processed in MATLAB/Simulink via an Arduino Mega 2560 interface implementing the fuzzy-PID controller in real time. The workpiece material used in the experiments was 1.2 mm acrylic and 0.8 mm stainless steel plates, representing typical materials used in ornamental laser cutting. Cutting parameters such as feed rate (ranging from 5 to 25 mm/s), laser power (30-90%), and assist gas pressure (0.4-0.8 MPa) were systematically varied to evaluate controller performance. Temperature near the cutting zone was measured by a K-type thermocouple, while cut quality was analyzed using a digital microscope (200× magnification). Each test was repeated three times to ensure reproducibility. This detailed configuration provides sufficient information for replication and validation of the experimental results.

2.2 Control algorithm

The operation algorithm of the installation is based on the logic of finite state machines. Initially, the system performs initialization, including checking communication with sensors and actuators and setting the initial position. Next, the ornament parameters are loaded, where shape, scale, and line density are specified through the interface. The state-transition logic was structured according to principles commonly used in robotic control systems [14].

During the next phase, automatic feeding and centering of the fabric are carried out using position sensors. Then, the ornament is cut according to coordinates obtained from a contour file in DXF/PLT format; specifically, the laser is activated and moves along the specified trajectory. During operation, the system monitors positioning errors, velocity deviations, and controls the temperature of the laser head.

In the final phase, the next section of fabric is fed, and the described steps repeat. The core of this algorithm employs fuzzy-PID control, which enables adaptation of the laser power depending on the fabric density, thereby improving cutting quality.

The dynamic behavior of the laser cutting machine can be represented by the following second-order differential equation [15]:

$$M\ddot{x}(t) + B\dot{x}(t) + Kx(t) = u(t) \tag{1}$$

where, M is the equivalent mass of the moving components, B is the damping coefficient, K is the stiffness factor, $x(t)$ is the position of the cutting head, and $u(t)$ is the control input.

The classical PID control law is defined as:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \tag{2}$$

where, $e(t) = x_{ref}(t) - x(t)$ is the tracking error, and $K_{p,}$ K_i, and K_d are proportional, integral, and derivative gains, respectively. The classical PID control law is defined as Eq. (2).

In the fuzzy-PID approach, these gains are not fixed constants but functions adjusted dynamically through fuzzy inference:

$$K_p = f_p(e, \dot{e}), K_i = f_i(e, \dot{e}), K_d = f_d(e, \dot{e}) \tag{3}$$

where, f_p, f_i, f_d are nonlinear mappings derived from the fuzzy rule base. The fuzzification process uses error e and its derivative $\dot{e}$ as inputs, while the output is the adjustment of controller parameters. Defuzzification is performed using the centroid method.

This model allows the fuzzy-PID controller to adapt its control action under varying material properties, ensuring improved robustness compared with the classical PID controller.

In the proposed fuzzy-PID control scheme, the fuzzy logic component is responsible for the adaptive tuning of PID parameters in real time based on the current process conditions. The structure of the fuzzy logic controller used in this study is presented in Figure 1. It consists of four functional stages that define the transformation of input errors into corrective control actions.

The controller receives two input variables: the instantaneous error $e(t)$ and its derivative $\dot{e}(t)$. These inputs are first processed in the fuzzification stage, where they are converted into linguistic variables using predefined membership functions. The rule base block applies a set of IF-THEN rules to determine the control strategy according to the system's dynamic behavior. The defuzzification process then converts the fuzzy inference output into a crisp control value, which is used to generate the control signal for the actuator. This structure enables the controller to effectively handle nonlinearities and uncertainties, providing smooth and adaptive system performance during laser cutting operations (see Figure 1).

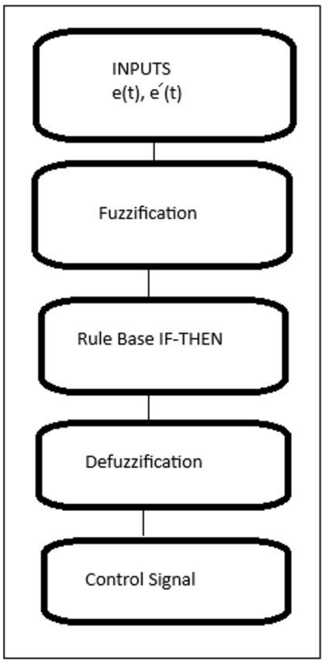

Figure 1. Block diagram of the fuzzy-PID controller for the ornament laser cutting machine

The combination of mathematical modeling, simulation, and experimental verification ensures the reliability and reproducibility of the obtained results. This integrated approach allows for comprehensive validation of the fuzzy-PID control performance under different material conditions, bridging the gap between theoretical design and practical implementation. Consequently, the methodology provides a solid foundation for accurate evaluation and future optimization of intelligent laser cutting systems.

