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Multi-agent System of Automatic Control of a Modern Electric Drives in the Age of Industry 4.0

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Abstract. *Industry 4.0 is characterized by the use of interconnected intelligent systems capable of real-time data exchange, distributed decision-making, and automation. The electric drive is one of the main components for the implementation of rotational and translational motion in complex electromechanical systems, such as Cyber-Physical Systems. Modern technological innovations lead to the increasing penetration of information technologies into various levels of electromechanical systems, including electric drive systems. As research shows, Embedded Computer Systems are widely used in automation systems nowadays. At the same time, the use of Digital Twins makes electric drives an object of* simulation *and leads to the need for real-time communication to monitor the status of electric drives and optimize their operation. The need for distributed decision-making when performing complex technological processes under conditions of uncertainty of external influences on the system requires a transition from rigidly specified electric drive control logic to adaptive and intelligent control systems. To this end, the current research proposes an intelligent automatic control system for a modern electric drive using a Multi-Agent control model. The proposed approach to developing an automatic control system provides flexibility to the control system in implementing intelligent control algorithms, adaptability to application conditions, and the possibility of continuous optimization using artificial intelligence elements.*

Keywords: *automatic control systems, electric drive, multi-agent system, Industry 4.0, Mechatronics, cyber-physical systems, embedded computer systems.*

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Introduction and statement of the research objective

The Industry 4.0 concept is characterized by the integration of information technology into industrial systems for real-time data exchange, distributed decision-making, and automation. The term "Industry 4.0" originated in Germany, but this concept largely overlaps with developments that may be called differently in other countries. According to this concept, everything in and around the production process is digitally connected, ensuring a highly integrated value chain. [1].

The study [2] identifies key technologies of the age of the fourth industrial revolution, which include: Additive Manufacturing, Internet of Things, Artificial Intelligence, Big Data Analysis and Cyber-Physical Systems.

An electric drive is one of the main components for implementing rotational and translational motion in complex electromechanical systems, such as Cyber-Physical Systems. Modern technological developments lead to the increasing penetration of information technologies into various levels of electromechanical systems, including electric drive systems.

As modern research demonstrates, embedded computer systems have wide application in automation systems. At the same time, the use of digital twins makes electric drives an object of simulation. This leads to the need for real-time communication to monitor the status of electric drives and optimize their operation.

The need for distributed decision-making when performing complex technological processes and operating under conditions of uncertainty of external influences on the system requires a transition from rigidly defined drive control logic to adaptive and intelligent control systems.

All this leads to the integration of edge computing directly into electromechanical systems including electric drives. This, in turn, expands the computing power of *automatic control systems (ACS)* and leads to new opportunities in building a programmable control algorithm for electric drives.

Therefore, the purpose of the current study is to review the key technologies of the age of the fourth industrial revolution and its impact on the transformation of the modern electric drive. As well as a description of the approach to building an intelligent ACS of a modern electric drive using a multi-agent control model.

The first section, “Analysis of Modern Research,” focuses on Cyber-Physical Systems, the Internet of Things, Digital Twins, Edge Computing, and Multi-Agent Systems. These technologies and systems are widely used in Industry 4.0 and are relevant in the context of modern electric drives and ACS.

The second section, “Description of a Modern Electric Drive,” examines the evolution of an electric drive from a local electromechanical system to a cyber-physical object within a cyber-physical system.

In the third section, “Multi-agent automatic control system,” a model based on agents that embody individual functional aspects of control into a single intelligent system is proposed.

The "Conclusion" section presents the results of the study and raises relevant questions regarding further research directions.

1 Analysis of modern research

The intensive use of information technologies in modern production leads to a narrowing of the gap between the cyber world and the physical world.

Of particular interest is *Cyber-Physical Systems (CPS)*, which are systems that integrate computing and communication components with physical processes, where physical processes influence computing and vice versa. Research [3] demonstrates the role of CPS in promoting the fourth industrial revolution by improving efficiency, flexibility, and management quality. One of the applied elements that make up CPS is embedded computer systems, with various sensors that record physical conditions in real time. The received data is processed by processors and influences the control of actuators through controllers. At the same time, artificial intelligence is widely used to improve real-time monitoring and control of technological processes. One example is the study [4], which analyses artificial intelligence methods for use in selecting the optimal material for manufacturing products in Industry 4.0 conditions.

The study [5] analysed the requirements for industrial CPS in the era of the fourth industrial revolution. These include *Autonomy*, which ensures the functioning of systems within the limits of defined functional goals through *Context-Awareness*. This provides a high degree of *Reliability* regarding *Availability* and system behaviour. In the context of maintaining system functionality under adverse conditions, CPS must be *Robust* and *Resilient* to environmental changes. At the same time, the state of the system must be *Observable* and *Trustworthy* for real-time decision-making. To ensure the *Controllability* of the system, an important requirement is the Predictability of the system, despite its complexity. To respond to changes and new requirements, industrial CPS must be *Scalable* and *Interoperable*. At the same time, all the above requirements must be met taking into account the principle of *Sustainable* development.

