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# DEVELOPMENT OF AN ENERGY-EFFICIENT AUTOMATIC CONTROL SYSTEM OF MOBILE INDUSTRIAL ROBOT

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***Abstract.*** *The use of neural networks in automatic control systems makes it possible to increase their compliance with the assigned tasks. Such automatic control systems are able not only to use the general control methods, but also offer their algorithmic approaches to solving the tasks related to the problem of identifying the parameters of the control object. In the article, adaptive control systems and control systems using neural networks are considered. An analysis of recent research in this direction has been conducted. A concept has been proposed for the development of an energy-efficient intelligent automatic control system for a multi-motor electric drive of a mobile industrial robot.*

***Keywords:*** *automatic control system, mobile industrial robot, nonlinearity, energy-efficiency, uncertainty, adaptability, neural network, mechatronic module.*

## Introduction

Modern industry is inextricably linked with the electric drive, which plays a key role in automation, increasing productivity and energy-efficiency of production processes. Based on the study of the International Energy Agency [1], from the energy point of view, electric drives are one of the main consumers of electric energy in many industrial sectors. At the same time, electric drives are most widely used in *mobile industrial robots (MIR)*.

In the MIR field, research related to the increase of energy-efficiency mainly follows two approaches, eco-efficient design methods and eco-efficient programming methods. These studies show that the introduction of modern high-tech solutions when building MIR control systems makes it possible to increase the energy efficiency of their motion systems.

One of the examples of eco-efficient programming is the reduction of energy consumption by programming using trajectory optimization methods taking into account energy costs during path planning, this method is reflected in the study [2]. The results of another study [3], demonstrate the possibility of reducing the energy consumption of a bionic palletizing robot due to the use of a planner based on a differential evolutionary algorithm and software for modeling and finding the most efficient bionic trajectory.

When designing electric drive control systems for the MIR, it should be taken into account that all real *automatic control systems (ACS)* are nonlinear. This is caused by the fact that the main element of the electric drive is an electric motor, the dynamic processes of which are described by nonlinear equations. In addition, friction and inertia of the elements of the mechanical part of the system also introduce nonlinearities into the system, especially with large amplitudes of movement [4].

Due to many uncertainties, such as unmodeled dynamics, parameter changes and external disturbances, modern automated control systems for nonlinear dynamic systems require improvement and the introduction of new high-tech solutions.



## 1. Problem formulation

One of the main problems of the modern theory of automatic control of the electric drive of a MIR is the control of nonlinear electromechanical systems for technological processes with rapid dynamics of changes in load torques under conditions of uncertainty.

Uncertainty is caused by the lack of complete information about the influence of external factors on the system. In addition, the mathematical model of the control object obtained analytically may have a significant error compared to the real technical system.

The study [5] considers the construction of the ACS for an electric drive with a complex mechanical structure and parameter uncertainty. To solve this problem, an adaptive controller with two neural networks has been developed to control the speed of a two-mass system. The idea of combining an intelligent controller with the use of elements of artificial intelligence and online data visualization requires special attention in this study. The developed data server allows real-time monitoring of plant status variables and basic remote control of the system. This is fully consistent with the concept of Industry 5.0 [6], which is a necessary feature in the construction of modern electromechanical systems of MIR.

Another problem in developing automatic control systems is the stability of dynamic systems. It depends on the physical properties and parameters of the system and the magnitude and location of the external action. Stability is determined by the ability of a system to maintain limited deviations from equilibrium or the initial state when exposed to external disturbances or changes in system parameters.

Ensuring system stability is the subject of the study [7], which proposes nonlinear control based on the Lyapunov method, defined using a neural network that uses Lyapunov theory to calculate the control law for a nonlinear system.

**2. Subject of research**

Currently, there are many classical methods that help to develop a stable automatic control system. For example, ACS that are designed using *proportional-integral (PI)* and *proportional-integral-derivative (PID)* controllers. They are widely used in existing industrial automatic control systems. This is due to their relative ease of setup, versatility and high reliability. However, they also have a few disadvantages, the main one of which is the limited ability to reconfigure the control structure when changing system parameters. Therefore, especially in complex nonlinear systems, more advanced control methods are being introduced, one of which is adaptive control systems and control systems using neural networks. Figure 1 shows areas of effective application of such control systems, depending on the completeness of information about the control object and the level of complexity of the control object.