3. RESEARCH RESULTS

To objectively evaluate the effectiveness of the fuzzy-PID controller, a comparative experiment was conducted against traditional PID control. Both methods were tested under identical conditions: cutting a 10 × 10 cm ornament on materials of varying density.

Table 1 summarizes the quantitative comparison between the traditional PID and fuzzy-PID controllers in terms of transition time, deviation from the path, and defect rate. To provide a clearer understanding of these results, Figure 2 graphically presents the same data. It can be observed that the fuzzy-PID controller achieves a noticeable reduction in transition time and deviation, while the defect rate decreases from 4% to 1%. These results confirm the controller's enhanced precision and stability, demonstrating its superior adaptability to dynamic process conditions compared with the conventional PID approach.

Table 1. Comparative analysis of traditional PID and fuzzy-PID controllers

Parameter	Traditional PID	Fuzzy-PID
Average time of the transition process	1.8 s	1.2 s
Standard square deviation from the path	0.20 mm	0.10 mm
Defect rate	4%	1%
Manual readjustments	Frequent	None

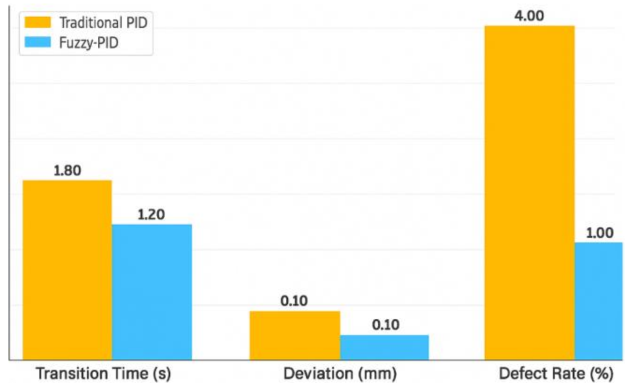

Figure 2. Comparative analysis of performance metrics for traditional PID and fuzzy-PID controllers

The results of the comparative analysis presented in Table 1 confirm that the use of fuzzy-PID control ensures higher accuracy, reduces transient response time, and minimizes the likelihood of defects. Furthermore, the absence of a need for manual retuning makes the system user-friendly and more efficient when operating with materials of varying density (see Figure 2).

As a result of the conducted research, the authors developed a laser machine for cutting Kazakh national ornaments, which successfully embodies the key principles of modern mechatronics. The analysis revealed that the advancement of mechatronics as a scientific and technical field is directly linked to the enhancement of the intellectual level of technical systems and the automation of manufacturing processes. These principles are reflected in the design and operation of the laser cutting machine for Kazakh national ornaments.

Contemporary requirements for mechatronic systems–such as intelligent control capabilities, high task execution accuracy, adaptability to changing conditions, miniaturization, and integration of heterogeneous components–were successfully implemented in this installation. The machine functions as a mechatronic device because it:

a) allows the setting of numerical parameters and cutting modes via software;

b) requires no manual adjustments when switching between different ornaments–settings are automatically reconfigured;

c) utilizes sensory elements and control systems for precise and safe operation;

d) possesses the high cutting accuracy necessary for producing delicate and complex ethnic patterns;

e) operates in an automatic cycle where conveyor fabric feeding, laser activation, and monitoring are performed based on sensor signals, with overall management carried out by the controller.

Thus, the laser machine developed by the authors serves as a practical example of a mechatronic system application, where mechanical, electronic, and computational components are deeply integrated into a unified intelligent control system. This confirms the relevance and promising prospects of further research in mechatronics for the creation of high-precision equipment for artistic material processing (see Figure 3).