The study [6] considers the extension of mechatronic systems to cyber-physical ones, reviews the design methods of such systems, and emphasizes their special role in the manufacturing sector. As emphasized in the study [7], mechatronics, combining elements of electrical, mechanical, electronic and information technologies, plays an important role in the fourth industrial revolution by providing the basis for communication, information processing, actuators and human-machine interaction. The study [8] examines the evolution of mechatronic systems, which are based on physical components, to information-oriented systems, where information is at the center of the system, providing improved interconnectivity, intelligence, and adaptability. In such a paradigm, mechatronic systems act not only as sensors and actuators, they become intelligent objects, with computing and communication capabilities and the ability to process data locally in real time, adapting to environmental conditions.

Technological developments in recent years have given rise to a trend of applying *Internet of Things (IoT)* devices to industrial automation. This helps ensure the cost-effectiveness of technological processes, expands capabilities, and contributes to achieving Industry 4.0 goals and standards. The article [9] investigates the use of a programmable logic controller to create a smart manufacturing platform in accordance with Industry 4.0 standards. The study [10] provides an overview of the use of inexpensive open-source devices, such as Raspberry Pi or Arduino, to extend the functional and communication capabilities of traditional industrial automation technologies to meet the requirements of Industry 4.0 implementation. Examples of the approach to using single-board computers for the development of programmable logic controllers and programmable logic computers are the manufacturers REVOLUTION

PI, Industrial Shields and others [11]. These devices combine the capabilities of classic programmable logic controllers with the operational and software capabilities of personal computers and various communication protocols.

As for condition monitoring, simulation of CPS and its components, in the context of the fourth industrial revolution, *Digital Twins (DT)*, which are a digital representation of an instance of a physical system, have become widely used. A key feature of DT is real-time simulation, which is performed in parallel with the physical system. This allows to detect anomalies and the state of the physical system in real time with high accuracy. This is then the starting point for applying corrective signals to improve accuracy or reduce the impact of the anomaly on the system as a whole. In the article [12], a systematic review of the literature on the development and implementation of DT in various industrial sectors was conducted. The study [13] focuses on the use of DT in the powertrain of electric vehicles, analysing their application and usage scenarios. The research [14] presents a method for assessing the state of an asynchronous electric drive without a speed sensor based on DT and the extended Kalman filter. The results of the study demonstrate higher accuracy in assessing the state of the electric drive compared to models using the ideal inverter model.

The study [15] focuses on the role of *edge computing* in various areas, including energy systems. At its core, edge computing is a paradigm of computing that is performed near the data source. This minimizes latency, reduces data exchange traffic, and increases system autonomy.

With the development of information technology, *multi-agent systems* have become widely used in various industries, including robotics, control systems, and automation. Multi-agent systems are a collection of agents equipped with computing, learning, communication, and execution capabilities. Such a system consists of autonomous entities, that is, agents. These entities can be purely software or with elements or access to artificial intelligence technologies. Agents can work independently of each other or under the direction of another agent. Multi-agent systems can have different organizational structures that determine the communication between them.

The research [16] considers the application of multi-agent systems in smart energy networks. Attention is paid to agent coordination, resource allocation, and system optimization. The study [17] considers the application of a multi-agent reinforcement learning system for the automation and control of water systems.

2 Description of a modern electric drive

In the context of digitalization of production and creation of smart, the evolution of the electric drive from a local electromechanical system to a cyber-physical object as part of the CPS is inevitable.

Let us consider a modern electric drive as a cyber-physical mechatronic system that implements the functions of a mechatronic motion module integrated into a digital production environment, which is hereinafter referred to as *Intelligent Mechatronic Motion Module (IMMM)*. This module is considered as a stand-alone system that can be used individually and in various combinations with other modules. IMMM consists of the following components:

- Mechanical part – motor shaft with gearbox.
- Electrical part – electric motor(s).
- Electronic part – inverter, sensors, power electronics.
- Information part – embedded computer systems, control system algorithms.

At the same time, these components are being expanded by information technologies, namely the Internet of Things, Artificial Intelligence, Big Data Analysis and Cloud Computing. Some of these technologies can be applied directly to the IMMM, while for others the IMMM will act as a data provider and an object of optimization or condition monitoring within the CPS component.

The concept of an Intelligent Mechatronic Motion Module in the age of Industry 4.0 is graphically presented in Figure 1.

