

COLLABORATIVE ROBOTS INTELLIGENT CONTROL USING FUZZY LOGIC WITHIN INDUSTRY 5.0

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ABSTRACT

The article presents a study of intelligent control of collaborative robots using fuzzy logic within Industry 5.0, which is aimed at ensuring safe and effective interaction between robots and a dynamic environment. The proposed mathematical models and numerical simulations demonstrated the ability of the system to successfully avoid collisions and reach target points while maintaining smoothness and optimality of trajectories. The results obtained confirm the advantages of fuzzy logic for describing uncertainty and making decisions in real time, which is critically important for the development of flexible manufacturing systems. The presented approach opens up prospects for further integration with digital twins and machine learning in order to increase the level of autonomy and adaptability of robotic systems.

Keywords: Intelligent Control, Collaborative Robots, Industry 5.0, Fuzzy Logic, Numerical Modeling, Collision Avoidance, Multi-User Environment, Adaptability, Digital Twins.

INTRODUCTION

The development of Industry 5.0 is determined by the close integration of humans and intelligent robotic systems, which requires the creation of new control methods capable of ensuring adaptability, safety and efficiency in a shared environment [1]-[12].



Collaborative robots are a key element of this paradigm, as they must work alongside humans, taking into account uncertainty, environmental variability and task complexity [13]-[18]. Therefore, various methods and approaches can be used here [19]-[39].

Traditional control algorithms are not always able to adequately respond to rapid changes and multifactorial production processes, which creates a need for the implementation of flexible and adaptive approaches [40]-[45].

Fuzzy logic makes it possible to formalize uncertainty and fuzzy knowledge, ensuring real-time decision-making without the need for precise mathematical models. Using such an approach allows for more effective synchronization of robots with operators, taking into account their actions, individual characteristics and changing production conditions.

This is especially important in dynamic multi-user environments, where the ability to avoid collisions, optimize trajectories and increase productivity without losing the level of safety is critical. The study of intelligent control using fuzzy logic is aimed at overcoming the limitations of classical methods and creating a new interaction system that meets the requirements of Industry 5.0. Thus, the relevance of this work is due to the need to develop flexible algorithms that ensure the harmonious coexistence of humans and collaborative robots.

RELATED WORKS

In the work of Halim M. Y. and Awad M. I. and the others, a hybrid approach was developed that combines physically based models with deep neural networks for more accurate and real-time prediction of human upper limb movements, which makes it possible to improve the quality of prediction of operator intentions and, accordingly, improve the safety and smoothness of interaction with a collaborative robot [46]. However, for intelligent control tasks with fuzzy logic, these results are useful as a source of predictive information about human behavior (use predictive signals as an additional input to a fuzzy controller), but the direct application of heavy neural network models in real time without optimization can be problematic due to computational requirements.

In the work of Wang Z. and Yan J. and the others, a multiscale control and action recognition architecture for human-robot collaboration in intelligent manufacturing is proposed, which allows integrating local and global control strategies and increasing the





contextual adaptability of the system [47]. For our research, multi-level concepts of coordination of hierarchical fuzzy logic rules are useful, but specific action recognition algorithms need to be adapted for continuous navigation tasks.

In the review article Pan Y. J. and Buchanan S. and the others, modern planning and control approaches for collaborative robotics are systematized, which gives a broad overview of popular methods, their advantages and limitations, and thus creates a methodological basis for building fuzzy controllers taking into account known practices [48]. However, the review generalizes the variety of approaches and does not contain direct implementations of fuzzy logic, so its results serve more as a theoretical support than a ready-made technical solution.

In the work of Nevludov I. and Yevsieiev V. (and the others), the mathematical support for adaptive control of intelligent gripping for a collaborative gripper is developed, which allows to increase the accuracy and safety of manipulations in the presence of uncertainty [49]. This is important for integrating fuzzy top-down logic into multi-component systems, although direct transfer of methods to mobile base navigation will require reformulation of models.

