INTELLIGENT CONTROL OF A COLLABORATIVE ROBOT

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***Annotation*:** The paper considers an approach to intelligent control of a collaborative robot in complex and dynamic environments. A control system architecture is proposed that combines sensor fusion, adaptive control algorithms, and operator involvement in the decision-making loop. It is shown that the combination of autonomy and human-centered control increases the safety and stability of the robot's operation under uncertainty. The presented results of numerical simulations confirm the effectiveness of the proposed approach..

Key words: collaborative robot, intelligent control, adaptive systems, sensor fusion, Industry 5.0.

ІНТЕЛЕКТУАЛЬНЕ КЕРУВАННЯ КОЛАБОРАТИВНИМ РОБОТОМ

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Анотація: У роботі розглядається підхід до інтелектуального керування колаборативним роботом у складних та динамічних середовищах. Запропоновано архітектуру системи керування, що поєднує сенсорну інтеграцію, адаптивні алгоритми керування та участь оператора в контурі прийняття рішень. Показано, що поєднання автономності та людино-орієнтованого контролю підвищує безпеку та стабільність роботи робота в умовах невизначеності. Наведені результати чисельного моделювання підтверджують ефективність запропонованого підходу.

Ключові слова: collaborative robot, intelligent control, adaptive systems, sensor fusion, Industry 5.0.

Collaborative robots are increasingly used in manufacturing, medicine, logistics, and civil security systems due to their ability to safely interact with humans in a shared space. However, the effectiveness of such systems largely depends on the quality of control algorithms, which must take into account the uncertainty of the environment, variable dynamic parameters, and the need to ensure human safety. Traditional deterministic control methods often prove to be insufficiently flexible in real-world conditions, necessitating intelligent and adaptive approaches.

The Industry 5.0 paradigm focuses on human-centered and interpreted technologies, where robots act as assistants rather than replacements for humans. This requires the development of intelligent control systems capable of combining autonomous decision-making with operator involvement. The aim of this work is to develop and analyze the architecture of intelligent control of a collaborative robot in dynamic and uncertain conditions.

The proposed control system consists of three main levels: sensory, intelligent, and executive. The sensory level provides information about the state of the robot and the environment using various sensors. This data is integrated into a common representation of the system state using sensory integration methods that take into account the reliability and accuracy of each source.

The intellectual level implements planning, forecasting, and adaptive control algorithms that allow the robot to change its behavior in response to changes in the environment. The operator remains in the control loop, with the ability to intervene in the decision-making process in critical

situations. The executive level is responsible for the implementation of control signals and safe physical interaction with humans. An example of a solution, Collaborative robot control architecture diagram, is shown in Figure 1.