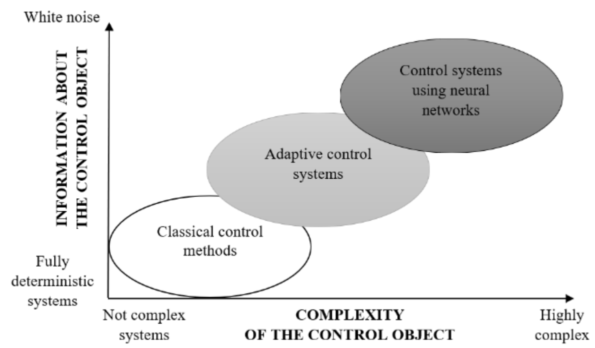


Fig. 1. Control systems depending on the complexity and information about the control object.

To control complex nonlinear dynamic systems, such as MIR, under conditions of uncertainty, the study discusses modern methods for developing adaptive control systems and control systems using neural networks, as well as hybrid forms that combine various methods. At the same time, a concept is proposed for developing an energy-efficient intelligent ACS for a multi-motor electric drive for a MIR.

**3. Adaptive control**

An automatic adaptive control system is a system in which parameters, system structure, or control actions are automatically changed based on current information to achieve an optimal state of the system under initial uncertainty and changing conditions [8].

The difference between classical regulators with feedback and adaptive regulators is that classical ones use the feedback principle to compensate for unknown disturbances and states of the object, where the approach is the same in all situations. While the main features of an adaptive system are a change in the approach to processing control errors and adaptation of the control law to unknown conditions.

Depending on the approaches to the formation of the adaptation mechanism, the control system is classified into systems:

– Based on a heuristic approach;
– With a reference model;
– With a variable structure;
– With self-adjusting.

Let us consider in detail the approach with self-adjustment of regulators in the formation of the adaptation mechanism, which can be direct and indirect.

In direct adaptive control, system parameters are adapted directly during operation of the control system. Adaptation occurs based on output signals and input disturbances of the system. The main idea is to adjust the system parameters to provide the necessary response to changes in the system. This approach has a relatively simple implementation and low computational complexity, because for simple linear systems it can be implemented using a PI controller. However, when controlling a nonlinear system, where an accurate model is difficult or impossible to construct, more advanced control methods are used.

One of the examples is the method proposed in study [9], where the speed control of a dual-flexible manipulator with a telescopic arm is built based on an adaptive PI controller with a disturbance observer to suppress fluctuations in the angular speed of the servo system. At the same time, the Lyapunov stability theorem is used to construct the adaptive law and the law of controller overload compensation.

In systems with an indirect approach to the development of adaptive control, the system parameters are adapted based on the model used to approx imate the controlled object. Adaptation is based on the discrepancy between the actual output of the system and the output predicted by the model. The value of system variable parameters is used to reconfigure the parameters of the control controller. Although this approach allows the use of identification techniques to improve accuracy, it also requires accuracy in the development of the system model, which may be difficult to achieve in nonlinear systems. The inaccuracy of the implemented estimation algorithm may lead to instability of the control structure.

An example of an indirect approach to the development of an adaptive control system is the study [10], which considers the development of the ACS of a two-mass system. For this, a system with a PI controller and additional feedback and a corresponding adaptation mechanism is proposed. The study considered of a classical and fuzzy approach, namely the Unscented Kalman Filter and the extended version of the Fuzzy Unscented Kalman Filter for the estimation of mechanical state variables and parameters in a drive system with an elastic connection. The simulation shows that the estimation accuracy when using the extended version of the Kalman filter increases from 21.9% to 42.8% for the estimated states, and from 6% to 24.1% for their derivatives (which means less influence of noise on the state estimates).

## 4. Control systems using neural networks

The development of microprocessor technologies and artificial intelligence has led to an increase in research aimed at introducing neural networks into automatic control systems for MIR.

A *neural network (NN)* is inherently an adaptive system, the life cycle of which consists of two independent phases, training and network operation. NN are not programmed in the usual sense of the word, they are trained. This is one of the main advantages of NN over traditional algorithms that are used in ACS.

Controllers based on NN can be effective in cases where creating an analytical model of the system is extremely difficult. This may be due to a number of factors, the most common of which are:

- The presence of predetermined external influences (for example, when MIR operate in extreme or uncertain environments).