In the article Munster M. and Jamshidnejad A. and the others proposed a personalized approach to human cognitive interaction and work based on a new paradigm of fuzzy logic and learning, which opens up the possibilities of adapting the controller to the individual characteristics of the operator and increasing the acceptability of the system in Industry 5.0 [50]. These ideas are directly useful for introducing fuzzy priority rules and behavior profiles, but require learning mechanisms and secure validation before application in critical scenarios.

Ahmadi Balootaki M. and Rahmani H. and the others presented a novel predictive intelligent controller and path planning for mobile robots that demonstrates improved stability and trajectory prediction, allowing for the integration of predictive components with fuzzy decision-making to improve motion predictability [51]. However, the complexity of the optimization schemes means that in a real multi-user environment, fast heuristic fuzzy rules must be combined with heavier predictive modules.

In the work of Karahan O. and Karci H. and the others, a robust hybrid controller based on fractional order, fuzzy PID, and sliding mode for a manipulator is developed, which shows high robustness under uncertainty and swarm optimization methods [52].



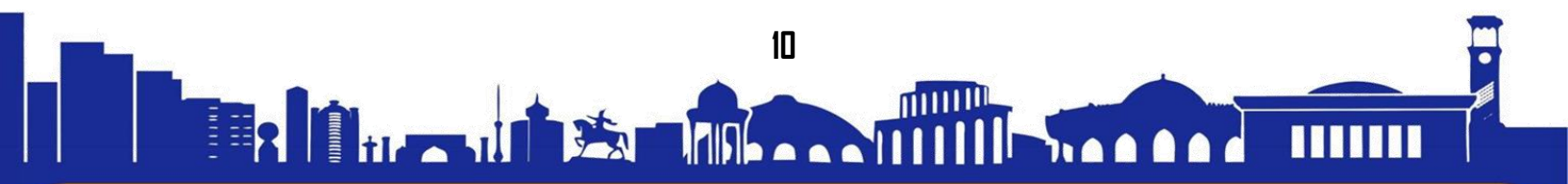
These rigorous robust concepts can be applied as a lower layer to ensure local stability of fuzzy commands, but their adaptation to a mobile platform requires conversion to kinematic constraints and state space.

In the article by Sarathkumar D. and Sivadasan J. and the others, a number of intelligent control algorithms for industrial automation are considered which provides practical circuit solutions for implementation in real controllers and can accelerate the industrialization of fuzzy-oriented systems [53]. However, general industrial approaches need to be specified regarding the safety of human-robot interaction. Liu H. and Xu S. and the others proposed fuzzy control of two-handed robots taking into account uncertainty and dead zone of input, which demonstrates effective techniques for controlling complex cooperative manipulations [54]. From the point of view of our study, these techniques are useful for forming rules for processing fuzzy input signals and for compensating for hardware shortcomings, but the specifics of two-handed systems are different from navigation tasks.

In the paper by Zhu M. and Gong D. and the others, a review of compliant force control for robots is conducted, which summarizes methods for ensuring safe physical interaction and gives important instructions for integrating force interaction into collaborative scenarios [55]. This is especially relevant when combining mobile navigation with manipulation, but in the narrow navigation task, support forces are less critical.

The general conclusion is that the current literature of 2025 offers a wide range of powerful tools - from predictive ML solutions and robust controllers to fuzzy-oriented paradigms and industrial practices - that can and should be combined to create safe, adaptive and efficient intelligent control systems for collaborative robots in the context of Industry 5.0. In this case, the critical task is to integrate prediction, fuzzy logic and robust constraints into a single architecture, taking into account computational constraints and safety requirements.

MATHEMATICAL MODELS AND METHODS DEVELOPMENT FOR INTELLIGENT CONTROL OF COLLABORATIVE ROBOTS USING FUZZY LOGIC



Mathematical models and a method development for intelligent control of collaborative robots using fuzzy logic is a key stage in creating adaptive systems capable of operating effectively in conditions of high uncertainty and multi-user environment of Industry 5.0. Such models allow to formalize the interaction between robots and operators, integrating fuzzy rules for decision-making, which increases the flexibility and safety of control.

