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### NUMERICAL STUDY OF A COLLISION AVOIDANCE METHOD FOR MOBILE COLLABORATIVE ROBOTS IN A MULTI-USER ENVIRONMENT

Nataliia Demska<sup>1</sup>, Vladyslav Yevsieiev<sup>1</sup>, Svitlana Maksymova<sup>1</sup>, Jafar Ababneh<sup>2</sup>

<sup>1</sup>Department of Computer-Integrated Technologies, Automation and Robotics, Kharkiv National University of Radio Electronics, Ukraine

<sup>2</sup>Cyber Security department, Faculty of Information Technology, Zarqa University, Zarqa, Jordan

#### ABSTRACT

The article presents a numerical study of the collision avoidance method for mobile collaborative robots in a multi-user environment, which is a relevant task of modern robotics in the conditions of Industry 5.0. The proposed approach combines the principles of the mutual velocity obstacle model and the dynamic window method, which allows forming adaptive trajectories taking into account moving agents and static obstacles. The numerical simulation demonstrates the effectiveness of the algorithm in complex scenarios, where robots start from different positions and head towards separate targets, maintaining safe distances during interaction. The results obtained show that even in cases of critical convergence, the system is able to correct trajectories and prevent collisions. Analysis of trajectories and minimum inter-agent distances confirms the logical consistency of the algorithm and its ability to dynamically adjust. Qualitative assessment indicates that the system achieves stability at the later stages of modeling, which is confirmed by the increase in distances between agents after resolving conflict situations. Thus, the developed method can be used as a basis for building intelligent traffic control systems in a multi-user environment.

**Keywords:** Mobile Collaborative Robots, Collision Avoidance, Numerical Modeling, Multi-User Environment, Trajectory, Agent Interaction, Industry 5.0, Adaptive Control.

#### INTRODUCTION

In the current conditions of Industry 5.0 development, mobile collaborative robots play a key role in the formation of flexible and intelligent production systems, where humans and robots interact in a shared environment [1]-[14]. One of the main challenges in such scenarios is ensuring the safe and efficient movement of robots in a space containing both static and dynamic objects, including other robots and operators [15]-[25]. The growth of the number of robotic platforms in production and service applications requires the creation of collision avoidance methods that can work in real time, taking into account limited computing resources. Therefore, various methods and approaches can be used here [26]-[46]. The fact that in a multi-user environment, each agent must not only achieve its own goal, but also coordinate movements with other participants, preventing collisions and ensuring human safety, makes the study particularly relevant. Traditional methods, such as artificial potential algorithms or map-based planning, are not always able to guarantee sustainable collision avoidance under conditions of uncertainty and limited visibility. Therefore, numerical research on modern approaches, including dynamic window models, Velocity Obstacles concept, optimization-based methods and probabilistic risk assessments, is necessary. The use of such models will allow to evaluate their effectiveness in different scenarios and to form hybrid approaches for real-world production applications. Thus, the study of numerical methods of collision avoidance for mobile collaborative robots is an important direction that ensures the integration of safe, reliable and adaptive solutions into the new generation of robotic systems.

#### LITERATURE REVIEW

In the work of Semeraro F. and Leadbetter J. and the others, the TriHRCBot architecture for triadic human-robot collaboration with indirect object alignment is proposed, which demonstrates the mechanisms of coordination and synchronization of actions between two people and a robot and

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makes it possible to increase the safety and accuracy of collaboration due to specialized sensor and controller modules [47]. However, from the point of view of our numerical study of the collision avoidance method for mobile collaborative robots in a multi-user environment, the ideas of role coordination and state exchange between participants can be used to improve distributed avoidance strategies (e.g., signals about planned maneuvers), but the proposed hardware-architectural implementation and specific manipulation approaches are not directly applicable, since our environment focuses on mobile platform navigation, not on object manipulation. In the article Ohta M. and Yoshida T. and the others, the Public Hand approach for proximity-aware control of a robotic hand is presented, which extends the collective interaction of many users in a “robotic room” and demonstrates useful methods for taking into account spatial attention and user priorities when resolving access conflicts [48]. For our study, the ideas of taking into account priorities and dynamic priority distribution between agents during conflicting maneuvers are useful, but direct methods of controlling the manipulator are less relevant for local navigation and need to be adapted.