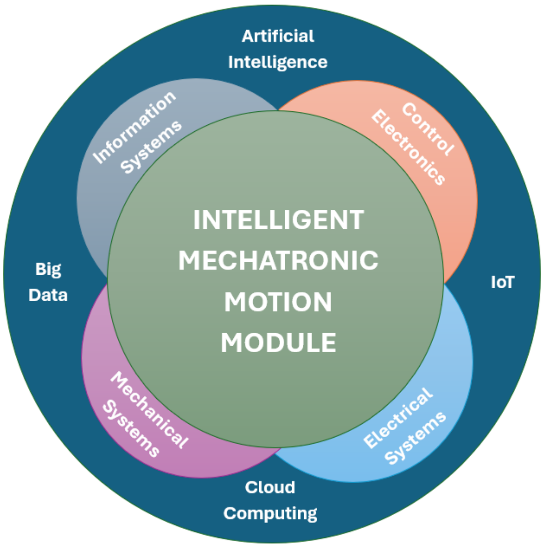

Fig. 1 – Components of an Intelligent Mechatronic Motion Module in the Industry 4.0 paradigm. (Source: compiled by the author)

Table 1 presents the evolution of the electric drive from a local electromechanical system to an IMMM as part of a CPS.

Table 1 – Evolution of the electric drive from a local electromechanical system to an IMMM as part of a CPS (Source: compiled by the author)

Characteristic	Local electromechanical system	IMMM
Architecture	Local	Distributed
Control	Classical methods (PI, PID, etc.)	Adaptive, Intelligent
Scaling	Limited	Modular, flexible
Data	Without accumulation and analysis	Accumulation and analysis
Condition assessment	Minimal	Multichannel, Simulated in real time
Energy efficiency	Fixed	Context-sensitive, capable of optimization
Safety	Functional	Functional, Informational

3. Multi-agent automatic control system

Growing technological requirements for CPS lead to growing requirements for IMMM and its components, including ACS. These requirements can be implemented through optimization and application of new technologies of the hardware and software components of ACS.

Thanks to the introduction of embedded computer systems as part of IMMM, the computing power and interaction interfaces of ACS are expanding. This enables flexible integration of IMMM into CPS, data exchange and continuous optimization, which is a necessary component of achieving energy efficiency and sustainable development.

When implementing energy-efficient programmable solutions in ACS, it is necessary to consider their impact on the accuracy and speed of the system. At the same time, an important component is the stability of this system in conditions of uncertainty, which generates the influence of external factors on this system, which is especially relevant for autonomous robotic systems. In addition to the components of accuracy, speed, energy efficiency, and system stability, an important component is the time spent on developing and implementing optimization or developing the system as a whole. At the same time, using information components in ACS, ensuring system security goes beyond the functional one and is supplemented by the information component. This makes it necessary to take into account functional and information security when developing programmable ACS.

Let's systematize and narrow down the requirements for ACS into five interconnected criteria: speed, accuracy, stability, energy efficiency, and system security. Noting that in our case we are talking about the functional components of the ACS in operation. Therefore, we take that the time for development and implementation does not affect the functionality of this system itself, therefore it is not taken into account.

functionality of this system itself, therefore it is not taken into account.

Let us consider the construction of a programmable ACS for IMMM based on the principle of a multi-agent system. Note that IMMM can consist of one or N-electric motors. From the point of view of the control system, the physical system will be considered as a single system, while the control itself will be multi-criteria in its principle. That is, each agent represents a separate control function and performs local goals, without realizing the overall system goal. In addition to the agents for speed, accuracy, stability, energy efficiency, and system security, a synchronization agent is added to ensure coordination of subsystems. Table 2 lists the agents and their functional roles.

Table 2 – Agents of the ACS and their functionality roles (Source: compiled by the author)

Agent	Functional role
Accuracy	Reducing the control error
Energy efficiency	Energy consumption optimization
Synchronization	Subsystem state coordination
Stability	System response to external disturbances
Speed	Ensuring a given speed
Safety	System anomaly detection

The proposed ACS has a hybrid structure. It includes:

- Decentralized group of target agents (Accuracy, Energy efficiency, Synchronization).
- Centralized system stability agent (Stability).
- Hierarchical execution relationship (Speed).
- Distributed security diagnostics (Safety).

The structural diagram of the hybrid multi-agent ACS is shown in Figure 2.

