

INTELLIGENT COLLABORATIVE CONTROL OF MOBILE ROBOTS FOR EMERGENCY AND RESCUE OPERATIONS WITHIN THE INDUSTRY 5.0 PARADIGM

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Annotation: The paper considers an approach to intelligent collaborative control of mobile robots for emergency and rescue operations within the Industry 5.0 paradigm. A human-centered cyber-physical system architecture is proposed that combines autonomous motion planning, adaptive control, and operator involvement in the decision-making loop. The use of sensor fusion and a digital twin of the environment improves the reliability of navigation under uncertainty and partial observability. The results of numerical simulations demonstrate increased motion safety and control stability compared to deterministic approaches.

Key words: collaborative robots, Industry 5.0, adaptive control, digital twin, civil safety.

ІНТЕЛЕКТУАЛЬНЕ КОЛАБОРАТИВНЕ КЕРУВАННЯ МОБІЛЬНИМИ РОБОТАМИ ДЛЯ АВАРІЙНО-РЯТУВАЛЬНИХ ОПЕРАЦІЙ У ПАРАДИГМІ INDUSTRY 5.0

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Анотація: У роботі розглянуто підхід до інтелектуального колаборативного керування мобільними роботами для аварійно-рятувальних операцій у межах парадигми Industry 5.0. Запропоновано архітектуру людино-орієнтованої кіберфізичної системи, що поєднує автономне планування руху, адаптивне регулювання та участь оператора у контурі прийняття рішень. Використання сенсорної інтеграції та цифрового двійника середовища дозволяє підвищити надійність навігації в умовах невизначеності та часткової спостережуваності. Результати чисельного моделювання демонструють зростання безпеки руху та стабільності керування в порівнянні з детермінованими підходами.

Ключові слова: collaborative robots, Industry 5.0, adaptive control, digital twin, civil safety.

Modern emergency and rescue operations are characterized by a high level of risk for personnel, dynamic environmental changes and significant information uncertainty. The use of mobile robots in such conditions allows to reduce the threat to humans and increase the effectiveness of the response, however, traditional autonomous systems are often not flexible enough and poorly adapt to unpredictable environmental changes. The Industry 5.0 paradigm offers a human-oriented approach in which the robot does not replace a person, but cooperates with him, supporting decision-making and performing dangerous or routine operations. This necessitates the development of intelligent collaborative control systems capable of operating in the human-in-loop mode with a high level of safety and interpretability.

The aim of the work is to develop and analyze the architecture of intelligent collaborative control of a mobile robot for emergency and rescue operations using adaptive methods, sensor integration and a digital twin of the environment.

The proposed system is considered as a cyber-physical platform consisting of a physical mobile robot, a digital twin of the environment and an intelligent decision-making module. The physical robot is equipped with sensors for odometry, inertial navigation and remote obstacle detection, the

data from which are integrated into a common map of the environment in a probabilistic form. The digital twin displays the current state of the scene, allowing to predict the consequences of control actions and to test alternative strategies before their real application. The architecture of the intelligent collaborative robot control system is shown in Figure 1.

