DIGITAL TWINS OF COLLABORATIVE ROBOTIC SYSTEMS FOR DECISION SUPPORT IN EMERGENCY SITUATIONS

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***Annotation*:** The paper considers the concept of digital twins of collaborative robotic systems as a tool for decision support in emergency situations. A cyber-physical system architecture is proposed that integrates a physical robotic platform, its virtual counterpart, and intelligent modules for prediction and control. It is shown that the use of a digital twin increases the soundness of managerial decisions, reduces risks for personnel, and enables more adaptive robot behavior in dynamic and uncertain environments. The results of numerical simulations are presented to confirm the effectiveness of the proposed approach.

Key words: digital twin, collaborative robots, decision support, Industry 5.0, civil safety.

ЦИФРОВІ ДВІЙНИКИ КОЛАБОРАТИВНИХ РОБОТОТЕХНІЧНИХ СИСТЕМ ДЛЯ ПІДТРИМКИ РІШЕНЬ У НАДЗВИЧАЙНИХ СИТУАЦІЯХ

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Анотація: У роботі розглядається концепція цифрових двійників колаборативних робототехнічних систем як інструменту підтримки прийняття рішень у надзвичайних ситуаціях. Запропоновано архітектуру кіберфізичної системи, що поєднує фізичну роботизовану платформу, її віртуальну копію та інтелектуальні модулі прогнозування і керування. Показано, що використання цифрового двійника дозволяє підвищити обґрунтованість управлінських рішень, зменшити ризики для персоналу та забезпечити більш адаптивну поведінку роботів у динамічному та невизначеному середовищі. Наведено результати чисельного моделювання, які підтверджують ефективність запропонованого підходу.

Ключові слова: digital twin, collaborative robots, decision support, Industry 5.0, civil safety..

Natural and man-made emergencies require rapid and informed decision-making in conditions of information scarcity, high risk, and limited time. The involvement of robotic systems in such scenarios reduces the risk to humans, but the effectiveness of their use largely depends on the quality of the operator's information support and the system's ability to adapt to environmental changes. The Industry 5.0 paradigm focuses on human-oriented, interpretable, and sustainable technologies that combine the autonomous capabilities of artificial intelligence with human control and responsibility.

In this context, digital twins are considered a promising tool for data integration, modeling, and forecasting, which allows for the formation of a virtual representation of a physical system and its operating environment. The aim of the work is to develop and analyze the architecture of a digital twin of a collaborative robotic system to support decision-making in emergency situations.

The proposed system consists of a physical layer, which includes mobile robots with a set of sensors, a virtual layer in the form of a digital twin, and an intelligent decision support layer. The physical layer provides data collection on the state of the robot and the environment, which are transmitted to the virtual layer to form the current scene model. The digital twin reproduces the geometry, dynamics and constraints of the environment and allows predicting the consequences of possible system actions. The intelligent layer includes algorithms for risk analysis, trajectory optimization and evaluation of alternative scenarios. The operator interacts with the system through the interface, receiving recommendations and forecasts, and can also adjust goals or constraints. Such an architecture provides a combination of autonomy and human-oriented control. An example of the architecture is shown in Figure 1.