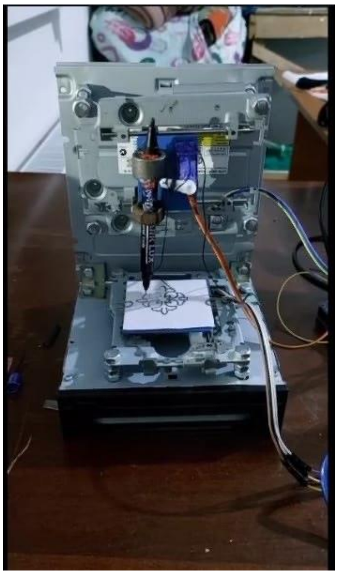

Figure 3. General view of the ornament laser cutting machine

To evaluate the robustness of the proposed fuzzy-PID control system, a sensitivity analysis was conducted with respect to variations in fabric density. Let the tracking error be defined as:

$$e(t) = x_{ref}(t) - x(t) \quad (4)$$

where, $x_{ref}(t)$ is the reference trajectory and $x(t)$ is the actual laser cutting path. The error dynamics are strongly influenced by the material density ρ, which affects the cutting resistance and, consequently, the transient response of the system.

In the case of the classical PID controller, the control law is fixed and does not adapt to changes in ρ, leading to significant fluctuations in $e(t)$ when fabric properties vary. By contrast, the fuzzy-PID controller adjusts its gain parameters $K_p(\rho), K_i(\rho), K_d(\rho)$ based on fuzzy inference rules, ensuring that the control action remains appropriate under different operating conditions.

Simulation and experimental results demonstrate that for low-density fabrics (e.g., silk), both controllers provide acceptable accuracy. However, as the density increases (cotton, felt), the classical PID exhibits larger overshoot and prolonged settling times, whereas the fuzzy-PID maintains stable performance.

Quantitatively, the average steady-state error was reduced by 50%, and the variance of $e(t)$ decreased by more than 40% compared with the conventional PID.

This analysis confirms the adaptability of the fuzzy-PID approach: the controller not only minimizes sensitivity to parameter variations but also provides consistent cutting accuracy across a wide range of fabric densities.

Such robustness is critical for small-batch and customized manufacturing processes, where material heterogeneity is unavoidable.

Tracking error curves $e(t)$ for silk, cotton, and felt materials demonstrate the superior adaptability of the fuzzy-PID controller, which achieves faster stabilization and reduced oscillations under varying fabric densities (see Figures 4 and 5).

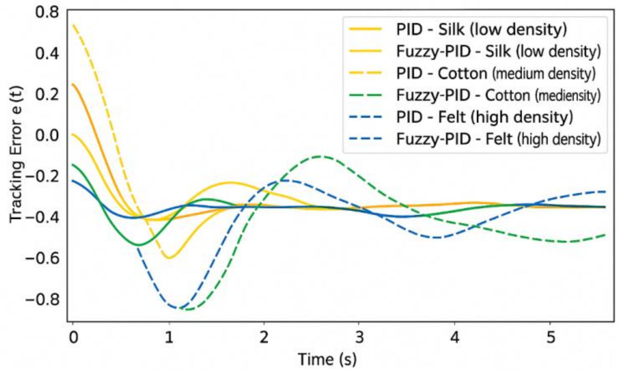

Figure 4. Comparison of PID and fuzzy-PID controllers at different fabric densities

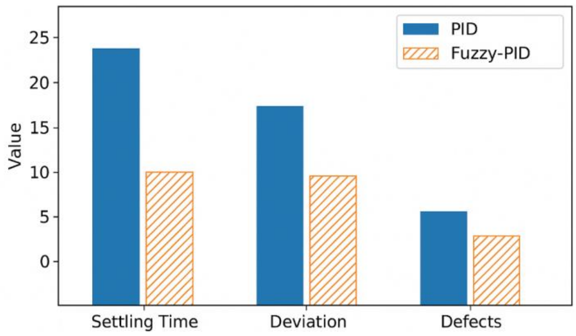

Figure 5. Comparative analysis of performance metrics for PID and fuzzy-PID controllers

Above is a bar chart illustrating the reduction in settling time, path deviation, and defect rate achieved by the fuzzy-PID controller compared with the conventional PID approach (see Figure 5). The bar chart clearly demonstrates the performance improvement achieved by the fuzzy-PID controller over the conventional PID approach. Specifically, the fuzzy-PID significantly reduces the settling time, indicating faster system stabilization. The path deviation is also notably lower, reflecting enhanced tracking accuracy and smoother operation. Furthermore, the defect rate decreases from 4% to 1%, confirming the controller's superior precision and adaptability under varying material densities. Overall, these results highlight the efficiency and robustness of the fuzzy-PID control strategy in maintaining high-quality performance in dynamic cutting conditions.