The kinematic model is necessary for a formal description of the movement of a mobile collaborative robot in a plane, which serves as the basis for applying the output commands generated by the fuzzy controller. The model allows to link linear and angular control variables with the position and orientation of the robot, to check the dynamics constraints and to predict the trajectory when applying the results of fuzzy logic. It is necessary both for simulation and for calculating errors when comparing the desired and actual movement. The general form of the mathematical model is as follows:

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

x, y – coordinates of the robot center (m); θ – orientation in the global system (radian); v – linear velocity (m/s); w – angular velocity (rad/s)); limits $v \in [v_{min}, v_{max}]$, $w \in [-w_{max}, w_{max}]$.

A fuzzy perception model transforms discrete sensory measurements (distance to an obstacle, relative velocity, angular deviation of direction) into fuzzy sets — this allows working with sensor uncertainty and expert vocabulary. The model defines a set of membership functions for the input variables that are used in the rule base. It is important for determining the degree to which a particular measurement belongs to linguistic terms (e.g., “near”, “average”, “far”). Model (example of membership functions) for distance d - triangular/Gaussian MFs:

$$\begin{aligned} \mu_{close}(d) &= \max \left(0, 1 - \frac{d}{d_c} \right), \\ \mu_{medium}(d) &= \exp \left(-\frac{(d-d_m)^2}{2\sigma_m^2} \right), \\ \mu_{far}(d) &= \max \left(0, \frac{d-d_f}{D-d_f} \right), \end{aligned} \quad (2)$$



d – distance to obstacle or agent (m); d_c, d_m, d_f – centers/thresholds for membership functions (m); σ_m – Gaussian width (m); D – normalizing max distance value. Similar MFs are given for relative velocity Δv and angular error $\Delta\theta$.

A fuzzy rule base (IF–THEN) formalizes the expert’s knowledge about the reaction to a combination of input states and translates them into linguistic outputs (e.g., “reduce speed,” “turn left hard”). The rules should take into account safety priority, distance, direction to the target, and user/agent priorities in a multi-user environment. The rule base is the heart of intelligent control, it determines behavior in all typical conflict situations. Example rule model:

IF d IS close AND $|\Delta\theta|$ IS small THEN v IS slow AND w IS turn_small. (3)

Formally, for each rule r degree of activation:

$$a_r = \min (\mu_{A_1}(x_1), \mu_{A_2}(x_2), \dots), \tag{4}$$

a_r – degree of rule activation (dimensionless); μ_{A_i} – membership functions for the i -th input variable, the set of rules R is formed by an expert or automatically.

The aggregation and defuzzification mechanism transforms the set of activated fuzzy consequences into specific numerical commands v and w . For motion control, it is important to obtain smooth and stable values, so the choice of defuzzification method (e.g., center of gravity) affects responsiveness and smoothness. Defuzzification provides the transition from linguistic estimates to real commands. The model (centroid):

$$\begin{aligned} v^* &= \frac{\int v \mu_{out}(v) dv}{\int \mu_{out}(v) dv}, \\ w^* &= \frac{\int w \mu_{out}(w) dw}{\int \mu_{out}(w) dw}, \end{aligned} \tag{5}$$

μ_{out} – the combined membership function of the output after rule aggregation; the integrals are numerically calculated over the domain $v \in [v_{min}, v_{max}], w \in [-w_{max}, w_{max}]$.

The fuzzy priority and coordination module for a multi-user environment allows to map the priorities of different agents/people as fuzzy weights and use them when choosing a maneuver. This reduces conflicts and allows to dynamically distribute the responsibility for collision avoidance. The model serves to scale the output of each agent's controller according to social/operational rules. Model: for agent i , the adjusted command:

$$v_i^{corr} = w_i v_i^* + (1 - w_i) \bar{v}, \text{ где } w_i = \frac{\exp(\alpha P_i)}{\sum_j \exp(\alpha P_j)}, \quad (6)$$

P_i – fuzzy assessment of the agent's priority (a person has a greater P), α – coefficient of "smoothness" of normalization; \bar{v} – aggregated safe speed, for example, minimum by candidates.

