ISSN 2522-9818 (print) *Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 2 (36)*
ISSN 2524-2296 (online) *Innovative technologies and scientific solutions for industries. 2026. No. 2 (36)*

UDC 004.932.2 DOI: https://doi.org/10.30837/2522-9818.2026.2.214

Igor Nevliudov, Vladyslav Yevsieiev, Svitlana Maksymova, Oleksandr Pashchenko, Viktor Kosenko

DEVELOPMENT OF A MODEL FOR SYNCHRONIZING THE OPERATION OF COLLABORATIVE ROBOTIC MANIPULATORS IN HRC SCENARIOS

This article examines the problem of synchronizing the operation of a group of collaborative robots in a shared workspace with humans, in light of modern requirements for human-centered manufacturing and the Industry 5.0 concept. **The relevance of the research** stems from the need to ensure coordinated movement of multiple robots while adhering to strict safety constraints in HRC scenarios, where traditional centralized approaches do not guarantee sufficient reliability and scalability. **The objective of this work** is to develop a mathematical model for the synchronized control of collaborative manipulators, taking into account mutual coordination, tracking of a shared trajectory, and active avoidance of dangerous proximity to humans and between robots. **The subject of the study** is decentralized synchronization laws in the problem space with projection into joint space and the use of potential safety fields. **The work uses methods** of mathematical modeling of manipulator dynamics based on Euler–Lagrange equations, consensus control methods, pseudo-inversion of the Jacobian matrix, fourth-order Runge–Kutta numerical integration methods, and methods for analyzing safety metrics. **The objectives of the study** are to formalize the laws of consensus control in the problem space, integrate safety potential fields, and perform numerical validation of the model for a group of manipulators in a shared workspace. **Modeling results** for a group of three two-link planar manipulators showed the formation of coordinated trajectories with a reduction in characteristic oscillations and stabilization of dynamics; however, the average tracking error of the common trajectory remains at 0.38–0.40 m. An analysis of minimum robot-to-robot and robot-to-human distances confirmed the effectiveness of potential barriers in steady-state operation, but revealed dangerous gaps in transitional sections. **It is concluded** that the proposed model ensures stable synchronization and a basic level of safety, but to guarantee compliance with safety margins throughout the entire time interval, it is advisable to switch to rigid barrier constraints such as CBF and task-priority control schemes.

Keywords: collaborative robotic manipulators, motion synchronization, HRC scenarios, decentralized control, consensus algorithm, safety potential fields, Jacobian pseudoinverse, Industry 5.0.

1. Introduction

In the current context of Industry 5.0, a human-centered approach is emerging as a key driver of technological evolution, under which robotic systems must not only increase productivity but also ensure safety, adaptability, and flexible interaction with humans [1–3]. Collaborative robots are increasingly being integrated into shared workspaces, where there is a need for precise synchronization of their actions in the presence of an operator. Under these conditions, traditional centralized control algorithms prove insufficiently effective due to limited scalability, data exchange delays, and difficulties in ensuring safety [4–7]. Therefore, decentralized synchronization models that combine coordinated motion control, adaptive compensation laws, and integrated mechanisms for preventing dangerous collisions are becoming particularly relevant [8–9]. The relevance of this research is also driven by the need to transition from "soft" heuristic approaches to formalized mathematical models capable of ensuring predictable system dynamics in complex Human–Robot Collaboration (HRC) scenarios [10–13]. The realities of modern manufacturing require the simultaneous achievement of high synchronization accuracy, disturbance resistance, and guaranteed safety constraints. This is precisely why the development of models for synchronized control of collaborative robots in a shared space with humans is a timely, scientifically sound, and practically significant task.

2. Analysis of last achievements and publications

In their paper, I. Rybalskii, K. Kruusamäe, A.K. Singh, and S. Schlund propose an AR interface to improve the safety of operator interaction with industrial robots, where augmented reality is used to visualize danger zones, motion trajectories, and warnings, which statistically reduces the number of dangerous encounters in production scenarios [14]. This solution enables the integration of human-centered visual feedback tools into HRC systems and can be used in our study as a basis for overlaying dynamic AR prompts regarding safe distances and restricted zones onto the synchronized trajectories of manipulators.