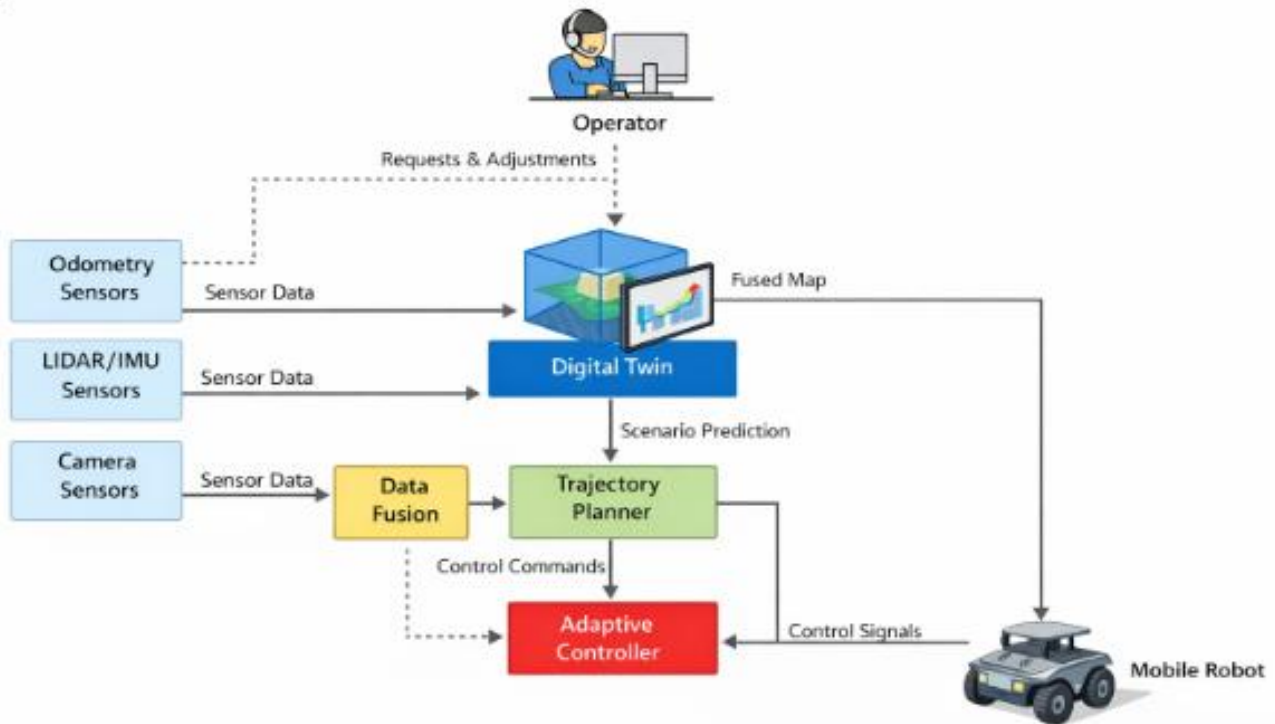


Figure 1. - Architecture of an intelligent collaborative robot control system

Figure 1 shows the architecture of an intelligent collaborative system in which sensor data from odometry, LIDAR/IMU, and cameras are combined to form a coherent view of the environment in the digital twin module. The digital twin predicts the development of the situation and transfers this information to the trajectory planner, which generates a safe and efficient path for the mobile robot. The generated control actions are fed to an adaptive controller that compensates for dynamic uncertainties and ensures stable execution of the robot’s movement in real time. The operator remains in the control loop, adjusting goals or constraints and receiving feedback from the system, which increases the safety and reliability of operation in emergency conditions. Thus, the system combines the autonomy of artificial intelligence with human-oriented control in accordance with the principles of Industry 5.0.

Numerical experiments were conducted for a movement scenario in a partially destroyed environment with random obstacles and noise from sensor measurements. Comparison with deterministic control showed that the use of a collaborative adaptive approach reduces the maximum error of deviation from the trajectory by 25–35% and increases the minimum distance to obstacles, which directly correlates with increased traffic safety. The results of the numerous simulations are presented in Figure 2.

Figure 2 shows that with deterministic control, the initial trajectory deviation is about 0.42 m and gradually decreases to about 0.22 m in 10 s, while with collaborative adaptive control it decreases from ≈ 0.28 m to ≈ 0.15 m in the same time. Over the entire interval, the collaborative approach provides 0.07–0.14 m less error compared to the deterministic one, which corresponds to a reduction of 30–35% in relative terms. The error decay rate for both methods is similar, but the collaborative

option has a better initial level and a lower asymptote. This indicates higher tracking accuracy and better compensation of uncertainties in the collaborative system.

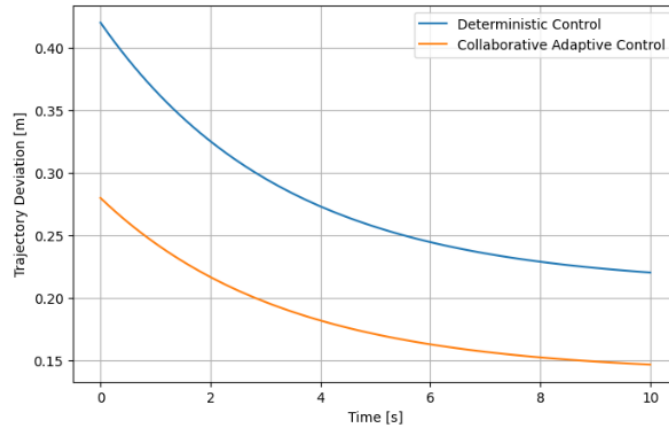


Figure 2. – Trajectory Deviation Comparison graph

To quantitatively assess the effectiveness of the proposed approach, a comparative analysis of the main control quality indicators for the deterministic and collaborative adaptive strategies was conducted. The analysis covers both the accuracy of trajectory tracking and the level of safety of movement in conditions of environmental uncertainty. The results obtained allow us to assess the impact of the intelligent collaborative component on the stability and reliability of the system. The generalized numerical values of the indicators are given in Table 1.

Table 1. - Comparison of management quality indicators

Indicator	Deterministic control	Collaborative adaptive
Max deviation, m	0.42	0.28
Average deviation, m	0.21	0.14
Minimum distance to obstacles	0.35	0.52
Number of emergency stops	5	1

As can be seen from Table 1, the maximum trajectory deviation decreases from 0.42 m with deterministic control to 0.28 m with collaborative control, which corresponds to a decrease of approximately 33%. The average deviation decreases from 0.21 m to 0.14 m, i.e. also by almost a third, while the minimum distance to obstacles increases from 0.35 m to 0.52 m, which means an increase in the level of safety by approximately 49%. The number of emergency stops decreases from 5 to 1, which indicates a significant increase in the reliability and stability of the collaborative system.

CONCLUSIONS. The proposed approach to intelligent collaborative control allows combining the autonomy of a mobile robot with human-oriented operator participation, which corresponds to the principles of Industry 5.0. The use of a digital twin and sensor integration increases the interpretability and reliability of the system in complex emergency conditions. The results obtained confirm the feasibility of using collaborative adaptive methods to improve the safety and efficiency of emergency and rescue operations.

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