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DEVELOPMENT OF A MODEL OF DYNAMIC DESCRIPTION OF THE ENVIRONMENT OF A COLLABORATIVE MANIPULATOR ROBOT WITHIN THE CONCEPT OF INDUSTRY 5.0

This article is devoted to the development of the dynamic description model of the environment of a collaborative manipulator robot within the framework of the Industry 5.0 concept. A need in creating new approaches to interaction between robots and humans in production conditions arises with the development of robotics technologies and the integration of robots into cyber-physical systems. The purpose of the study is to increase the efficiency of the interaction of a collaborative robot with the environment by creating an adaptive, safe and intelligent model of dynamic description that meets the modern requirements of Industry 5.0. As part of this work, a model was developed and visualized that allows the manipulator robot to react more accurately and timely to changes in the environment. The presented model of dynamic description includes mechanisms for processing data on external factors, which allows work to adapt to new conditions faster, ensuring the safety of interaction with the operator and other elements of the production system. The use of this model in the work of collaborative robots makes it possible to increase their flexibility and ability to make independent decisions in various work situations. This is especially important for robots that work in environments with constant change or unpredictable events. Thanks to the ability to quickly analyze the state of the environment and make decisions based on the received data, the collaborative robot can perform production tasks more efficiently, minimizing operator risks and increasing overall productivity. The article also provides a visual presentation of the model, which clearly demonstrates the possibilities of its application in production conditions. This allows a better understanding of how the model helps the work to integrate into the cyber-physical system and work in cooperation with other elements of the production system, including people. The proposed approach opens up new perspectives for the development of robotic systems focused on human-robot interaction and allows to increase the level of safety and production efficiency. The study will be useful for specialists in the field of robotics, cyber-physical systems and Industry 5.0, as well as for enterprises seeking to increase the level of automation and integration of robots in production processes.

Key words: *Collaborative robot, Dynamic environment description, Industry 5.0, Cyber-physical systems, Human-robot interaction, Adaptive robotics, Intelligent manufacturing, Manipulator robot, Safety in robotics, Production systems automation.*

Formulation of the problem. In the modern world, there is a rapid development of industrial robots, in particular, collaborative manipulator robots, which are increasingly being introduced into production processes within the framework of the Industry 5.0 concept. This concept aims to integrate advanced technologies into production environments with an emphasis on human-machine collaboration. The main task of Industry 5.0 is to increase production efficiency due to the flexibility, adaptability and interactivity of robotic systems. One of the key challenges is that current robot systems are often not flexible enough to effectively adapt to changes in the work environment where a human and a robot perform joint tasks. This creates risks to human safety and reduces the overall performance of the system. Therefore, the development of models capable of providing an accurate, timely and dynamic description of the environment becomes a key task for collaborative manipulator robots.

Therefore, the relevance of the research lies in the need to develop innovative approaches to the dynamic modeling of the working environment of collaborative manipulator robots, which will contribute to increasing the safety, adaptability and efficiency of robotic systems within the framework of Industry 5.0.

Analysis of recent research and publications. Recent Gao J., Han H. studies of kinematic calibration include an iterative optimization process based on the theory of least squares for typical industrial robots with 6 degrees of freedom [1, p. 751]. In the C. Faria, J.L. Vilaça & S. Monteiro work proposed an automatic algorithm for determining the DH parameters of serial manipulators [2, p. 613], where a geometric operation and double vector algebra were used to determine the relative transformation matrices, from which the DH parameters are then calculated. Boby R.A., Klimchik A. reported a combination of geometric and parametric identification methods to take advantage of both methods for industrial robots [3, p. 5]. They have shown that their method works well even with a limited workspace. Similarly, in the Hayat A.A. and Boby R.A. article a general formulation was proposed for determining the kinematic parameters of an industrial robot using a geometric approach when no prior information about the robot kinematics was available. They used a monocular camera to determine the parameters of a typical industrial robot with 6 degrees of freedom [4, p. 329]. In the Brau-Avila A. and Acero R. research an indexed measuring platform was used as a measuring platform to determine kinematic parameters [5, p. 1031]. The assessment of the accuracy of the calibration of the kinematic parameters of industrial robots was analyzed in the work of He S., Ma L. [6, p. 1049], with the aim of improving the calibration on site. Similarly, but with a rigid-flexible communication error model, which consists of geometric and malleable errors for industrial robots with non-negligible flexibility, was used in Chen X., Zhang Q [7, p. 55]. In addition to typical industrial robots, identification of parameters and calibration of a not fully symmetrical parallel delta robot were presented in [8, p. 9]. As can be seen with the increase in the number of collaborative robots and their integration in industries such as production lines and daily environments, increasing the absolute accuracy due to the description of the dynamic space of the work area remains an urgent problem for the realizations of human joint work and the collaborative robot manipulator within the concepts of Industry 5.0 [9, p. 92].