- Significant disturbing internal influences (for example, the action of dry and viscous friction forces in electromechanical devices of MIR).

- Inconstancy of parameters and structure of the MIR (for example, replacement of modules of the MIR during partial optimization or repair).

In the study [11], control algorithms based on radial basis function NN are proposed for speed control of two-mass systems. Analysis of the results of simulation experiments demonstrates that the proposed control algorithms significantly improve the performance of classical feedback controllers applied to two-mass systems in the presence of parameter uncertainty. Another advantage of the presented control algorithms is a model-free approach. Without any state observer, there is no need to perform an additional recalculation of the plant parameters to adapt to the current state of the drive.

A manipulator control scheme based on a fuzzy NN was proposed in the study [12]. At the same time, the learning speed and generalization ability of the network are improved using a combination of the particle swarm search algorithm and real-time adjustment of the back propagation NN algorithm. The research results demonstrate that the system achieves high tracking accuracy, adaptability and stability when using the proposed control system.

The possibilities of recurrent NN to improve the response of the feedback control system to uncertainties are studied in [13]. Recurrent NN, as a disturbance observer, estimates the unknown uncertainties and allows achieving a zero steady state error. The weight of the network is adapted in real-time based on the stability of the closed loop system, which is implemented using the Lyapunov stability theorem. Research shows that recurrent NN requires only tracking error information, while its transient response is faster than the feed forward NN.

## 5. A generalized definition of a multi-motor electric drive of a MIR

A modern electric drive for the movement of a MIR can be considered as a mechatronic movement module with intelligent control. This is due to the development of digital technologies, which leads to an increasing expansion of mechanical systems with components from the electronics and software industries. There is a growing amount of research aimed at developing and using intelligent mechatronic modules. This issue is addressed, for example, in the study [14], in which attention is paid to the issue of interdisciplinary design of modules in mechatronic modular systems.

An *intelligent mechatronic motion module (IMMM)* should be understood as a product that is structurally and functionally independent with a synergistic integration of mechanical, electrical and computer parts, which can be used individually and in various combinations with other modules. In addition to providing intelligent control, the main difference between the IMMM and the general industrial drive is the use of the motor shaft as one of the elements of the mechanical motion converter [15]. The generalized scheme of IMMM is shown in Figure 2.

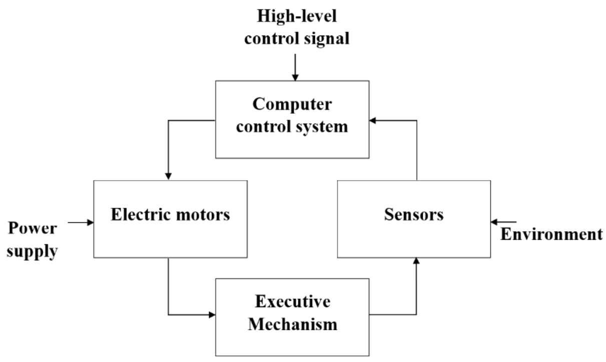


Fig. 2. Generalized scheme of IMMM.

The development of a modern electric drive for the movement of a MIR based on the IMMM principle provides the following advantages:

- The ability to perform complex tasks independently, without the participation of the higher-level control system. This increases the flexibility of the system and provides an opportunity to use intelligent control methods directly at the executive level, which significantly increases the quality of control processes when the system operates in variable and uncertain conditions of the external environment.
- Creation of modules for distributed automated control systems based on personal computers, which greatly simplifies and expands the possibilities of information interaction between system modules, due to use of a single high-level information interface.
- Increasing the reliability and safety of the module and the whole system, due to intelligent fault diagnosis and protection in abnormal operating modes.

## 6. Determination of requirements for the ACS of a multi-motor electric drive of a MIR

A necessary component of the construction of ACS is the determination of requirements for it, which are built depending on the purpose and characteristics of the electromechanical system [16].

In our case, a multi-motor electric drive for moving a MIR is considered. The main feature of this system is the nonlinearity of its components. In turn, the application environment requires highly dynamic movement when changing the working environment in real time.

The multi-motor electric drive of the movement of a MIR is considered as a multi-mass system, where each motor, including the executive mechanism, forms a separate mass in the system.