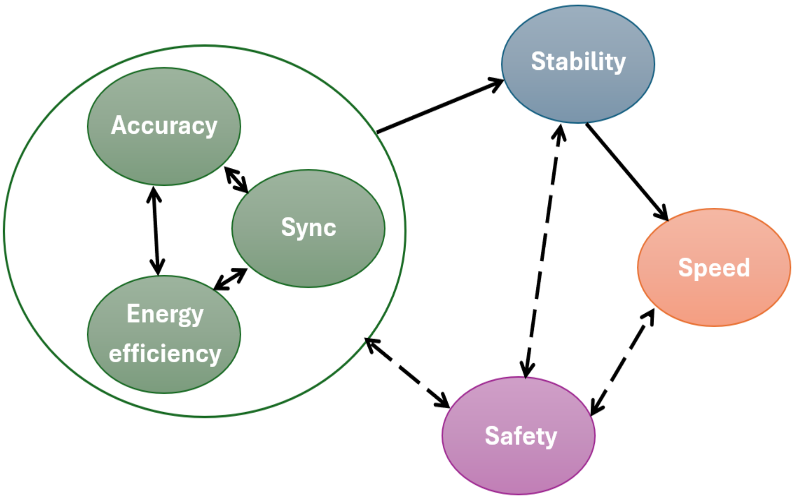

Fig. 2 – Structural diagram of a hybrid multi-agent ACS.
(Source: compiled by the author)

The multi-agent model for constructing an ACS with a multi-motor IMMM is a system that forms, corrects, and limits the control signal depending on the specified criteria. In this case, the final control signal is formed through coordination, provided that the specified stability is observed. At the same time, the criteria can be expanded by introducing additional agents.

The proposed approach to building an ACS gives the control system flexibility in implementing intelligent control algorithms, adaptability to application conditions, and the possibility of continuous optimization through the use of artificial intelligence elements.

Conclusion

The Industry 4.0 paradigm leads to the digitization and expansion of the capabilities of mechatronic systems, including electric drives. This clearly illustrates the vector of development and penetration of information technologies into automatic control systems. Information technology enables the implementation of distributed decision-making using programmable algorithms, machine learning methods, high-level communication, and real-time status monitoring. This provides opportunities for self-improvement of automatic control algorithms and identification of system anomalies.

The result of the current study is a description of the main technologies of the age of the fourth idustrial revolution and their impact on electric drives and their ACS. A modern electric drive in the form of IMMM is presented. A model for constructing an ACS based on a multi-agent control system for a multi-engine IMMM is proposed and characterized.

The next stage of the research is the mathematical description of the proposed ACS intellectual model and the implementation of software for conducting the planned physical experiments and mathematical simulation.

Conflicts of interest

The author of this paper declares that there is no conflict of interest regarding this study, including financial, personal, authorial, or any other that could influence the research, as well as the results presented in this paper.

Financing

The research was conducted without financial support.

Data availability

All data are available in numerical or graphical form in the main text of the research.

Using artificial intelligence

The author confirms that he used artificial intelligence technologies to search and review publicly available information. At the same time, the finalized analysis of scientific research, conclusions and writing of the text, creation of figures and tables of this article are the exclusive results of the author's work.

Author`s contribution

Oleksii S. Shevchuk: The research, data processing, creation of visualization of results and text, conceptualization and other activities are entirely the work of the author.

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Багатоагентна система автоматичного керування сучасним електроприводом в епоху Індустрії 4.0

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Анотація: *Індустрія 4.0 характеризується застосуванням взаємопов'язаних інтелектуальних систем, здатних до обміну даними в режимі реального часу, розподіленого прийняття рішень та автоматизації. Електропривід є одним з основних компонентів для реалізації обертового та поступального руху в складних електромеханічних системах, таких як Кібер-Фізичні Системи. Сучасний розвиток технологій призводить до все більшого проникнення інформаційних технологій на різні рівні електромеханічних систем, в тому числі систем електроприводу. Як демонструють дослідження, вбудовані комп'ютерні системи мають широке застосування в системах автоматизації. В той же час, застосування цифрових двійників робить електроприводи об'єктом моделювання та призводить до необхідності комунікації в режимі реального часу для контролю стану електроприводів та оптимізації їх роботи. Необхідність розподіленого прийняття рішень, при виконанні складних технологічних процесів в умовах невизначеності зовнішніх впливів на систему, вимагає переходу від жорстко заданої логіки керування електроприводом до адаптивної та інтелектуальної систем керування. Для цього в поточному дослідженні пропонується побудова інтелектуальної системи автоматичного керування сучасного електропривода з застосуванням багатоагентної моделі керування. Запропонований підхід в побудові системи автоматичного керування надає гнучкості системі керування в реалізації інтелектуальних алгоритмів керування, адаптивності під умови застосування та можливості безперервної оптимізації завдяки застосуванню елементів штучного інтелекту.*

Ключові слова: *Системи Автоматичного Керування, Електропривід, Багатоагентна система, Індустрія 4.0, Мехатроніка, Кібер-Фізичні Системи, Вбудовані Комп'ютерні Системи.*

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