Task statement development of a model of a dynamic description of the environment of a collaborative robot-manipulator within the framework of the concept of Industry 5.0, which will allow to increase the efficiency of its interaction with a person and other elements of the production system, ensuring a more adaptive, safe and intelligent robotic interaction in the conditions of cyber-physical systems.

Outline of the main material of the study. To describe the environment of a collaborative industrial manipulator robot that works together with a person, you can use a mathematical model that includes several main components: a description of space, objects, movements, and safety [10, p. 221; 11, p. 114]. As a result, the mathematical model of the representation of the environment of the collaborative industrial manipulator robot can be presented as follows:

$$CR = \left(\mathbb{R}^3, \mathbb{D}, \Omega_i, \boldsymbol{q}, \tau, \Omega_{safe}, u, \mathbb{M}\right) dt \tag{1}$$

Where: CR – a model of the representation of the environment of a corporate industrial manipulator robot;

$\mathbb{R}^3$ – three-dimensional space of the working area of the robot (coordinate system);

$\mathbb{D}$ – working area (space) of a collaborative industrial robot manipulator (a limited space with certain boundaries);

Ω_i – objects in space;

$\boldsymbol{q}$ – movement of a collaborative industrial robot manipulator;

τ – the dynamics of the movement of a collaborative industrial manipulator robot;

Ω_{safe} – security perimeters;

u – communication (commands that can be given to the operator or work);

$\mathbb{M}$ – adaptation (machine learning).

We will give a description of each parameter, starting with the three-dimensional space of the robot's working area ($\mathbb{R}^3$), which within the framework of these studies can be presented in the following form:

$$\mathbb{R}^3 = \langle G, L \rangle \tag{2}$$

Where G – the global coordinate system sets the absolute position of objects in the working area. It can be described using three orthogonal axes: x – horizontal axis (front/back); y – horizontal axis (left/right) and z – vertical axis (up/down). Each point in this space can be represented as:

$$\mathbb{x} = (x, y, z) dt \tag{3}$$

L – the object's local coordinate system is defined relative to the global coordinate system. For example, the local coordinate system of the robot manipulator can be defined in the center of its base or in the middle of the manipulator, and the local coordinate system can be tied to the middle of the human body located in the working area.

$\mathbb{D}$ – the working area (space) of a collaborative industrial robot manipulator can be represented as a limited space $\mathbb{D} \subset \mathbb{R}^3$ with certain limits b_{min} та b_{max}, and can be described by the following expressions:

$$\mathbb{D} = \{\mathbb{x} \in \mathbb{R}^3 | b_{min} \le \mathbb{x} \le b_{max}\} \tag{4}$$

Where: $\mathbb{D}$ – a subset of three-dimensional space $\mathbb{R}^3$ which defines a limited area where the robot can operate;

$\mathbb{D} \in \mathbb{R}^3$ – vectors $\mathbb{x} = (x, y, z)$ represent the coordinates of points in three-dimensional space, where each point is inside the space $\mathbb{D}$ has these coordinates;

b_{min} – a vector defining the minimum space coordinates $\mathbb{D}$.

Thus the area $\mathbb{D}$ allows it to be defined as a rectangular parallelepiped or a cube (depending on the values b_{min} або b_{max}) in the three-dimensional space, inside which the working environment for the manipulator unfolds. Each parameter plays a role in limiting and defining the boundaries of this space, which allows you to precisely position and control the robot in the given coordinates.