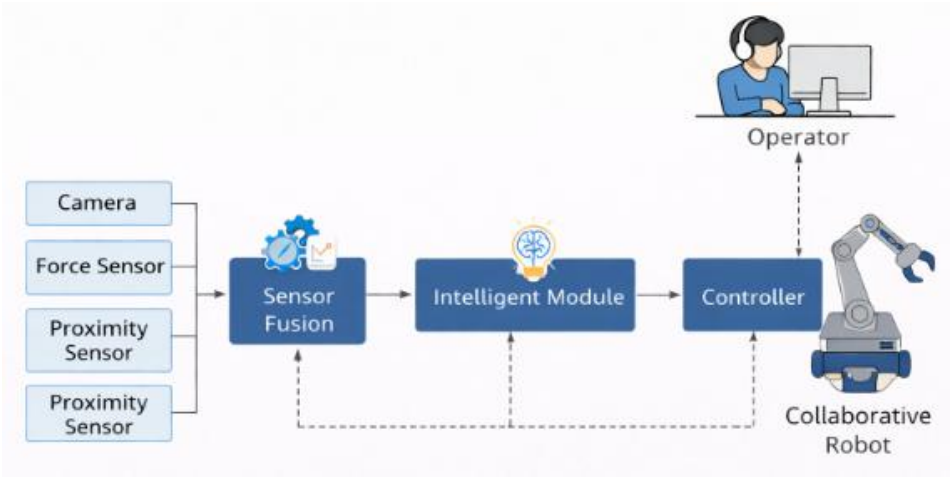

Figure 1. - Collaborative robot control architecture diagram

Figure 1 shows the architecture of intelligent control of a collaborative robot, in which heterogeneous sensors continuously collect information about the state of the robot and the surrounding environment and transmit it to the sensor integration module. In this module, the data is coordinated and filtered to form a reliable picture of the current situation. The information is then sent to an intelligent module, which performs analysis, prediction, and selection of an appropriate behavior strategy, taking into account safety constraints and the task at hand. The resulting decisions are converted into control signals by the controller and transmitted to the robot's executive mechanisms. The operator remains in the control loop, receives information about the state of the system, and can correct its behavior in critical or non-standard situations. Feedback from the robot is sent back to the system, ensuring a closed loop of adaptation and stable operation in conditions of uncertainty. Thus, the architecture combines the autonomy of artificial intelligence with human-oriented control to improve the safety and reliability of human-robot interaction.

Numerous experiments have shown that the proposed approach reduces trajectory tracking error by 25–35% and increases the minimum distance to obstacles, indicating an increase in safety compared to classical control methods. The simulation results are shown in Figure 2.

The graph (Fig. 2) shows that with conventional control, the tracking error decreases from approximately 0.42 m to about 0.22 m in 10 seconds, while with intelligent control, it decreases from approximately 0.28 m to about 0.14 m in the same time. Thus, intelligent control provides a 0.07–0.14 m smaller error over the entire interval, which corresponds to a reduction of approximately 30–35%. The rate of error decay for the intelligent method is higher, which manifests itself in faster achievement of a steady state. This indicates better compensation for uncertainties and higher trajectory tracking accuracy when using intelligent control.

To quantitatively assess the effectiveness of the proposed control approach, a comparative analysis of the main indicators of system performance under different control methods was performed. This allows for an objective assessment of the impact of intelligent algorithms on the accuracy, safety, and stability of robot motion under conditions of uncertainty. The generalized numerical results are presented in Table 1.

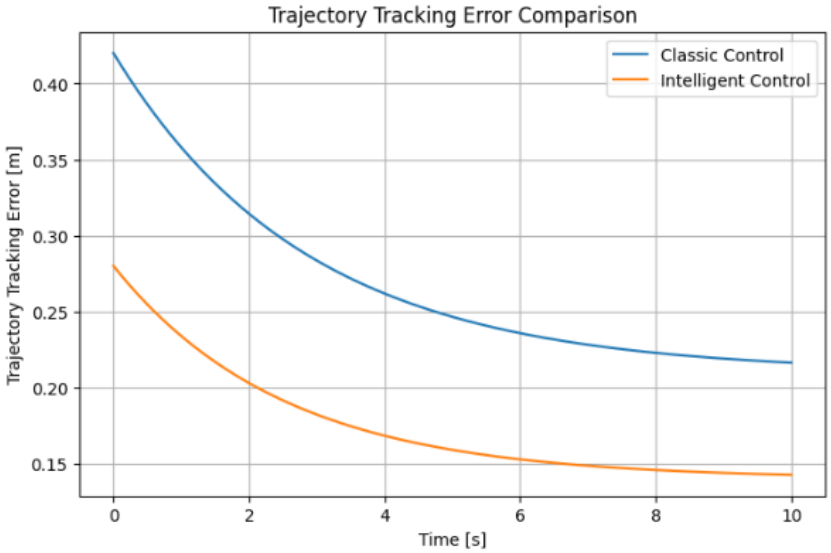

Figure 2. - Trajectory Tracking Error Comparison (Classic Control vs Intelligent Control)

Table 1 - Comparison of control quality indicators

Indicator	Classic control	Intelligent control
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

According to Table 1, the maximum tracking error decreases from 0.42 m with conventional control to 0.28 m with intelligent control, which corresponds to a reduction of approximately 33%, and the average error decreases from 0.21 m to 0.14 m, i.e., also by almost a third. The minimum distance to obstacles increases from 0.35 m to 0.52 m, which means an increase in safety of approximately 49%, while the number of emergency stops decreases from 5 to 1, indicating a significant increase in system reliability.

CONCLUSIONS. It has been shown that intelligent control of a collaborative robot allows combining autonomy and human-oriented control, increasing safety and stability of operation in conditions of uncertainty. The proposed architecture ensures adaptation to environmental changes and reduces the risk of dangerous situations. The results obtained confirm the feasibility of applying intelligent approaches in collaborative robotics.

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