КОЛАБОРАТИВНІ РОБОТИ ТА ЇХ ІНТЕГРАЦІЯ У КІБЕРФІЗИЧНІ СИСТЕМИ

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Анотація: У тезах розглянуто сучасний стан розвитку колаборативних роботів (cobots) та їх інтеграцію у кіберфізичні системи (КФС). Проаналізовано принципи взаємодії людини і робота, архітектурні особливості КФС, а також переваги та проблеми впровадження таких рішень у виробничих середовищах. Узагальнено підходи до інтеграції, наведено приклади застосування та виконано порівняльний аналіз ефективності.

Ключові слова: колаборативні роботи, кіберфізичні системи, Industry 4.0, автоматизація, робототехніка., Industry 5.0.

COLLABORATIVE ROBOTS AND THEIR INTEGRATION INTO CYBER-PHYSICAL SYSTEMS

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Annotation**:** The abstracts consider the current state of development of collaborative robots (cobots) and their integration into cyber-physical systems (CPS). The principles of human-robot interaction, architectural features of CPS, as well as the advantages and problems of implementing such solutions in production environments are analyzed. Integration approaches are summarized, application examples are provided, and a comparative analysis of effectiveness is performed.

Keywords: collaborative robots, cyber-physical systems, Industry 4.0, automation, robotics, Industry 5.0.

The active development of the Industry 4.0 concept has led to the transformation of traditional production processes in the direction of their intellectualization and digitalization. One of the key elements of this transformation has become collaborative robots, which, unlike classic industrial robots, are able to function in direct interaction with a person without the need for physical delimitation of work zones.

In parallel, the concept of cyber-physical systems is developing, combining physical objects, computing resources and communication networks into a single integrated system. Such a combination allows for monitoring, analysis and control of production processes in real time.

The integration of collaborative robots into cyber-physical systems creates the prerequisites for increasing production flexibility, reducing costs and improving working conditions. The purpose of this work is to study approaches to such integration and assess its effectiveness.

Collaborative robots are a new class of robotic systems focused on joint activities with humans. Their key feature is the presence of built-in safety systems that allow detecting contact or approach of a person and adapting the robot’s behavior accordingly. This is achieved through the use of force, torque, computer vision and adaptive control algorithms. Interaction between a person and a robot can take various forms, ranging from sequential execution of operations to fully collaborative work on a single task. In modern production conditions, the most promising approach is one in which a person performs intellectually complex or variable operations, while the robot takes on routine and physically difficult tasks. Due to the ease of programming and reconfiguration, collaborative robots are widely used in small-scale and individualized production.

Cyber-physical systems are integrated complexes in which physical processes are closely linked to computational and information components. The main idea of CPS is to create a digital representation of a physical object, which allows its analysis and control based on data obtained in real time.

A typical architecture of a cyber-physical system, table 1, includes a physical layer represented by sensors and actuators, a cybernetic layer where data processing and decision-making take place, and a network layer that provides information transfer between system components.

Table 1 – Cyber-physical system levels.

Level	**Description**	**Main functions**
Physical	Sensors and actuators	Data collection, action execution
Cybernetic	Computing systems	Data processing, decision making
Network	Communication protocols	Data transmission

Analysis of the structure of the cyber-physical system indicates a clear division of functions between levels, which ensures scalability and modularity of the system. The physical level is a source of primary information, and the quality of the entire system depends on the accuracy and speed of the sensors. In the context of the integration of collaborative robots, this level is of particular importance, since it includes safety, force and visual control sensors that ensure safe interaction with a person.

The cybernetic level performs the functions of processing large amounts of data and making decisions. This is where artificial intelligence, machine learning and adaptive control algorithms are implemented. For collaborative robots, this means the ability to dynamically adjust the trajectories of movement, speed and force of interaction depending on environmental conditions.

The network level ensures the integration of all components into a single system. Its effectiveness is determined by bandwidth, data transmission delays and communication reliability. Modern CPSs widely use industrial real-time protocols that minimize delays and ensure synchronization between physical and cybernetic processes.

Thus, the effectiveness of a cyber-physical system is determined not only by the characteristics of individual levels, but also by the consistency of their interaction. Disruption of any level leads to a decrease in the overall performance of the system.

Thanks to this structure, a continuous cycle of "perception - analysis - action" is ensured, which is the basis of intelligent production management.

The integration of collaborative robots into cyber-physical systems involves their inclusion in a single information space of the enterprise. In such a system, the robot acts not only as an executive mechanism, but also as a source of data used for analysis and optimization of processes.

From a technical point of view, integration is implemented through the use of IoT platforms, manufacturing management systems (MES), SCADA systems and cloud services. Data received from the robot's sensors are transmitted to computing modules, where they are processed, after which control actions are formed.

The integration model involves a closed loop of information exchange, in which data about the system state is used to adapt the robot's behavior in real time. This allows for high flexibility and stability of production processes.

To assess the effectiveness of integrating collaborative robots into cyber-physical systems, it is advisable to compare them with traditional approaches to automation. The main differences are in the level of flexibility, security, and implementation costs. The main differences are presented in table 2.

Table 2 – Comparison of traditional and collaborative automation.

Parameter	Traditional	Cobots in CPS
Flexibility	Low	High
Safety	Medium	High
Implementation Cost	High	Medium
Reconfigure Time	Long	Short

An in-depth analysis of the above table demonstrates the fundamental differences between traditional automation and the use of collaborative robots as part of cyber-physical systems. The low flexibility of traditional robots is due to their rigid binding to specific production operations and the need for significant time and resources for reconfiguration. In contrast, cobots integrated into the CPS can quickly adapt to changes due to program flexibility and the ability to obtain data in real time.

The safety indicator is also significantly different. In traditional systems, safety is achieved by isolating the robot from a person, which limits the possibility of their interaction. In the case of cobots, intelligent collision detection and force control systems are used, which allows organizing a shared workspace without risk to the operator.

Regarding the cost of implementation, although the initial costs of collaborative systems can be significant, the overall cost-effectiveness is higher due to reduced costs for security infrastructure, reduced downtime and increased versatility of equipment. Another important factor is the reduction of programming costs, as modern cobots support intuitive configuration interfaces.

Reducing the time of reconfiguration is a critical indicator for modern production, focused on product individualization. In traditional systems, this process can take hours or even days, while in the case of cobots it is limited to minutes or tens of minutes.

In general, we can conclude that the integration of collaborative robots into cyber-physical systems provides not only an increase in technical characteristics, but also creates economic benefits by optimizing production processes. Under the conditions of proper integration, the productivity increase can be up to 25–40%, which is explained by reduced downtime, increased flexibility and efficient use of resources.

The integration of collaborative robots into cyber-physical systems is accompanied by both significant advantages and certain difficulties. The main positive effects include increased productivity, reduced operating costs and improved working conditions for personnel. At the same time, problems arise related to the need to ensure cybersecurity, the complexity of integrating heterogeneous systems and the need for highly qualified personnel. The issue of standardization of interfaces and data exchange protocols requires special attention, which is critically important for ensuring the compatibility of CPS components.

CONCLUSION. The analysis shows that the integration of collaborative robots into cyber-physical systems is one of the key directions of development of modern production. This approach allows to achieve a high level of flexibility, efficiency and safety of production processes. At the same time, to fully utilize the potential of these technologies it is necessary to solve a number of problems related to ensuring cybersecurity, standardization and personnel training. Further research should be aimed at developing methods for optimizing human-robot interaction and improving the architectures of cyber-physical systems..

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