Ω_i – objects in space can be represented as areas with certain geometric shapes and sizes. But can be represented in the following expression:

$$\Omega_i = \langle \Omega_c, \Omega_{cy}, \Omega_{co}, \Omega_{cu}, \Omega_{rp}, \Omega_{hp}, \Omega_{qp}, \rangle \quad (5)$$

Where: Ω_c – area with the geometric shape of a sphere (sphere);

Ω_o – areas with a geometric shape of a cylinder (cylinder);

Ω_t – areas with the geometric shape of a cone (cone);

Ω_s – area with a geometric shape of a cube (cube);

Ω_{rh} – region with the geometric shape of a rectangular parallelepiped (rectangular parallelepiped);

Ω_{re} – areas with the geometric shape of a hexagonal prism (hexagonal prism);

Ω_q – area with the geometric shape of a quadrangular pyramid (quadrangular pyramid).

The selection of an area with one or another geometric shape depends on the type of object and its size, for example, in the framework of these studies, a rectangular object Ω_s with the center c_i and sizes d_i, can be represented as follows:

$$\Omega_c = \{\mathbb{x} \in \mathbb{R}^3 | \mathbb{x} - c_i| \leq d_i\} \quad (6)$$

Where: Ω_c – an area in three-dimensional space defined by a center and a radius, representing an object of a certain shape (in this case, spherical);

$\mathbb{x} \in \mathbb{R}^3$ – coordinates in the vector form $\mathbb{x} = (x, y, z)$ represent the coordinates of points in three-dimensional space that may be inside Ω_s;

c_i – center in the form of a vector $c_i = (c_{i,x}, c_{i,y}, c_{i,z})$ determines the coordinates of the center of object i in three-dimensional space, it follows that this is the point from which the distance to other points within the area is measured Ω_s. For example, if $c_i = (3, 8, 4)$, then it is the center of the sphere in space;

d_i – the value of which determines the radius of the area Ω_s. This is the maximum distance from the center c_i to any point in the area. In this case d_i represents the radius of the sphere that describes the object i. Example $d_i = 5$, this means that the object has a radius of 5 units from the center c_i;

$\mathbb{x}$ – are the coordinates of a point in three-dimensional space that are checked for belonging to an area Ω_s

$|\mathbb{x} - c_i| \leq d_i$ – means that the point x is inside or on the boundary of the sphere with center in c_i and radius d_i.

Using an expression 2.5 makes it possible to present objects located in the working area of a collaborative industrial robot manipulator in the form of geometric figures in three-dimensional space, this will allow, within the framework of these studies, to simplify the modeling of the movement of objects with regular shapes, such as: boxes, tools, people, and other objects that can be in the working area.

$\boldsymbol{q}$ – movement of a collaborative industrial robot manipulator, its model can be described as a function of positions $\boldsymbol{q}(t)$ and speeds $\dot{\boldsymbol{q}}(t)$. Positions function $\boldsymbol{q}(t)$ describes the position of an object or system in three-dimensional space as a function of time t. This enables the modeling and management of robots and their mechanical systems, as it allows tracking and controlling changes in position over time. Mathematical representation of the position function $\boldsymbol{q}(t)$ given below:

$$\boldsymbol{q}(t) = \begin{pmatrix} x(t) \\ y(t) \\ z(t) \end{pmatrix} \quad (7)$$

Where: $x(t), y(t), z(t)$ – time functions describing the object's position along each of the three coordinate axes;

t – variable representing time, which can be expressed in different units (seconds, minutes, etc.).

τ – the dynamics of the movement of a collaborative industrial robot manipulator allows describing the relationship between the moments of force that are applied to the joints of the robot and the movement of these joints, taking into account masses, Coriolis forces, gravitational forces and acceleration. This equation is necessary for calculating the necessary moments of force to achieve the desired movements, planning trajectories, as well as for the correction and compensation of dynamic effects during robot operation, the following equation is proposed as part of this study:

$$\tau(t) = \boldsymbol{M}(\boldsymbol{q}(t))\ddot{\boldsymbol{q}}(t) + \boldsymbol{C}(\boldsymbol{q}(t), \dot{\boldsymbol{q}}(t))\dot{\boldsymbol{q}}(t) + \boldsymbol{G}(\boldsymbol{q}(t)) \quad (8)$$