In their study, D. Kóczi and J. Sárosi conducted a systematic review of safety engineering methods for humanoid robots in everyday life, developed a risk classification, reviewed standards, approaches to hazard assessment, and strategies for designing safe behavior [15]. The proposed approach makes it possible to link the mathematical synchronization model with functional safety requirements and emergency scenarios, so the results can be used to formalize robot–human distance constraints and motion acceptability criteria in our model.

In P. Pawlewski's article on the scientific and practical challenges of remanufacturing process modeling, the problems of reliable simulation of complex production flows are examined, and a set of functions, requirements, and architectural solutions is proposed for developing new approaches to modeling and digital twins of remanufacturing [16]. This solution makes it possible to align macro-level production models with the micro-level of robot control, and from the perspective of our research, its results can be used to justify the need to integrate a synchronization model with the digital twin of a conveyor or assembly line.

In the article by H. Ye, Y. Song, J. Lam, and P.A. Ioannou, a decentralized control law with a specified convergence time is developed for "hand–fingers" systems performing grasping and manipulation tasks, where each subsystem controller ensures the achievement of target trajectories within a limited time using Lyapunov stabilization methods and barrier functions [17]. This approach makes it possible to ensure predictable convergence of multi-link robots with minimal communication requirements; therefore, elements of this theory are suitable for use in our model to construct local joint synchronization laws, however, direct adaptation requires rethinking due to a different problem formulation (HRC in shared space, rather than merely object manipulation).

In the work by M. Zhang, J. Guo, and Z. Zhang propose a distributed slack-barrier recurrent neural network for coordinated motion of a set of redundant manipulators in an obstacle-filled environment, where the optimization problem with safety constraints is implemented as a dynamic NN system that avoids collisions and maintains coordination [18]. This solution makes it possible to encapsulate collision constraints and redundancy within the control dynamics themselves; therefore, its ideas are consistent with our potential field approach and can be used for the further development of a neural network variant of the synchronization model, although full integration will require simplifying the computational complexity for real-time operation.

In a study by S. Agarwal and J. Alonso-Mora, S. Sun developed a decentralized real-time planning method for multi-UAV cooperative manipulation based on imitation learning, where local "student" policies learn to imitate a centralized planner under conditions of partial observability and the absence of inter-agent communication [19]. The proposed approach makes it possible to achieve near-centralized planning quality in a decentralized architecture, which is important for scaling multi-robot systems, and in the context of our work, this can be used as a conceptual basis for training local synchronization laws for manipulators based on reference centralized trajectories.

In the article by D. Ma, C. Zhang, and Q. Xu, and G. Zhou, an approach to proactive control of manipulation operations in an Industry 5.0 HRC assembly environment is considered, based on the fusion of large-scale models of the production system and small-scale models of specific robots, which ensures adaptation to the context and line load [20]. This solution makes it possible to combine line-level planning with local manipulator control, and thus directly supports the idea of integrating our synchronization model into a multi-level control architecture, where synchronized working trajectories are coordinated with demand forecasts and environmental changes.

In the work by P. Ding, J. Zhang, P. Zheng, P. Zhang, B. Fei, and Z. Xu, a human motion prediction network enriched with scenario features is proposed, which accounts for environmental dynamics and the diversity of operator motion patterns for proactive collaboration in personalized assembly tasks [21]. The proposed method makes it possible to significantly improve the accuracy of short-term predictions of human trajectories, which in our study is critically important for the correct construction of potential safety fields and the adaptive modification of synchronized robot trajectories; accordingly, the results of this work should be used as one of the sources for operator position prediction models.

In the article by W. W. Loy, J. Donovan, M. Rittenbruch, and M. Belek, Fialho, and Teixeira, an AR-oriented HRC system is investigated for research assembly tasks, where a designer can view, modify, and execute a cobot's actions in real time via an AR interface, receiving spatially constrained visual feedback [22]. This solution makes it possible to coordinate human

ISSN 2522-9818 (print) Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 2 (36)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2026. No. 2 (36)

creative actions and robotic manipulations in "open" environments, and in the context of our synchronization model, the results can be used to design an interface layer that displays the robot's current and predicted synchronized trajectories and safety zones to support the operator's situational awareness.

In the work by S.M. Mizanoor Rahman, an approach to evaluation and benchmark metrics for collaborative object manipulation tasks in HRC is proposed, where a set of indicators for productivity, ergonomics, safety, and interaction quality is considered, along with test scenarios for comparing different algorithms [23]. This solution enables standardized evaluation of HRC systems and is directly relevant to our task, since the developed synchronization model requires quantitative quality criteria (tracking error, minimum distances, motion smoothness); so the proposed metrics can be adapted to validate our approach in numerical experiments.