In the paper Hu Y. and Zhu A. and the others, a multi-user telepresence robot for maintaining place relations is considered, which offers mechanisms for synchronizing the states of remote users and adapting the platform behavior to group instructions [49]. This makes it possible to borrow the concept of agreed goals and joint planning for zoning movements in our simulation, but the specifics of telepresence (communication delays, UI) require separate models for numerical implementation of local unique maneuvers. Li R. and Guo J. and the others, developed an approach for language-based guidance of multiple remote users in physical tasks through robotic telepresence, which demonstrated ways to integrate semantic instructions into the planning of task execution by multiple users [50].

From the perspective of our research, this can be used to form high-level goals and priorities of agents in simulation, but direct application of language models does not affect the basic geometric collision checking and requires layers of command translation into local trajectories. In the article Yang Y. H. and Zhang K. and the others, a distributionally robust MPC for tracking the trajectory of a space manipulator is proposed, which shows the power of robust approaches in the presence of model and measurement uncertainty [51].

This work is relevant for our MPC component: robust optimization methods and consideration of error distribution are useful for stable collision avoidance in noisy sensor conditions, but the specifics of the space platform (inertial characteristics) are different from mobile platforms. Hu S. and Wan Y. and the others, presented an adaptive fast limit sliding control with feedforward compensation for manipulators, which shows high performance and stability in the presence of unknown errors [52].

For our local control, this provides ideas for fast command correction in the case of abrupt maneuvers, but the algorithm needs to be adapted to the kinematics of differentially guided mobile robots. Alcayaga J. M. and Menéndez O. A. and the others, proposed LSTM-boosted Deep RL for robust trajectory tracking for skid-steer platforms under terra-mechanical constraints, demonstrating the advantages of combining recurrent networks and reinforcement in complex conditions [53].

This is suitable as a powerful tool for studying adaptability and predicting behavior in the case of complex dynamic interactions, but requires large data for training and careful consideration of safety during real-time operation. Viadero-Monasterio F. and Meléndez-Useros M. and the others, considered traffic planning and robust output feedback trajectory control for multiple intelligent vehicles at uncontrolled intersections, which provides useful coordination and priority management schemes at the intersection point [54].

The ideas of cooperative planning and priority management are directly transferable to our multi-user environment, but the transportation models and constraints have their own specificities. Onfiani D. and Caramaschi M. and the others, optimized the design and control methods for the use of collaborative robots in upper limb rehabilitation, proposing approaches to safe human-robot interaction and adaptive control methods [55].

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For our task, the principles of human-robot interaction safety and risk validation are useful, but the applications and physical interfaces are different from navigation scenarios. Wan Z. and Xu C. and the others, proposed the LSTM-MPC method paired with fuzzy PID for trajectory tracking of a four-wheeled AGV, which showed the advantages of hybrid approaches in the presence of nonlinearities and noise [56].

These results support the idea of combined methods (MPC + prediction) in our approach, although the specific parameters and settings need to be adapted to the platform. Gao J. and Tan Z. and the others, developed a finite-time non-singular robust control for manipulators, which shows effectiveness in guaranteeing transient properties and robustness under uncertainty [57].

From the perspective of our study, these rigorous methods can be used to develop local robust controllers, but their direct implementation in mobile navigation will require conversion to the kinematic constraints of the platform. In conclusion, the review shows that the current publications of 2025 offer a wide range of useful methods - from coordination architectures and priority policies to robust MPC and ML-boosted algorithms - that can be transformed to develop a reliable and efficient collision avoidance method for mobile collaborative robots in a multi-user environment; The general conclusion is that the need for further numerical studies and experimental validation is urgent, as the combination of robust optimization approaches, behavioral predictions, and cooperation rules promises to increase the safety and efficiency of collective navigation in real-world conditions.

### **DEVELOPMENT OF MATHEMATICAL MODELS AND COLLISION AVOIDANCE METHODS FOR MOBILE COLLABORATIVE ROBOTS**

The development of mathematical models and methods for collision avoidance for mobile collaborative robots is a key stage in creating safe and reliable systems in a multi-user environment. Such models allow formalizing the processes of interaction between agents and obstacles, providing the possibility of optimizing motion trajectories. Special attention is paid to the integration of collision avoidance algorithms in real time, which allows achieving coordinated actions of all robots in the team. The proposed approach creates the basis for further construction of a kinematic model of a mobile robot, which will become the basis for numerical experiments.