Where: $\tau(t)$ – a vector representing the moments of force applied to the joints of the robot at an instant in time (t). Suppose the collaborative robot is a manipulator with several joints, $\tau(t)$ will be a vector that describes what forces need to be applied to each joint to maintain a desired trajectory or provide a specific position;

$M(q(t))$ – the inertia matrix, which depends on the positions of the joints $q(t)$, which allows describing the masses and their distribution among the joints of the robot, as well as the interaction between different joints. Represents a square matrix of size $n \times n$, where n – the number of joints;

$\ddot{q}(t)$ – the vector of joint accelerations at the instant of time (t). In the framework of these studies, it is accepted as the second derivative of the position function ($q(t)$), which describes how joint velocity changes over time. What allows when controlling the speed of a collaborative manipulator robot, it makes it possible to determine how quickly it is necessary to increase or decrease the speed of movement;

$C(q(t), \dot{q}(t))$ – the Coriolis matrix represents the effects of Coriolis forces and centrifugal forces on the system (arising due to rotational effects and changes in velocities), which depend on both positions $q(t)$, as well as from speeds $\dot{q}(t)$. At high speeds of movement of the collaborative robot manipulator, the Coriolis force and centrifugal forces can significantly affect the required moments of force;

$\dot{q}(t)$ – is the vector of joint velocities at the instant of time (t), is the first derivative of the position function $q(t)$, which describes how quickly joint positions change. To ensure a certain speed of movement of the robot, $\dot{q}(t)$ makes it possible to describe at what speed each joint of the collaborative manipulator robot needs to be moved;

$G(q(t)$ – is a vector representing the effect of gravity on the robot manipulator system, and depends on the position of the joints $q(t)$ and takes into account the forces that arise due to gravity. Allows you to take into account the position of the manipulator robot in space, that is, if the robot is tilted or raised to a certain height, the gravitational forces will affect what moment of force must be met to keep the robot in a stable state.

Expression 2.8 allows for precise control over the movement of the collaborative robot manipulator and its position, which is critical for ensuring human safety when the robot is working in the working area with the collaborative robot manipulator.

Ω_{safe} – safety perimeters or safety zone for people and objects in the working area of the robot manipulator. It is an area in three-dimensional space that defines a zone that meets security requirements. In this zone, certain conditions, such as the distance to objects (e.g. a person), must be met to ensure safety, provided that the set of all points x, that satisfy the condition $|x - c_{human}| \geq r$. The mathematical representation is given below:

$$\Omega_{safe} = \{x \in \mathbb{R}^3 \mid |x - c_{human}| \geq r\} \quad (9)$$

Where: $x \in \mathbb{R}^3$ – coordinates of a point in three-dimensional space, where is a vector $x = (x, y, z)$ represents the coordinates of any point in three-dimensional space. This is the point (x), which is checked for belonging to a secure area Ω_{safe}, if x is within this area, it means it complies with the security requirements;

c_{human} – the center of the object located in the working area of the robot manipulator. In case of 2.14 vector $c_{human} = (c_x, c_y, c_z)$ represents the coordinates of the center of a person or an object around which a safe distance must be provided, makes it possible to determine the position of a person or another object in three-dimensional space. The distance to this point is used to determine the safe zone. r – the radius of the safe zone, the value of which (r) defines the minimum permissible distance from the center of a person or object to any point within the safe area Ω_{safe}, that is r establishes a safety margin. All points for which the distance to c_{human} smaller r, not included in the safe zone. This ensures that the robot or automated system does not approach the dangerous area;

$|x - c_{human}|$ – the distance between the point x and the center of man c_{human}, is calculated as the Euclidean distance between two points in three-dimensional space, which allows determining whether point x is inside or outside the safe zone.

Expression Ω_{safe} (2.9) defines a safe area around a person or object that helps provide a safe distance in three-dimensional space to avoid hazards and ensure safety in work environments and to solve tasks.

u – communication (commands that can be given to an operator or a job) that can be represented as a function $u(t)$, which is a mechanism for converting commands entered by the operator into commands that the robot understands and executes. This may include the conversion of signals from various types of interfaces into specific instructions for a collaborative robot manipulator, and have the following form:

$$u(t) = \{\text{Human input}, \text{Mapping}\} \quad (10)$$

Where: $u(t)$ – a function that determines how the input commands of the operators are converted into specific control signals for the manipulator robot. It can be presented in the form of an algorithm or a model that processes input data and generates appropriate commands. It can be a simple linear converter or a complex algorithm with filtering and data processing;

Human input – operator input commands, can represent signals or commands given by the operator through various interfaces (eg buttons, joysticks, touchpads). Can include different types of input, such as digital signals, analog signals, or voice commands;

Mapping – a function that determines the sequence and transformation of control signals for the robot manipulator.