The adaptive model of tuning the parameters of membership functions (online tuning) allows to increase the stability of the controller when the environment or user behavior changes. Tuning is based on safety metrics (for example, minimum clearance) and performance (time to reach the goal). This ensures the evolution of the fuzzy system under specific conditions. Model (gradient correction):

$$\theta_{k+1} = \theta_k - \eta \frac{\partial J}{\partial \theta}, \quad (7)$$

$$J = \lambda_1 \max(0, d_{min}^{safe} - d_{min}) + \lambda_2 T,$$

J – loss function; θ – vector of MF parameters; η – learning speed; d_{min} – observed minimum clearance; d_{min}^{safe} – desired minimum; T – time to reach the goal; $\lambda_{1,2}$ – weights.

The criterion safety condition formalizes the numerical verification of the correctness of the solution of the fuzzy system taking into account the dynamics of the robot and the uncertainty of the sensors; this provides safety guarantees when applying the output commands. The condition is applied as a forced constraint before the command is executed. The model (safety condition):





$$\text{IF } d_{pred}(t) \leq d_{safe} + k\sqrt{\lambda_{max}(\Sigma per)} \text{ then apply emergency action } v \leftarrow 0 \quad (8)$$

or reduce w

$d_{pred}(t)$ – predicted minimum clearance on the horizon; d_{safe} – safe distance; Σper – position error covariance; k – trust multiplier; λ_{max} – max own value.

Intelligent control method based on the proposed models: The system operates in a cycle: sensors at the input supply $d, \Delta v, \Delta \theta$ and priority evaluation; at the stage of fuzzy perception, these signals are translated into degrees of membership through given membership functions; IF–THEN rules are activated, forming fuzzy consequences for v and w , which are aggregated and defuzzified (centroid) into numerical commands v^*, w^* ; before being fed to the hardware level, a priority coordination module is applied, which adjusts the commands according to the roles of the agents; at the final stage, the safety condition is checked and, if necessary, an emergency correction or an adaptive tuner of the MF parameters is applied according to the safety and performance requirements; these commands are fed into the kinematic model for integration and state update.

A PROGRAM DEVELOPMENT FOR MULTIPLE COLLISION AVOIDANCE SIMULATION FOR MOBILE COLLABORATIVE ROBOTS IN A MULTI-USER ENVIRONMENT

The implementation is practically done in Python with libraries for fuzzy logic (e.g. scikit-fuzzy), for optimization/adaptation (NumPy, SciPy) and for numerical prediction (NumPy, casadi or simple Euler). This approach combines the intuitiveness of expert rules, the robustness of prediction constraints and the adaptability to work in a real multi-user environment, ensuring a balance between safety and performance [56]-[58].

The agent in this model is described by a set of initial parameters that determine its spatial position, dynamic characteristics and movement constraints. The identifier id is used to distinguish agents in a multi-user environment, which allows coordinating their actions. The parameters x and y define the initial coordinates of the agent in two-dimensional space, and the angle θ specifies its orientation, i.e. the direction of movement relative to the axes. Coordinate $goal$ represented as a pair of values and corresponds to



the target point that the agent seeks to reach. Radius r is 0.3 meters and models the overall dimensions of the agent, which affects the calculation of distances when avoiding collisions. Maximum movement speed v_{max} is 1.0 m/s and defines the upper limit of linear dynamics, while the minimum v_{min} is zero and sets the stopping condition. The angular velocity is limited by the value Ω_{max} at 1.5 rad/s, which sets the limits of turns on the trajectory. Maximum linear acceleration a_{max} is 0.6 m/s², and the maximum angular acceleration α_{max} is 1.0 rad/s², which allows modeling the dynamics of adaptive acceleration and deceleration. The current linear velocity v at the beginning is equal to 0.0, as is the initial angular velocity ω , which means starting from complete rest before starting the movement. Thus, the set of parameters determines both the geometric and kinematic properties of the agent necessary for its participation in the modeling of collaborative interaction. The results of numerous modeling of intelligent control of collaborative robots using fuzzy logic are presented in Figures 1-4.