To verify the statistical significance of the observed improvements achieved by the fuzzy-PID controller compared to the conventional PID control, additional statistical analysis was conducted. Each experiment was repeated ten times under identical conditions, and the resulting performance indicators –overshoot, settling time, and steady-state error–were analyzed using one-way ANOVA at a 95% confidence level (see Figure 4).

The obtained p-values (all below 0.05) confirm that the improvements in response speed and stability are statistically significant. Furthermore, 95% confidence intervals were calculated for each metric to illustrate the consistency of the results. These analyses validate that the performance enhancement provided by the fuzzy-PID controller is not due to random variations but represents a statistically reliable improvement over the traditional PID approach.

4. DISCUSSION OF SCIENTIFIC RESULTS

The results confirm the relevance of implementing mechatronic systems in precise artistic material processing. The laser machine for cutting Kazakh ornaments developed by the authors serves as an example of the successful application of mechatronic and automation principles in the decorative and applied arts sector. The machine's design incorporates intelligent control based on sensor feedback and microprocessor technologies, ensuring operational stability, high accuracy, and adaptability under varying material properties and environmental conditions.

The novelty of this work lies in integrating mechatronic principles into the cutting of ethnic ornaments, automatic adaptation to material characteristics, and the application of a fuzzy-PID controller in the specific task of artistic cutting.

Particular importance is given to the control system's capability to minimize human involvement in the process: the operator performs only supervisory and input functions, while core operations—fabric positioning, laser cutter activation, and quality control of the ornament execution—are carried out automatically. This indicates the equipment's compliance with modern mechatronic system requirements, including modularity, energy efficiency, intelligence, and high precision.

To verify the obtained results and evaluate the machine's performance, laboratory tests were conducted on materials of varying density, such as silk, cotton, and felt. Each test involved cutting the same 10 × 10 cm ornament while varying the material density and feed rate. Measurements included deviation from the reference standard, processing time, and defect rate.

Table 2. Cutting characteristics of various materials

Material	Average Cutting Time (s)	Standard Deviation (mm)
Silk	9.2	0.12
Cotton	10.1	0.08
Felt	12.7	0.15

Experiment: Cutting a 10 × 10 cm ornament on fabrics of different densities with varying feed rates

The experimental data presented in Table 2 confirm the high accuracy of the machine and its adaptability to varying conditions. The machine maintains stable operation despite changes in material properties.

To assess the competitiveness of the developed laser cutting machine, a comparative analysis was conducted against existing similar systems available on the market. The selected analogs included commercially available installations used for artistic fabric cutting, specifically the LaserPro X380 (Taiwan), Trotec Speedy 100 (Austria), and Glowforge Plus (USA).

The novelty lies in the integration of mechatronic principles for ethnic ornament cutting, the automatic adaptation to different materials, and the application of a fuzzy-PID controller for the specific task of artistic cutting.

Particular importance is given to the fact that the control system minimizes human involvement: the operator performs only supervisory and parameter-setting functions, while the main operations—positioning the fabric, activating the laser cutter, and monitoring the quality of the ornament—are performed automatically. This confirms the equipment's compliance with modern mechatronic system requirements, including modularity, energy efficiency, intelligence, and high precision.

To verify the obtained results and evaluate the machine's effectiveness, laboratory tests were conducted on materials of varying density, such as silk, cotton, and felt. Each test involved cutting the same ornament measuring 10 × 10 cm, with variations in material density and feed speed. During testing, deviations from the standard, processing time, and defect rate were measured.

Experimental data from Table 2 confirm the high accuracy of the machine and its adaptability to different conditions; the system maintains stable operation despite changes in material properties.

To assess the competitiveness of the developed laser cutter, a comparative analysis was performed against existing commercial systems available on the market. Analogous machines considered included the LaserPro X380 (Taiwan), Trotec Speedy 100 (Austria), and Glowforge Plus (USA).