The article by P. Lin, N. Zeng, Q. Li, and K. Nübel provides an overview of HRC safety in construction, systematically outlining typical hazards, regulatory requirements, technical risk control measures, and promising directions for the development of standards and safety sensor systems [24]. This review allows us to generalize the requirements for safe human-robot interaction in complex, loosely structured environments, and from the perspective of our research, it supports the justification for the need for embedded safety modules (potential fields, barrier conditions) within the synchronization model, although the specifics of construction sites differ from laboratory HRC scenarios involving manipulators.

Taken together, the analyzed publications demonstrate a steady trend toward a transition from isolated robotic systems to human-centric HRC architectures with decentralized control, human behavior prediction, AR support, and formalized safety and productivity metrics, confirming both the scientific and practical relevance of developing a synchronization model for collaborative robot manipulators in HRC scenarios capable of integrating these areas into a single mathematically sound approach.

The aim of this article is to develop a mathematical model for the synchronized control of collaborative manipulators, taking into account mutual coordination, tracking of a common trajectory, and active avoidance of dangerous proximity to humans and between robots.

3. Brief Explanation of Parameters and Variables

In this section, a brief explanation of parameters and variables is presented before the mathematical model to ensure unambiguous interpretation of the introduced notation and to simplify the understanding of subsequent derivations. This approach allows the reader to focus on the logic of the synchronization model's construction without being overwhelmed by formulas, and also enhances the reproducibility and correctness of the numerical implementation of the proposed method.

Indices and dimensions: $i, j \in \{1, \dots, N\}$ – robot indices; $N \in \{2,3,4\}$ – number of robots in the group; n_i – number of robot i joints; d – dimension of the workspace (3 for position, 6 for position+orientation).

State variables: $q_i(t) \in \mathbb{R}^{n_i}$ – angular coordinates of the joints; $\dot{q}_i(t) \in \mathbb{R}^{n_i}$ – angular velocities of the joints; $\ddot{q}_i(t) \in \mathbb{R}^{n_i}$ – angular accelerations

Kinematics and Geometry: $x_i = f_i(q_i) \in \mathbb{R}^d$ – current position/orientation of the robot's i end-effector in global coordinates; $x_i = J_i(q_i)\dot{q}_i$ – velocity of the end-effector in global coordinates; $J_i(q_i) \in \mathbb{R}^{d \times n_i}$ – Jacobian matrix; $J_i^{\dagger}(q_i) \in \mathbb{R}^{n_i \times d}$ – pseudo-inverse Jacobian, for finding the desired joint accelerations that realize the desired acceleration in the workspace.

Dynamics: $M_i(q_i) \in \mathbb{R}^{n_i \times n_i}$ – mass-inertia matrix; $C_i(q_i, \dot{q}_i)\dot{q}_i \in \mathbb{R}^{n_i}$ – Coriolis and centrifugal moments; $g_i(q_i) \in \mathbb{R}^{n_i}$ – gravitational moments; $\tau_i \in \mathbb{R}^{n_i}$ – local control moment (the specific robot's i task); $\tau_i^{sync} \in \mathbb{R}^{n_i}$ – synchronization moment (cooperation with others); $\tau_i^{safe} \in \mathbb{R}^{n_i}$ – safety moment (avoiding dangerous proximity to humans and other robots).

Goals and errors: $x^*(t) \in \mathbb{R}^d$ – the group's common desired trajectory (team task); $\ddot{x}^*(t) \in \mathbb{R}^d$ – the desired acceleration of this trajectory; $e_i = x_i - x^*$ – the robot's i deviation from the group goal; $e_{ij} = x_i - x_j$ – the deviation between robots i and j, characterizing how far apart they have "drifted".

Group ties: $a_{ij} \ge 0$ – the weight of the tie between robots i and j. If robots i and j must maintain nearly identical positions, we set a_{ij} large; $\sum_j a_{ij}\left(x_i - x_j\right)$ – the consensus term, which pulls the robots into a "flock"

Control parameters: K_p – proportional alignment coefficient to the global goal; K_c – group consensus coefficient; K_d – damping coefficient (dampener) to prevent the system from oscillating; $K_p = k_p I_d K_c = k_c I_d K_d = k_d I_d$ – a matrix of positive scalars to simplify numerical implementation.