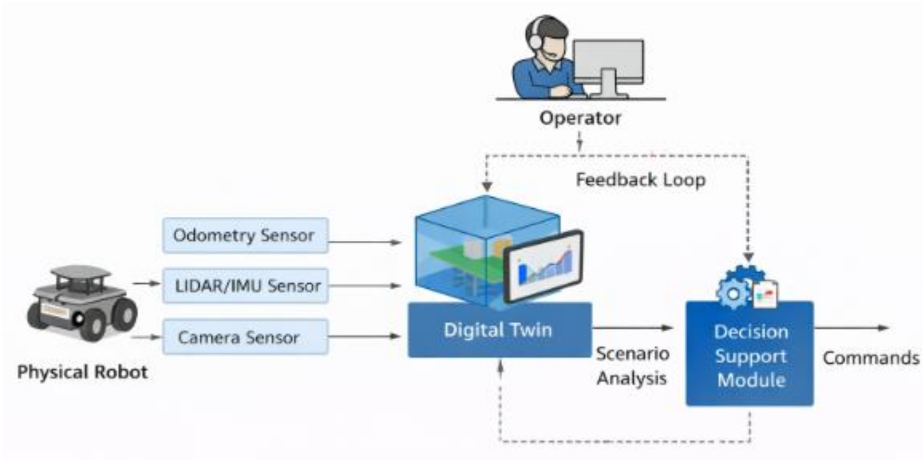

Figure 1. - Collaborative robot system architecture diagram

Figure 1 shows how a physical mobile robot transmits data about its state and environment through sensors to a digital twin, which forms a consistent virtual model of the system and the scene. Based on this model, the decision support module analyzes possible scenarios of the situation and generates recommendations or control commands. The operator, being in the control loop, receives the results of the analysis, can correct or confirm them and influence the further behavior of the system. The generated commands are transmitted back to the robot for execution in the real environment, and new sensor data again updates the digital twin. Thus, a continuous closed loop of perception, analysis, decision-making and action is ensured, focused on increasing the safety and efficiency of work in dynamic and dangerous conditions.

Numerical modeling was carried out for scenarios of searching for victims in partially destroyed buildings. The results showed that the use of a digital twin allows reducing decision-making time by 20–30% and increasing the probability of successful mission completion due to preliminary analysis of alternative strategies. The obtained modeling results are presented in Figure 2.

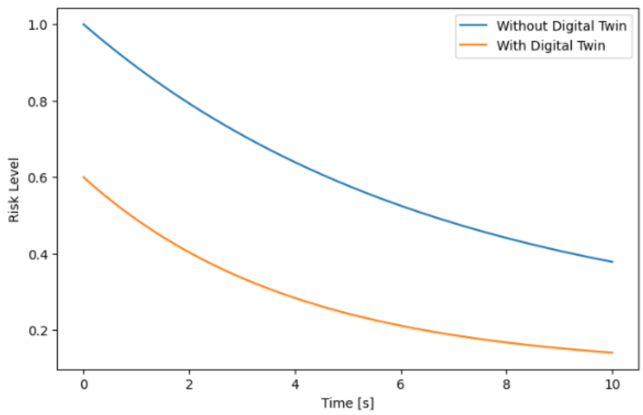

Figure 2. - Risk Evolution and Decision Efficiency Comparison

The graph (Fig. 2) shows that without a digital twin, the risk level decreases from approximately 1.0 to approximately 0.38 in 10 s, while with a digital twin it decreases from approximately 0.6 to approximately 0.14 in the same time. Thus, the final risk level when using a digital twin is almost 2.7 times lower than without it. The rate of risk decline in the case of a digital twin is higher, which is manifested in a steeper initial decline in the curve. This indicates more effective situation management and faster risk reduction when supporting decision-making with a digital twin. To assess the impact of a digital twin on the decision-making process, a comparative analysis of key indicators of system performance in emergency situations was conducted. The analysis allows us to quantify changes in response speed, mission reliability, and error rates with different approaches to decision support. The results obtained reflect the advantages of using a virtual environment model for preliminary scenario analysis and risk reduction. The summarized numerical values of the indicators are given in Table 1.

Table 1. - Comparison of decision-making efficiency

Indicator	Without a digital twin	With a digital twin
Decision time, s	15	10
Probability of successful mission	0.72	0.89
Number of erroneous actions	4	1

According to Table 1, the decision time decreases from 15 s to 10 s, which corresponds to a reduction of approximately 33%. The probability of successful mission completion increases from 0.72 to 0.89, i.e. increases by 0.17 or about 24% in relative terms. The number of erroneous actions decreases from 4 to 1, which means a decrease of 75% and indicates a significant increase in the reliability of decision-making when using a digital twin.

CONCLUSIONS. It is shown that digital twins of collaborative robotic systems are an effective tool for supporting decision-making in emergency situations. They provide data integration, scenario prediction, and risk reduction, which is consistent with the principles of Industry 5.0. The proposed approach increases the safety, adaptability, and validity of decisions and has prospects for implementation in civil protection systems.

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