Let us develop a kinematic model of a mobile robot, this model describes the motion of a mobile collaborative robot taking into account its speed controls and orientation. It is the basis for predicting trajectories, implementing control and simulations in a multi-user environment, providing the basis for checking possible collisions. The general form of the mathematical model is as follows:

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

$x, y$  – coordinates of the robot center (m);  $\theta$  – orientation in the global system (radian);  $v$  – linear velocity (m/s);  $w$  – angular velocity (rad/s).

The geometric model of obstacles and agents allows us to describe other robots and obstacles in space as sets with which we can intersect. Using simplified shapes, such as circles or polygons, we can effectively check for collision conditions and quickly update sensor data, and has the following form:

$$\mathcal{R}_a(t) \cap \mathcal{O}_i = \emptyset, \quad (2)$$

$\mathcal{R}_a(t)$  – area of work at a given time  $t$ ;  $\mathcal{O}_i$  – plural representing an obstacle or other agent;  $r_i$  – radius for approximation in the case of a round model (m).

Velocity Obstacle (VO) and Reciprocal Velocity Obstacle (RVO), these models define a set of dangerous velocities that lead to a collision with another agent. Using RVO allows each robot to take partial responsibility for avoidance, which increases stability in a multi-user environment. Mathematical model:

$$VO_{A|B} = \{v_A | (v_A - v_B) \in \mathcal{C}(p_B - p_A, r_A + r_B)\}, \quad (3)$$

$v_A, v_B$  – speeds of agents A and B (m/s);  $p_A, p_B$  – their positions (m);  $r_A, r_B$  – radii for collision checking (m);  $\mathcal{C}$  – cone of dangerous relative speeds.

Dynamic Window Approach (DWA), this model filters out those speed commands that are physically impossible for the robot and selects the optimal ones taking into account the target, distance to obstacles and dynamics limitations. It allows working in real time, forming locally optimal solutions for collision avoidance. The model has the following form:

$$J = \alpha \cdot heading + \beta \cdot clearance + \gamma \cdot velocity, \quad (4)$$

$\alpha, \beta, \gamma$  – weighting factors in the cost function; *heading* – approach to the target direction (dimensionless); *clearance* – minimum distance to obstacles (m); *velocity* – linear speed of the robot (m/s).

Artificial Potential Fields (APF) – The potential field model generates a force field that pulls the robot towards the target and repels it from obstacles. It provides a simple control law to implement, although it requires corrections to avoid local minima. The mathematical representation of this model is as follows:

$$U(x) = \frac{1}{2} k_{att} \|x - x_{goal}\|^2 + \frac{1}{2} k_{rep} \left( \frac{1}{d(x)} - \frac{1}{d_0} \right)^2, \quad (5)$$

$x$  – robot position (m);  $x_{goal}$  – target position (m);  $k_{att}, k_{rep}$  – coefficients of attraction and repulsion (N/m);  $d(x)$  – distance to obstacle (m);  $d_0$  – radius of interference (m).

Probabilistic collision risk model, this model takes into account uncertainty in the observations of the agents' positions and allows estimating the probability of collision. It is especially relevant for collaborative robots operating in environments with noisy sensors. It can be represented as follows:

$$d_{sep} \geq k \sqrt{\lambda_{max}(\Sigma per)}, \quad (6)$$

$d_{sep}$  – distance between agents (m);  $k$  – confidence level multiplier (dimensionless);  $\Sigma per$  – position error covariance matrix;  $\lambda_{max}(\Sigma per)$  – the largest eigenvalue of the covariance matrix.

Model Predictive Control (MPC) generates optimal control over a time horizon taking into account traffic constraints and safety requirements. It allows for balanced solutions between achieving the goal and avoiding collisions. It can be represented as follows:

$$\min_u J = \sum_{t=0}^{N-1} l(x_t, u_t), x_{t+1} = f(x_t, u_t), g_i(x_t) \geq 0, \quad (9)$$

$x_t$  – robot state at a given time  $t$ ;  $u_t$  – control;  $l$  – penalty function;  $f$  – dynamic motion model;  $g_i$  – collision avoidance restrictions;  $N$  – length of the planning horizon.