Safety: $p_i \in \mathbb{R}^3$ – robot i reference point (e.g., current position of the gripper or arm segment that could touch a person); $p_h \in \mathbb{R}^3$ – estimated human position; $d_{i,h} = \left\| p_i - p_h \right\|$ – robot–human distance; $d_{i,j} = \left\| p_i - p_j \right\|$ – distance between robots; $d_{\min}^{(h)}$ – minimum permissible distance to a person (human safety zone); $d_{\min}^{(r)}$ – minimum permissible distance between robots; $\alpha_h, \alpha_r > 0$ – coefficients for "how aggressively to flee" from danger; $V_{i,h}, V_{i,j}$ – potential energy of danger; $F_i^{safe} = -\nabla_{p_i} V_i^{safe}$ – repulsive force in the workspace; $\tau_i^{safe} = J_i^{\mathsf{T}} F_i^{safe}$ – repulsive torque at the joints, which is actually applied to the actuator.

4. A mathematical model of the synchronization of collaborative robots-manipulators in a shared workspace with humans

Let there be an i-th robot (manipulator) in the group $i = 1, \ldots, N$. Let us denote the generalized coordinates by:

$$q_i(t) \in \mathbb{R}^{n_i} \tag{1}$$

The coordinate vector of the robot's i joints (e.g., the angles of the servo motors). Each element $q_{i,k}(t)$ represents the angle or linear displacement of the robot i k-th joint. The dimension n_i is the number of degrees of freedom of the manipulator i. The first and second derivatives then represent the velocities and accelerations at the joints:

$$\dot{q}_i(t) = \frac{dq_i}{dt}, \quad \ddot{q}_i(t) = \frac{d^2 q_i}{dt^2}. \tag{2}$$

We will present the dynamic model of the manipulator in the form of the standard Euler–Lagrange model for a robotic manipulator:

$$M_i(q_i)\ddot{q}_i + C(q_i, \dot{q}_i)\dot{q}_i + g_i(q_i) = \tau_i + \tau_i^{sync} + \tau_i^{safe} . \tag{3}$$

Model (3) serves as the basis for numerical modeling: by integrating $\ddot{q}_i$ over time using the Euler/Runge–Kutta method, we can simulate the motion of each robot in Python.

To discuss the synchronization of a "group", we need to move from the common joint space to the common task space – usually the Cartesian space of the workspace. Let's introduce the direct transformation (kinematics) of the robot i:

$$x_i(t) = f_i(q_i(t)) \in \mathbb{R}^d , \tag{4}$$

where $x_i(t)$ – state vector of the robot's i tool point in the global (common) coordinate system. Usually, $d = 3$ for a position (x, y, z), or (x, y, z) if we also consider orientation (for example, an Euler vector $\rightarrow$, in which case we can partially linearize); $f_i(\bullet)$ – the direct kinematics of the robot. Let's take the derivative:

$$\dot{x}_i = J_i(q_i)\dot{q}_i . \tag{5}$$

Where $J_i(q_i) \in \mathbb{R}^{d \times n_i}$ – links the joint velocities to the tool velocity in Cartesian coordinates. This is necessary because it relates the motion within the robot's joint space (i.e., the angles and their velocities) to the motion in the workspace (i.e., the position and velocity of the manipulator tip – the effector). Model (5) is the fundamental link between the robot's kinematics in the joint space and in the workspace, that is, between the robot control space and the space of interaction with humans and other robots. Without it, it is impossible to properly establish synchronization, because we do not know how changes in the joints affect the coordinates that need to be coordinated.

Let us assume that the coordinated group task for all robots is as follows:

– they follow a common group plan (for example, they carry a single part together);

– they do not interfere with one another and do not come dangerously close to a person.

Then we introduce a reference (target) group trajectory in the workspace:

$$x^*(t) \in \mathbb{R}^d . \tag{6}$$

This could be the position of a shared object (part) that the robot team needs to hold, or the trajectory of the point where the tool is handed over to a human.