$\mathbb{M}$ – adaptation (machine learning) can be represented as a model of predictive functions $f(\mathbb{X})$ based on the collected data, is a process in which the function f transforms the input data $\mathbb{X}$ in prediction $\hat{y}$ using parameters θ. Expression 2.11 is the basis for machine learning and statistics models, where the learning process focuses on parameter optimization θ to improve the accuracy of predictions.

$$\hat{y} = f(\mathbb{X}; \theta) \quad (11)$$

Where: $\hat{y}$ – the predicted value is the output of the model, which is the result of the transformation of the input data $\mathbb{X}$ taking into account the parameters θ. Value $\hat{y}$ is an estimate or prediction of how the model will respond to the data $\mathbb{X}$, can take as a numerical value (in the case of regression) or a class (in the case of classification);

f – model function can be of different types depending on the machine learning model. It can be a linear function, a polynomial function, a neural network, a tree structure, etc.;

$\mathbb{X}$ – input data is a set of data used to train or test a model. Within the framework of these studies $\mathbb{X}$ can be a feature vector or a matrix representing various characteristics or properties of objects to be predicted or classified;

θ – model parameters that govern the function f and defined as input data $\mathbb{X}$ are converted into the predicted value $\hat{y}$. Parameter θ includes regression coefficients in linear models, weights in neural networks, or other configuration settings. The model training process involves optimizing these parameters to minimize prediction errors.

For a better presentation of the interrelationship of the parameters of the developed model for describing the environment of a collaborative industrial manipulator robot (RC), we will visualize them as shown in the figure 1.

Conclusions. The developed model of the dynamic description of the environment of the collaborative manipulator robot is an important step in increasing the efficiency of the interaction between the robot and the person and other components of the production system in the conditions of Industry 5.0. The proposed model allows adaptive response to changes in the working environment, ensuring increased safety and intelligence of the robot's task performance. The visual presentation of the model helps to better understand how a collaborative robot can integrate into cyber-physical systems, respond to external factors and perform adaptive actions. The research will be of interest to scientists and engineers working in the field of robotics, cyber-physical systems and Industry 5.0, as well as to enterprises seeking to improve the efficiency of process automation. Prospects for further research include improving the model with an emphasis on integration with other elements of cyber-physical systems, expanding its capabilities for processing large volumes of data in real time, and applying artificial intelligence algorithms to increase adaptability and predict robot actions.