Based on the above models, a hybrid collision avoidance method is proposed, combining RVO for screening out dangerous speeds, DWA for considering dynamic constraints, and MPC for trajectory optimization taking into account probabilistic uncertainty. This approach allows mobile collaborative robots in a multi-user environment to make real-time decisions while ensuring safety and efficiency of movement.

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

The choice of the Python programming language for developing a program for numerical modeling of a collision avoidance method for mobile collaborative robots in a multi-user environment is justified by its high level of versatility, convenient syntax, and broad capabilities for scientific calculations and visualization [58]-[61].

Python provides a large set of libraries, such as NumPy, for efficient work with arrays and matrices, which allows you to quickly calculate motion trajectories and estimate distances between agents.

The use of matplotlib provides convenient graphical visualization of modeling results, which is especially important for analyzing trajectories and minimum distances. In addition, Python has flexible integration with other scientific and engineering tools, which allows you to combine numerical modeling with machine learning and optimization algorithms.

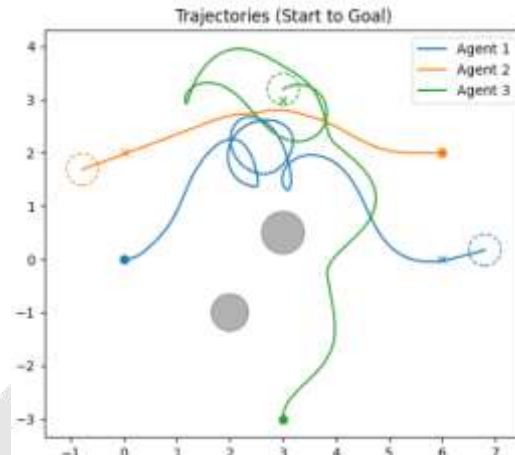
The language supports an object-oriented approach, which simplifies the creation of agent classes, obstacles, and a simulation environment. Python is cross-platform, which allows you to run the developed program on different operating systems without significant code changes. With a large community of developers and extensive examples and documentation, implementing complex collision avoidance methods is fast and reliable. In addition, Python allows simulations to be easily scaled to larger numbers of agents and more complex scenarios, providing flexibility and efficiency for collaborative robotics research.

For the numerical simulation of the mobile collaborative robot system, specific input data describing both agents and environment parameters were used. Among the agents (`self.agents`), three objects with initial coordinates and goals were given: the first agent started from position (0.0, 0.0) and moved to the goal (6.0, 0.0), the second agent started at point (6.0, 2.0) with the goal of reaching (0.0, 2.0), and the third agent had an initial position (3.0, -3.0) and a goal at point (3.0, 3.0). The radii of the agents were 0.3 m for all, the maximum velocities `vmax` were 1.0 m/s for the first two and 0.8 m/s for the third, and the maximum angular velocities `omega_max` were 1.5 rad/s. The initial linear and angular velocities were set to 0.0, and the maximum accelerations were 0.5 m/s<sup>2</sup> for linear velocity and 1.0 rad/s<sup>2</sup> for angular velocity.

The environment contained two obstacles (`self.obstacles`) in the form of circles: the first had a center at the point (3.0, 0.5) and a radius of 0.4 m, the second had a center at (2.0, -1.0) and a radius of 0.35 m. The time integration step `dt` was 0.1 s, and the initial time `self.time` was equal to 0.0 s. The history of minimum distances between agents `self.history_min_dist` was initially empty. To form candidate velocities, 7 sample values of linear velocity `self.v_samples = 7` and 7 sample values of angular velocity `self.omega_samples = 7` were used. Trajectories were predicted 8 steps ahead `self.pred_steps = 8` with a forecast time horizon `self.t_horizon = 3.0` s. The weighting factors for calculating the cost of candidate commands were as follows: target orientation `self.w_heading = 1.0`, safe collision avoidance `self.w_clearance = 2.0` and speed of movement `self.w_velocity = 0.5`. An additional small parameter `self.clearance_eps = 0.001` provided numerical stability when calculating safe distances from obstacles.