As for the state variables, the system is multidimensional with simultaneous control of the electromagnetic torque and speed of the motor shaft, the time of optimal acceleration and deceleration depending on energy consumption.

When building the ACS, it is planned to use a digital computing device, so the system acquires the character of discrete. At the same time, it is planned to perform quantization of the signal by time, which is typical for pulse systems.

A general requirement for the ACS is the automatic change of parameters, structure or control algorithm to ensure energy-efficient movement of the MIR and maintain system stability under arbitrarily variable external influences and arbitrarily variable internal parameters of the system.

## 7. Description of the concept of developing an energy-efficient intelligent ACS

Based on the defined requirements for the ACS of a multi-motor electric drive of a MIR, the concept of building an energy-efficient system with intelligent control was developed, the structural diagram of which is shown in Figure 3. At the same time, a diagram of the algorithm for energy-efficient control of a multi-motor electric drive for the movement of the MIR was developed, which is shown in Figure 4.

The main ideas of the proposed concept of an intelligent ACS are:

- Developing of a MIR movement module with its own intelligent ACS capable of performing complex application tasks independently, without the participation of a higher-level control system, which can increase the flexibility and speed of building a MIR as a whole.
- Energy-efficient control of the connection of electric motors depending on the load and external disturbing factors. Energy-efficient control of acceleration and deceleration based on the energy-efficient control law, which is formed depending on the priority of the movement mode (levers of influence - speed or energy efficiency of movement).
- Intelligent monitoring of system component health and power supply availability to improve system reliability and safety.

The main disadvantage of the proposed approach is the need for complex mathematical analysis when building stability and energy-efficiency laws that will ensure stability and energy-efficiency for a wide range of different operating conditions of the system.

To solve this problem, it is proposed to implement the use of a NN in the development of the ACS. It can help solve the problem of complex

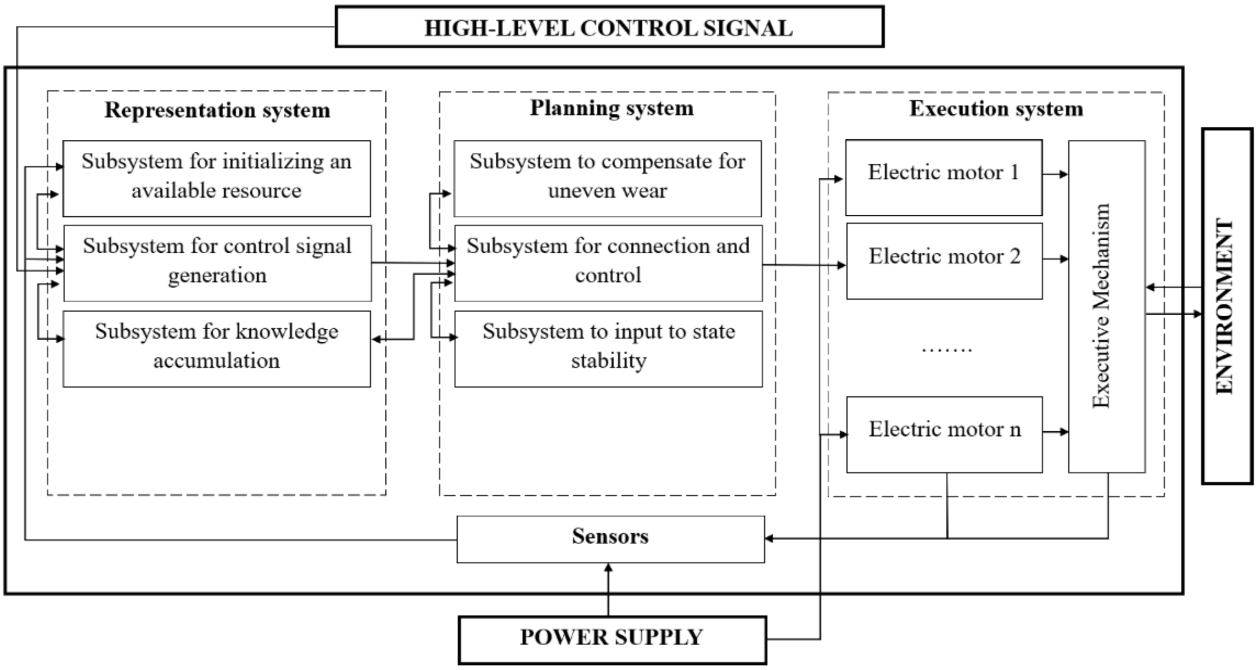


Fig. 3. Structural diagram of an intelligent ACS for a multi-motor electric drive of a MIR.

mathematical analysis in the development of stability and energy-efficiency laws, due to the ability of the NN to adapt to real conditions and learn from experience. A NN can be used to approximate complex mathematical functions that arise in the process of analyzing and controlling a nonlinear system under conditions of uncertainty.