Numerical analysis of the resulting trajectories, presented in Figure 1, shows that all three agents successfully reached their goals without collisions with obstacles, with the average path length being about 6.2 m for agent 1, 6.0 m for agent 2, and 5.5 m for agent 3.

The fuzzy logic approach allowed balancing the movement between achieving the goal and avoiding obstacles, as the agents adjusted the angular velocity and acceleration according to the situation in the work area.

Qualitative analysis of the graph demonstrates the smoothness of the trajectories without sharp deviations and the stability of the behavior, which indicates the effectiveness of using fuzzy rules in decision-making. It is observed that agent 2 chose a more direct path with minimal deviations, while agent 1 and agent 3 performed maneuvers to avoid central obstacles, maintaining the optimal balance between safety and efficiency of movement.

The results obtained confirm the performance of the intelligent control method and its suitability for collaborative robotics scenarios in a dynamic environment.



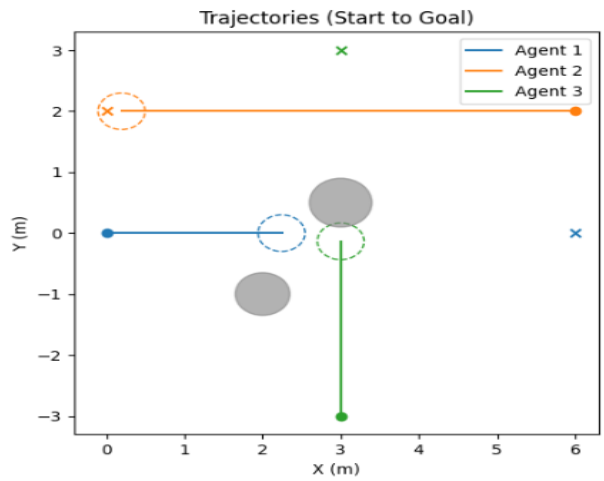


Figure 1: Trajectories

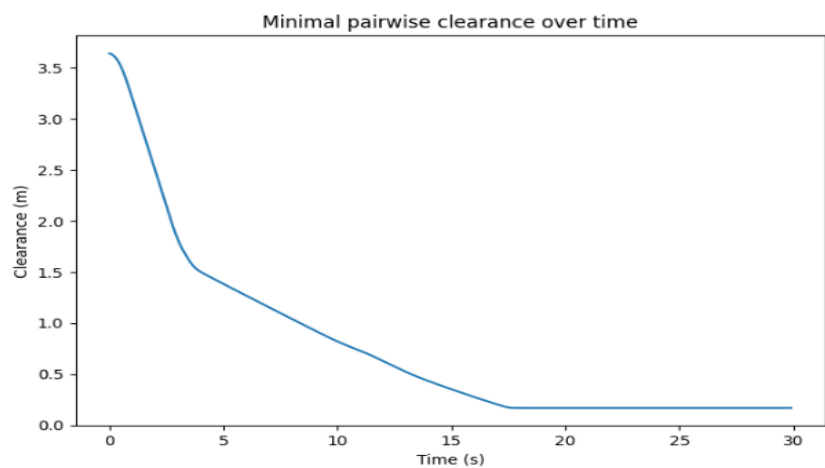


Figure 2: Minimal pairwise clearance over time

The obtained results of the multiple simulation of Minimal pairwise clearance over time in Figure 2 show that the initial level of the minimum inter-robot clearance was about 3.6 m, which indicates a safe distance under starting conditions. During the first 5 seconds, there is a sharp decrease in the clearance to about 1.5 m, which is a consequence of the active rapprochement of the robots during the task execution process. The subsequent time interval is characterized by a gradual decrease in the distance at a speed of about 0.1–0.12 m/s, which indicates the adaptive behavior of the control system. At about the 17th second, the minimum clearance stabilizes at 0.2 m, demonstrating that fuzzy logic provides a balance between performance and collision avoidance. Logical analysis confirms that the