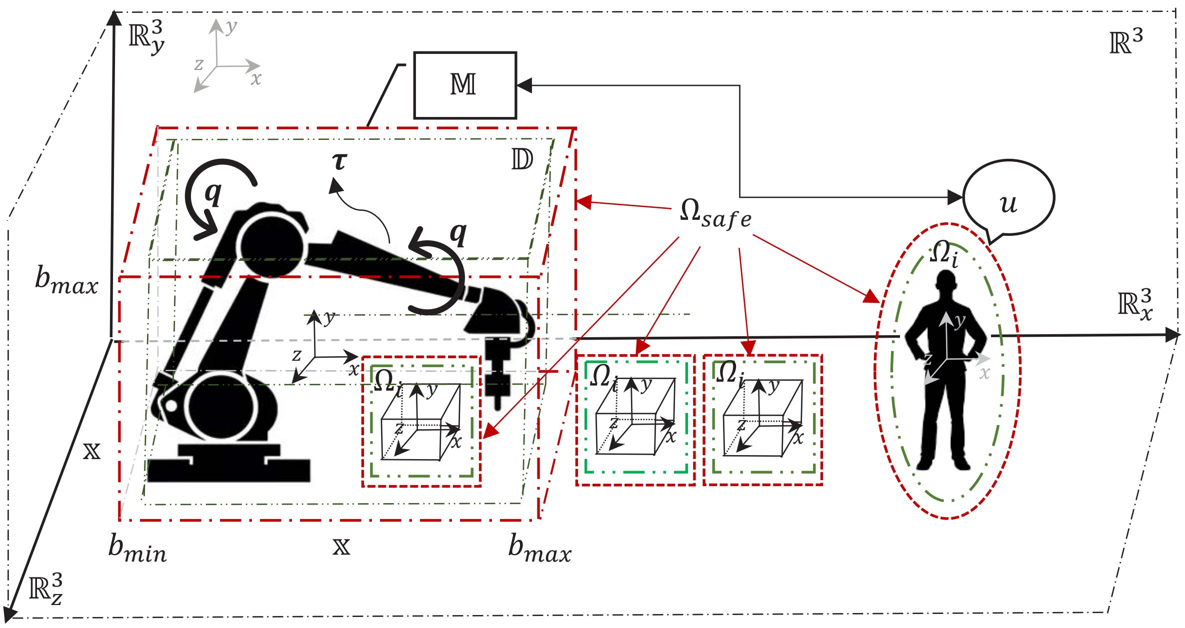

Fig. 1. Visual representation of the environmental description model of a collaborative industrial manipulator robot

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Невлюдов І.Ш., Євсєєв В.В., Гурін Д.В. РОЗРОБКА МОДЕЛІ ДИНАМІЧНОГО ОПИСУ НАВКОЛИШНЬОЇ СЕРЕДОВИЩА КОЛОБОРАТИВНОГО РОБОТА-МАНІПУЛЯТОРА В РАМКАХ КОНЦЕПЦІЇ ІНДУСТРІЇ 5.0

Данна стаття присвячена розробці моделі динамічного опису навколишнього середовища колаборативного робота-маніпулятора в рамках концепції Індустрії 5.0. З розвитком технологій робототехніки та інтеграцією роботів у кіберфізичні системи виникає потреба у створенні нових підходів до взаємодії між роботами та людиною в умовах виробництва. Метою дослідження є підвищення ефективності інтеракції колаборативного робота з навколишнім середовищем шляхом створення адаптивної, безпечної та інтелектуальної моделі динамічного опису, що відповідає сучасним вимогам Індустрії 5.0. У рамках цієї роботи було розроблено та візуалізовано модель, яка дозволяє роботу-маніпулятору більш точно та своєчасно реагувати на зміни в навколишньому середовищі. Представлена модель динамічного опису включає механізми обробки даних про зовнішні фактори, що дозволяє роботу швидше адаптуватися до нових умов, забезпечуючи безпеку взаємодії з оператором та іншими елементами виробничої системи.Використання даної моделі в роботі колаборативних роботів дає можливість підвищити їхню гнучкість і здатність до самостійного прийняття рішень у різних робочих ситуаціях. Це особливо важливо для роботів, які працюють у середовищах з постійними змінами або непередбачуваними подіями. Завдяки можливості оперативно аналізувати стан навколишнього середовища і приймати рішення на основі отриманих даних, колаборативний робот може ефективніше виконувати виробничі завдання, мінімізуючи ризики для оператора та підвищуючи загальну продуктивність. У статті також наведено візуальне представлення моделі, що наочно демонструє можливості її застосування у виробничих умовах. Це дозволяє краще зрозуміти, як модель допомагає роботу інтегруватися в кіберфізичну систему і працювати в умовах співпраці з іншими елементами виробничої системи, включаючи людей. Запропонований підхід відкриває нові перспективи для розвитку робототехнічних систем, орієнтованих на взаємодію людина-робот, та дозволяє підвищити рівень безпеки та ефективності виробництва.Дослідження буде корисним для фахівців у галузі робототехніки, кіберфізичних систем та Індустрії 5.0, а також для підприємств, які прагнуть підвищити рівень автоматизації та інтеграції роботів у виробничі процеси.

Ключові слова: *колаборативний робот, опис динамічного середовища, Індустрія 5.0, кіберфізичні системи, взаємодія людина-робот, адаптивна робототехніка, інтелектуальне виробництво, робот-маніпулятор, безпека в робототехніці, автоматизація виробничих систем.*