## Conclusions

Considering the large number of various modules, sensors and executive devices used in modern MIR, the question arises as to the feasibility of using a centralized intelligent ACS.

In addition, many studies are directed at the development of intelligent ACS with an emphasis on determining the optimal trajectory of the movement.

At the same time, the potential for increasing energy-efficiency due to the use of a multi-motor electric drive in the movement system of a MIR remains unexplored. In combination with a NN, this can allow building a stable and energy-efficient intelligent ACS taking into account nonlinearities, rather than generalizing them to the level of linear ones when developing a control object model under conditions of uncertainty. It is these issues that were paid attention to when developing the proposed concept for the development of an energy-efficient intelligent ACS for a multi-motor electric drive of a MIR.

It is appropriate to direct subsequent research to a mathematical description of the proposed model of an intelligent ACS. This will form the basis for the implementation of software during developing an experimental model for case studies of energy-efficiency and system stability under the control of the proposed intelligent ACS for a multi-motor electric drive of a MIR.

## References

1. IEA, Motor-driven system electricity use as a share of electricity use by industry subsector, IEA, Paris. [Electronic Resource]. – Access Mode https://www.iea.org/data-and-statistics/charts/motor-driven-system-electricity-use-as-a-share-of-electricity-use-by-industry-subsector, IEA. License: CC BY 4.0

2. Garriz C, Domingo R. Trajectory Optimization in Terms of Energy and Performance of an Industrial Robot in the Manufacturing Industry. Sensors. 2022; 22(19):7538. https://doi.org/10.3390/s22197538

3. Deng Y, Zhou T, Zhao G, Zhu K, Xu Z, Liu H. Energy Saving Planner Model via Differential Evolutionary Algorithm for Bionic Palletizing Robot. Sensors. 2022; 22(19):7545. https://doi.org/10.3390/s22197545

4. Nonlinear and discrete automatic control systems. Course of lectures [Electronic resource]: textbook for students of specialty 141 “Power engineering, electrical engineering and electromechanics” / National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnik Institute”; compiled by B. I. Priymak. – Electronic text data (1 file:

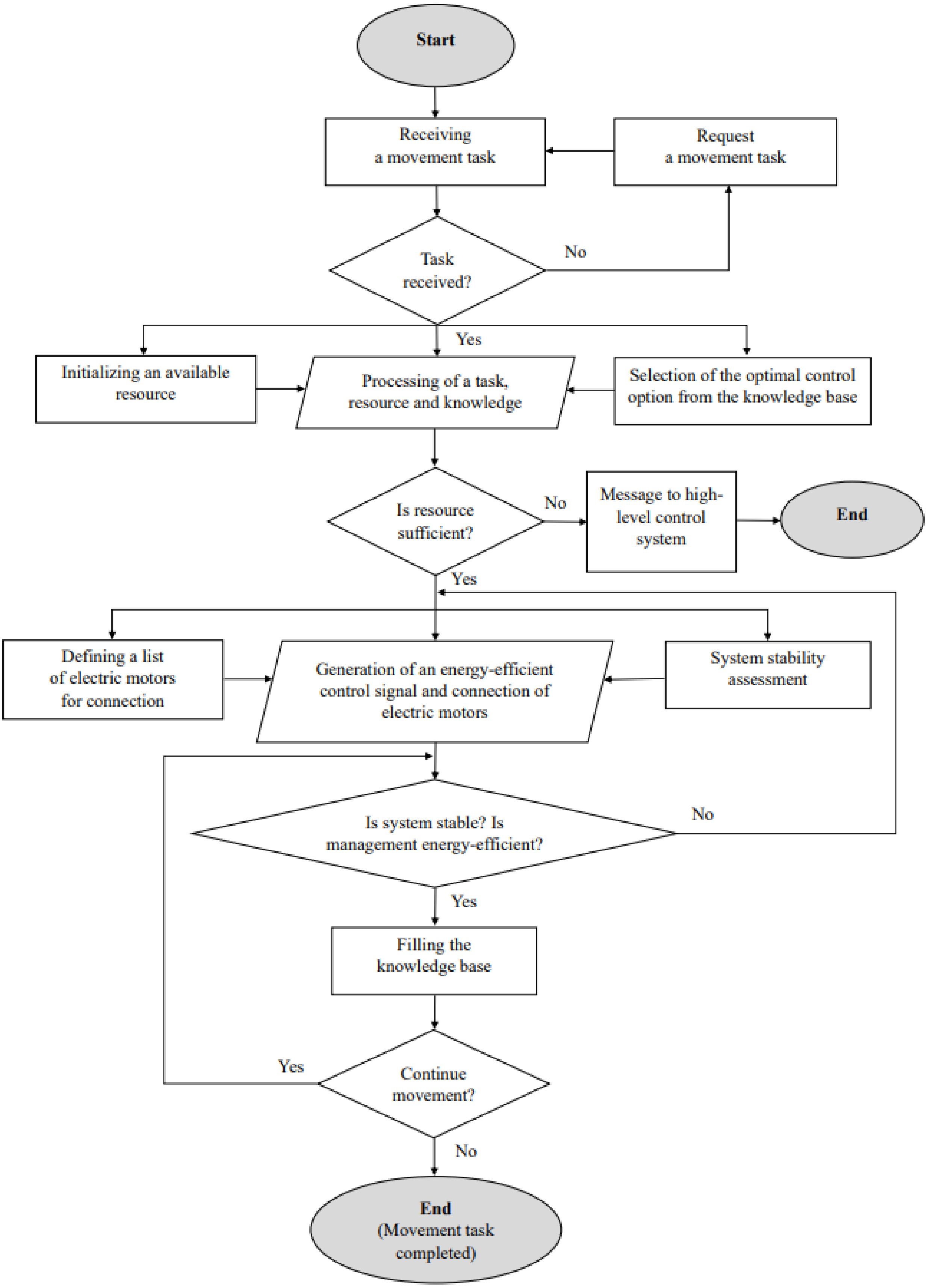


Fig. 4. Simplified algorithm diagram for energy-efficient intelligent control of a multi-motor electric drive of a MIR

4.07 MB). – Kyiv: National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnik Institute", 2019. – 198 pages. https://ela.kpi.ua/handle/123456789/32086

5. Malarczyk M, Zychlewicz M, Stanislawski R, Kaminski M. Electric Drive with an Adaptive Controller and Wireless Communication System. Future Internet. 2023; 15(2):49. https://doi.org/10.3390/fi15020049

6. European Commission, Industry 5.0. [Electronic Resource]. – Access Mode https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/industry-50_en

7. Rosana C.B. Rego, Fábio Meneghetti U. de Araújo, Lyapunov-based continuous-time nonlinear control using deep neural network applied to underactuated systems, Engineering Applications of Artificial Intelligence, Volume 107, 2022, 104519, ISSN 0952-1976, https://doi.org/10.1016/j.engappai.2021.104519

8. Modern control theory. Part 2. Applied aspects of modern control theory [Electronic resource]: textbook for students of specialty 151 "Automation and computer-integrated technologies", specializations "Automated control of technological processes", "Computer-integrated technological processes and production" / Y. M. Kovrygo, O. V. Stepanets, T. G. Bagan, O. S. Bunke; National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnik Institute". – Electronic text data (1 file: 4,32 MB). – Kyiv: National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnik Institute", 2018. – 155 pages. https://ela.kpi.ua/handle/123456789/23117

9. Dongyang Shang, Xiaopeng Li, Meng Yin, Fanjie Li, Speed control method for dual-flexible manipulator with a telescopic arm considering bearing friction based on adaptive PI controller with DOB, Alexandria Engineering Journal, Volume 61, Issue 6, 2022, Pages 4741-4756, ISSN 1110-0168, https://doi.org/10.1016/j.aej.2021.10.026