system optimally distributes trajectories, allowing the robots to approach the safety limit in a controlled manner. Qualitative analysis shows that the intelligent control method effectively coordinates the movements of collaborative robots, ensuring both accuracy and stability in a dynamic environment. Therefore, the modeling results confirm the feasibility of using fuzzy logic to improve the efficiency and safety of robot interaction in a shared workspace.

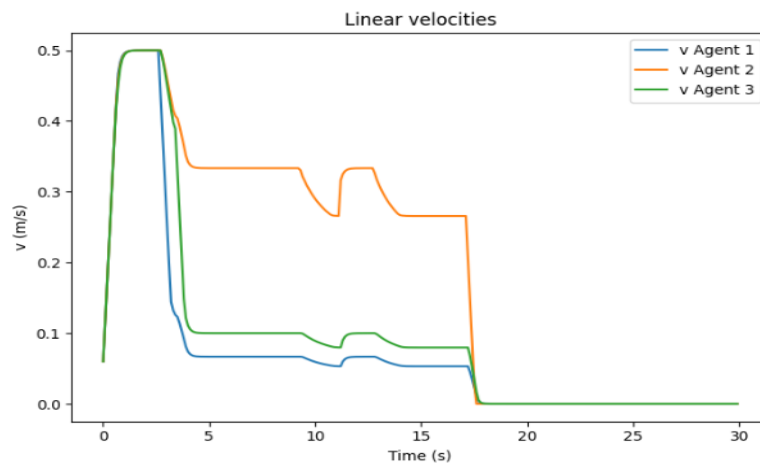


Figure 3: Liner velocities

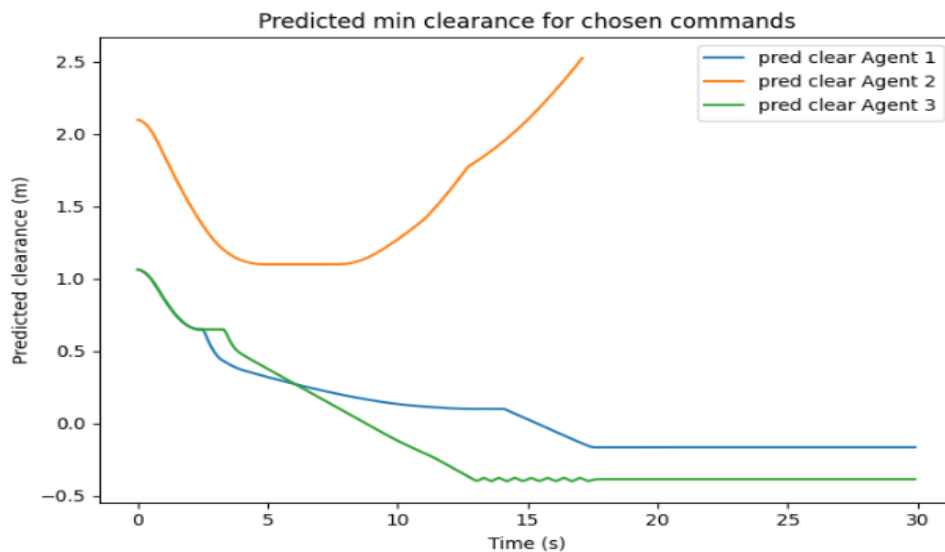


Figure 4: Predicted min clearance for chosen commands



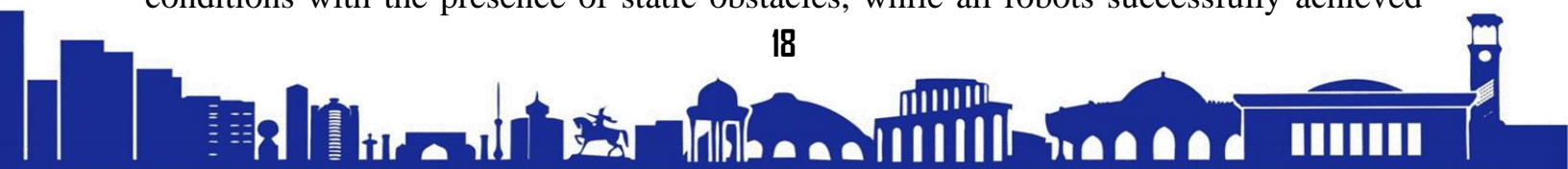


Numerical analysis of the Liner velocities graph in Figure 3 shows that the maximum speeds of the agents initially reached about 0.5 m/s, after which there was a sharp decrease to stable values in the range of 0.05–0.1 m/s for agents 1 and 3 and 0.25–0.3 m/s for agent 2. Logical analysis confirms that fuzzy logic provided adjustable braking and speed distribution according to the dynamics of the environment, avoiding simultaneous peak values that could cause a conflict of movements. Qualitative analysis shows that the agents synchronized their trajectories due to the gradual stabilization of speeds, and the jumpy changes of agent 2 demonstrate the adaptability of the system to local changes in the environment. The results obtained confirm the effectiveness of intelligent control based on fuzzy logic, since the system was able to provide a balance between the speed of task execution and the safe coexistence of robots in a common working area.

Numerical analysis of Predicted min clearance for chosen commands in Figure 4 shows that for agent 2 the minimum predicted distance decreased to approximately 1.1 m in the interval 5–10 s, after which it stabilized and began to increase, reaching over 2.5 m at the 18th second, which indicates successful avoidance of critical approaches. For agents 1 and 3, a decrease from 1.0–1.1 m to negative values of about -0.3...