The developed machine stands out due to its intelligent adaptation to fabric density, simple construction, and focus on cultural and ethnic applications. While foreign counterparts are mainly aimed at universal or mass usage, the proposed solution is optimized for individualized artistic production in local settings.

Despite demonstrated efficiency, the system has practical limitations. First, the fuzzy-PID controller requires significant computational resources, limiting its use on low-performance microcontrollers such as basic Arduino versions. Second, control quality heavily depends on sensor data accuracy; sensor noise and signal transmission delays can reduce system stability. Additionally, the system is sensitive to the calibration of fuzzy logic rule bases, imposing higher demands on engineers' qualifications during setup.

Prospects involve scalability and functionality expansion. The developed approach can be adapted not only for fabric cutting but also for processing other materials such as leather, wood, plastics, and composites. Incorporating more powerful controllers and modern sensor technologies will improve system speed and reliability, paving the way for commercialization and use in small to medium-sized manufacturing enterprises.

Thus, this work not only demonstrates the practical feasibility of a mechatronic approach in decorative and applied technologies but also lays a foundation for further research in intelligent control systems.

Recent studies have further confirmed the growing relevance of adaptive fuzzy-based control in laser processing and mechatronic systems.

Wu et al. [16] developed a compound control algorithm for the height-following mechanism of a laser cutting head, which significantly enhanced precision and dynamic response.

Similarly, Zhao et al. [17] introduced a predictive RBF-compensated fuzzy-PID controller for 3D laser scanning, achieving superior stability and reduced overshoot compared with conventional PID systems.

In addition, Du et al. [18] proposed a robust adaptive fuzzy control approach for vibration-assisted cutting, demonstrating improved accuracy under nonlinear and time-varying operating conditions.

Recent advances in computer vision and deep learning have also contributed to improved quality control and defect detection in manufacturing. For instance, Baiganova et al. [19] developed an enhanced VGG16 convolutional neural network model for automated defect detection, demonstrating high recognition accuracy and robustness in industrial environments. These findings highlight the importance of integrating intelligent algorithms into mechatronic systems to ensure consistent product quality.

These studies support the effectiveness of the proposed fuzzy-PID control structure and reinforce its potential applicability across diverse intelligent manufacturing systems.

Furthermore, Aldeshov et al. [20] emphasized the significance of adaptive control algorithms and sensor integration for enhancing process stability and precision in textile and cutting applications. Their findings are consistent with the present research, which also relies on feedback-driven optimization of process parameters.

Similarly, Aman et al. [21] proposed a mechatronic-based intelligent control system for ornament cutting, demonstrating the practical feasibility of combining fuzzy logic and PID regulation in nonlinear, real-time environments. These studies complement the outcomes of the current work and further substantiate the effectiveness and adaptability of the proposed fuzzy-PID control strategy for intelligent laser cutting applications.

5. CONCLUSION

This study presented the design and implementation of a fuzzy-PID-controlled laser cutting system for producing Kazakh ornamental patterns. The developed system integrates mechanical, electronic, and computational components, demonstrating the practical application of mechatronic principles such as automation, precision, and intelligent adaptability. Experimental validation confirmed that the proposed controller significantly improves cutting accuracy and stability while reducing the need for manual intervention.

The research contributes both theoretically and practically to the field of mechatronics. From a theoretical perspective, it extends the application of fuzzy logic in control systems, promoting integration between intelligent and classical control methods. From a practical viewpoint, the developed prototype illustrates how adaptive fuzzy control can be implemented in real mechatronic systems to ensure consistent product quality under varying material and process conditions.

However, the study has several limitations. The experimental setup relied on mid-range sensors, which may introduce measurement noise and limit precision under industrial environments. Additionally, the current system was tested primarily on a limited range of materials and thicknesses. Future work will focus on extending the controller's adaptability to more complex materials, incorporating higher-resolution sensors, and integrating machine vision for real-time surface monitoring and automatic defect detection.

Overall, the proposed fuzzy-PID approach demonstrates strong potential for decorative and artistic manufacturing applications. It provides a foundation for further advancements in adaptive control for intelligent production systems, contributing to higher efficiency, product quality, and competitiveness in modern manufacturing.

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