10. Szabat K, Wróbel K, Dróżdż K, Janiszewski D, Pajchrowski T, Wójcik A. A Fuzzy Unscented Kalman Filter in the Adaptive Control System of a Drive System with a Flexible Joint. Energies. 2020; 13(8):2056. https://doi.org/10.3390/en13082056

11. Stanislawski R, Tapamo J-R, Kaminski M. Virtual Signal Calculation Using Radial Neural Model Applied in a State Controller of a Two-Mass System. Energies. 2023; 16(15):5629. https://doi.org/10.3390/en16155629

12. Yanhe Shen, Robotic trajectory tracking control system based on fuzzy neural network, Measurement: Sensors, Volume 31, 2024, 101006, ISSN 2665-9174, https://doi.org/10.1016/j.measen.2023.101006

13. Adel Merabet, Saikrishna Kanukollu, Ahmed Al-Durra, Ehab F. El-Saadany, Adaptive recurrent neural network for uncertainties estimation in feedback control system, Journal of Automation and Intelligence, Volume 2, Issue 3, 2023, Pages 119-129, ISSN 2949-8554, https://doi.org/10.1016/j.jai.2023.07.001

14. Michael Riesener, Maximilian Kuhn, Carsten Boβmann, Günther Schuh, Methodology for the Design of Interdisciplinary Modules for Mechatronic Modular Product Platforms, Procedia CIRP, Volume 119, 2023, Pages 675-680, ISSN 2212-8271, https://doi.org/10.1016/j.procir.2023.03.119

15. Loveykin V.S., Romasevich Y.O., Chovniuk Y.V. Mechatronics. Educational manual. – Kyiv, 2012. - 357 pages.

16. Automated electromechanical systems: lecture notes / compilers: Chervyakov V. D., Leontiev P. V., Sokolov S. V. – Sumy: Sumy State University, 2022. – 253 pages.

## ПОБУДОВА ЕНЕРГОЕФЕКТИВНОЇ СИСТЕМИ АВТОМАТИЧНОГО КЕРУВАННЯ МОБІЛЬНОГО ПРОМИСЛОВОГО РОБОТА

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***Анотація.*** *Сучасна промисловість невід'ємно пов'язана з електроприводом, який відіграє ключову роль, забезпечуючи автоматизацію, підвищення продуктивності та енергоефективність виробничих процесів. При цьому електроприводи мають найбільше застосування в мобільних промислових роботах. Дослідження демонструють, що впровадження сучасних високотехнологічних рішень при побудові систем керування електроприводом мобільних промислових роботів дозволяє підвищити енергоефективність їх систем переміщення. На даний час існує багато класичних методів, які допомагають розробити стійку систему автоматичного керування. Однак, таким методам властивий ряд недоліків, головним з яких є обмежені можливості переналаштування структури керування при зміні параметрів системи. Через це, особливо в складних нелінійних системах, які працюють в умо-*

*вах невизначеності, впроваджують більш розширені методи керування, одними з яких є адаптивні системи керування та системи керування з використанням нейромереж. Такі системи автоматичного керування здатні не тільки використовувати класичні методи керування, але й пропонують свої алгоритмічні підходи до розв'язання ряду завдань, пов'язаних з проблемою ідентифікації параметрів об'єкта керування. В статті розглядаються сучасні методи побудови адаптивних систем керування та систем керування з використанням нейромереж, а також гібридні форми, які об'єднують різні методи. В той же час в статті запропонована концепція побудови енергоефективної інтелектуальної системи автоматичного керування багатодвигунним електроприводом мобільного промислового робота. Описаний підхід покликаний розкрити потенціал енергозбереження за допомогою використання багатодвигунного електроприводу в системі переміщення мобільного промислового робота, що у поєднанні з нейромережею може дозволити побудувати стійку та енергоефективну інтелектуальну систему автоматичного керування з врахуванням нелінійностей, а не їх узагальненням до рівня лінійних при побудові моделі об'єкта керування в умовах невизначеності.*

***Ключові слова:*** *система автоматичного керування, мобільний промисловий робот, нелінійність, енергоефективність, невизначеність, адаптивність, нейронна мережа, мехатронний модуль.*

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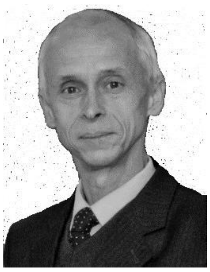

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