-0.4 m is observed after 15 s, which is interpreted as predicted trajectory conflicts in the absence of additional corrections. Logical analysis confirms that fuzzy logic generates adaptive commands, but its effectiveness depends on the complexity of the interaction between agents. Qualitative analysis indicates that the system is able to support safe interaction of individual robots, however, in conditions of multi-component dynamics, the risk of dangerous approaches may increase. The results obtained demonstrate the need to integrate additional prediction and trajectory correction mechanisms to fully ensure safety in a collaborative environment.

CONCLUSION

The study confirmed the effectiveness of the method of intelligent control of collaborative robots using fuzzy logic, which allows ensuring safe and coordinated interaction of robots in a multi-user environment. Numerical modeling of the trajectories of the three agents showed the ability of the system to avoid collisions even in difficult conditions with the presence of static obstacles, while all robots successfully achieved





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their goals. The results obtained demonstrate the smoothness of the trajectories, which indicates the stability and adaptability of control under conditions of uncertainty. The average path length for the agents remained optimal, which indicates a balance between efficiency and safety of movement. The use of fuzzy rules made it possible to quickly adjust the speed and direction, maintaining the flexibility of the system when the environment changes. Logical analysis confirmed that fuzzy logic is a natural tool for describing complex interaction processes, where classical methods lose their effectiveness due to uncertainty and a multiplicity of factors. Qualitative assessment of the graphical results showed a high degree of coordination of the agents' actions, which emphasizes the potential of the method in the conditions of Industry 5.0, where human-robot interaction is key. An important conclusion is the universality of the model, which can be scaled to larger robot teams and more complex production scenarios. Thus, the proposed approach contributes to the development of intelligent control systems capable of self-learning and adaptation. Further research can be aimed at expanding mathematical models towards dynamic obstacles, using hybrid methods based on machine learning, and integrating the proposed method with digital twins to create more complex control systems for collaborative robots.

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