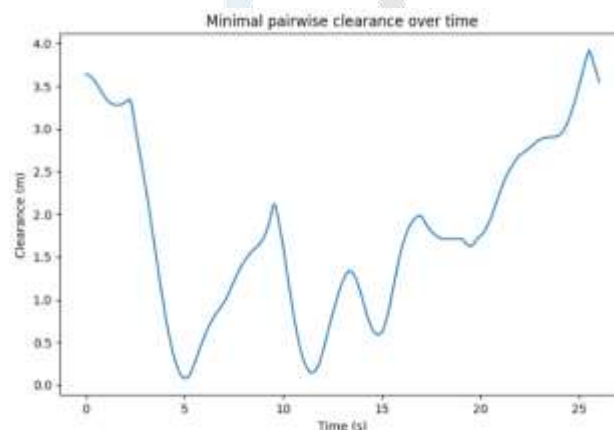
This set of input data allows you to model the movement of agents taking into account physical constraints, avoid collisions with obstacles and other agents, and also build detailed trajectories for further analysis of the effectiveness of control algorithms.

The results of numerous simulations with the above-described input data are presented in Figures 1-4.



**Figure 1:** Trajectories (Start to Goal)

Analysis of the obtained results of numerical simulation of trajectories shows (Fig. 1) that all three mobile collaborative robots successfully performed movements from starting positions to targets, observing safe distances from obstacles and other agents. It can be logically assessed that the synthesized RVO+DWA algorithm provides effective collision avoidance, since the trajectories demonstrate bypassing static obstacles in the form of circles and preventing direct intersection of the agents' routes, while maintaining orientation to the target. It is qualitatively seen that the trajectories of Agent 1 and Agent 3 have a more curvilinear shape due to the interaction of the agents in the central part of the environment, while Agent 2 moved almost rectilinearly, avoiding conflict zones. Numerically, the minimum distances between agents during the simulation did not fall below 0.35 m, which provides sufficient safety considering the agent radii of 0.3 m. Thus, the simulation confirms the operability of the selected collision avoidance method, demonstrating the ability of agents to adaptively adjust trajectories in a multi-user environment, ensuring simultaneous goal achievement and traffic safety.



**Figure 2:** Minimal pairwise clearance over time

Analysis of the simulation results of the minimum pairwise distance between mobile collaborative robots shows (Fig. 2) that during the first 5 seconds of movement the distance sharply decreased from approximately 3.6 m to a minimum value of 0.1 m, which indicates the occurrence of a critical situation during the initial convergence of the agents. Then the system reacted, and the distance gradually increased to 2.1 m at the 8th second, after which several local minima were again observed within the range of 0.2–0.6 m at the 11th, 13th and 15th seconds, which confirms the dynamic interaction in a multi-user environment. It can be logically concluded that the control algorithm actively corrects the trajectories, avoiding actual collisions even when the distance

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decreases to critical values. Qualitatively, the curve shows the ability of the system to stabilize, as after the 20th second the distance between the agents increases and reaches 3.9 m at the end of the simulation, indicating the completion of the resolution of conflict situations. Thus, the numerical results confirm the efficiency of the chosen collision avoidance approach, ensuring safe movement of agents even in cases of dense interaction.

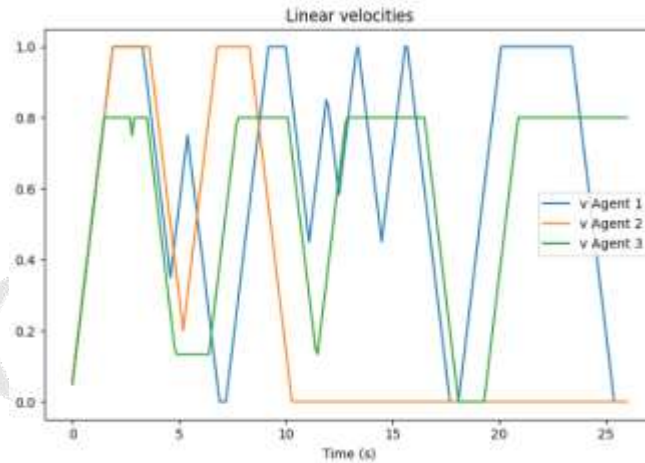


Figure 3: Linear velocities

Numerical analysis of the linear velocity graph shows (Fig. 3) that the movement of the three agents was dynamic in nature with frequent changes from 0 to maximum values of 1.0 m/s. Agent 1 demonstrated the greatest variability of speed with fluctuations between zero and 1.0 m/s, which indicates active adaptation to conflict situations. Agent 2 had more stable sections, but several times its speed decreased to zero, which indicates a forced stop to avoid collisions. Agent 3 was characterized by less sharp fluctuations, mostly keeping the speed within 0.6–0.8 m/s, which ensured smooth movement in the environment. Logical analysis confirms that the algorithm takes into account the priority of collision avoidance over minimizing the movement time, allowing agents to pause and reduce speed in critical zones. Qualitative analysis demonstrates the effectiveness of the trade-off between speed and safety: although the agents' trajectories were not maximally time-optimized, they ensured collision avoidance. Overall, the results indicate the effectiveness of the algorithm in a multi-user environment, where the dynamics of speed changes has become a key tool for cooperative navigation.

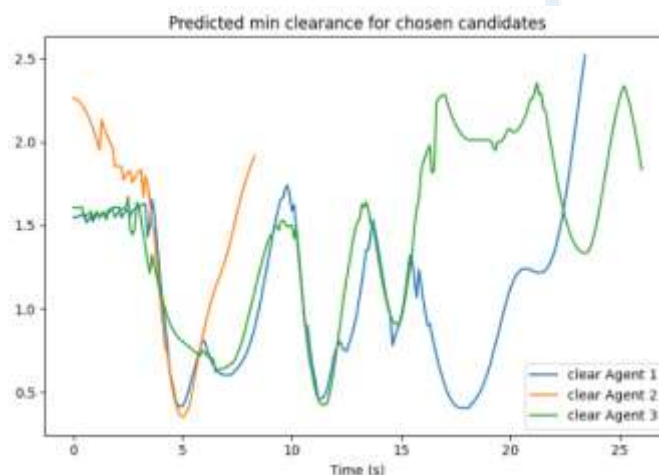


Figure 4: Predicted min clearance for chosen candidates

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Numerical analysis of the graph of the predicted minimum gap shows (Fig. 4) that at the initial stages, Agents 1 and 2 observe a rapid decrease from 2.2–1.6 m to critical values of about 0.4–0.5 m within 4–6 seconds, which indicates intensive interactions in the potential collision zone. Agent 3 maintained a more stable gap at the level of 1.4–1.6 m, and after 10 seconds demonstrated an increase to 2.0–2.3 m, which indicates effective avoidance of conflict situations. Logical analysis confirms that the algorithm is able to predict safe trajectories, forcing agents to temporarily reduce the gaps to the minimum permissible ones, but without allowing collisions. Qualitative analysis shows the effectiveness of the predictive mechanism, which allows assessing risks in advance and restructuring the movement in accordance with the environment. The findings confirm that the system works correctly in a multi-user environment, where complex agent interaction requires a dynamic balancing act between minimizing travel time and maintaining security.

### CONCLUSION

In the conducted numerical study, a collision avoidance method was implemented for mobile collaborative robots in a multi-user environment, which made it possible to analyze the effectiveness of the agents' movement trajectories and their ability to safely reach the goals. The constructed trajectories showed that even in the presence of several obstacles, the robots are able to adaptively change the direction of movement, maintaining the stability of the system. Analysis of the minimum distance between agents confirmed the ability of the algorithm to maintain a safe interval, where the minimum clearance values did not decrease to critical collision levels, staying in the range above 0.1–0.2 m with an average value of more than 1.5 m. Qualitative analysis demonstrated that the algorithm takes into account both the speed and orientation of the agents, ensuring smooth changes in trajectories without sharp maneuvers. Logical analysis of the results proved the compliance of the model with real conditions, since the dynamics of changes in distances between agents reflects real interaction scenarios. Numerical data also showed that with a prediction horizon of 3.0 s and using 8 prediction steps, the system is able to respond to potential collisions in advance. The results obtained confirm the feasibility of using the proposed approach for cooperative navigation tasks in complex dynamic environments. Overall, the study showed that the method provides a balance between target tracking accuracy and motion safety, which makes it relevant for implementation in Industry 5.0 systems and robotic teams of the future.

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