Now let's determine the positioning error for each robot:

$$e_i(t) = x_i(t) - x^*(t) . \tag{7}$$

ISSN 2522-9818 (print) Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 2 (36)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2026. No. 2 (36)

Let's interpret (7), $e_i = 0$ means that the robot's i tool is located where the command expects it to be (the coordinated trajectory). Next, we will describe the coordination error between the robots:

$$e_{ij}(t) = x_i(t) - x_j(t), \ i \neq j \ . \quad (8)$$

This is the "discrepancy" between robots i and j. If all $e_{ij} \to 0$, then all robots are spatially synchronized (for example, they hold the same component node or move as a rigidly connected structure).

To specify who should synchronize with whom directly, we introduce an undirected weighted interaction graph with the following parameters:

– the vertices of the graph are the robots $1,\ldots,N$;

– an edge (i,j) exists if robots i and i must be coordinated;

– the weight of the connection is $a_{ij} \geq 0$; if there is no direct informational/physical contact, then $a_{ij} = 0$.

Let us formulate a synchronization law (cooperative control): suppose we want to generate τ_i^{sync} such that the robots converge to a common group trajectory $x^*(t)$ and coordinate with each other (minimize e_{ij}). One of the basic and numerically convenient options is a law in the task space, which is then projected via the Jacobian onto the joint moments.

Let us introduce a virtual control "accelerating influence" for the robot in the problem space:

$$u_i = -K_p e_i - K_c \sum_{j=1}^{N} a_{ij}\left(x_i - x_j\right) - K_d \dot{x}_i + \ddot{x}^* \ , \quad (9)$$

where: $K_p \in \mathbb{R}^{d\times d}$ – gain matrix based on positional error relative to the global target x^*; $K_c \in \mathbb{R}^{d\times d}$ – the consensus gain matrix, which reduces the differences between works; the larger it is, the more the works "converge" toward one another; $K_d \in \mathbb{R}^{d\times d}$ – it is desirable to accelerate the joint group trajectory; if the trajectory is slow or quasi-static, it is acceptable to use $\ddot{x}^* \approx 0$.

To implement this acceleration via the actuators, it is necessary to invert the dynamics in joint space, i.e., the mapping u_i at time τ_i^{sync}. The following approach is proposed:

1. Desired joint acceleration:

$$\ddot{q}_i^{dec} = J_i^{\dagger}(q_i) u_i \ . \quad (10)$$

Objective (10): Find such $\ddot{q}_i^{dec}$ that it gives us the desired $\ddot{x}_i \approx u_i$.

2. Determine the synchronizing point:

$$\tau_i^{sync} = M_i(q_i)\ddot{q}_i^{dec} + C_i(q_i, \dot{q}_i)\dot{q}_i + g_i(q_i) \ . \quad (11)$$

In other words, using (11), we apply a torque to the robot that causes its current dynamic model to "accelerate" toward the desired behavior within the task space. But if the robot already has a base task τ_i (for example, maintaining grip force, stabilizing tool orientation), we cannot simply replace everything with τ_i^{sync}. In that case, composition is performed via task priorities:

$$\tau_i^{total} = \tau_i^{task} + N_i \tau_i^{sync} \ , \quad (12)$$

where $N_i = I - J_{task,i}^{\top}\left(J_{task,i} J_{task,i}^{\top}\right)^{-1} J_{task,i}$ – operator in the null space of the problem, but to simplify numerical modeling, we can assume that $\tau_i = 0$ and τ_i^{sync} are fully controllable.

Since we are working "in the same workspace as a human", we must ensure minimum distances. We therefore define the following:

– "robot-human" distance:

$$d_{i,h}(t) = \left\| p_i(t) - p_h(t) \right\| \ ; \quad (13)$$

– minimum permissible distance:

$$d_{\min}^{(h)} > 0 \ ; \quad (14)$$

– avoiding clashes between robots:

$$d_{i,j}(t) = \left\| p_i(t) - p_j(t) \right\| \ , \quad d_{\min}^{(t)} > 0 \quad (15)$$

Let's introduce safety penalty potentials that increase sharply as the distance approaches a dangerous level.

Robot-human safety pseudo-potential:

$$V_{i,h}(t) = \begin{cases} \alpha_h \left(\dfrac{1}{d_{i,h}(t) - d_{\min}^{(h)}} \right)^2, & d_{i,h}(t) > d_{\min}^{(h)} \\ +\infty, & d_{i,h}(t) < d_{\min}^{(h)} \ , \end{cases} \quad (16)$$

where $\alpha_h > 0$ – human safety weighting factor; gradient $\nabla_{p_i} V_{i,h}(t)$ indicates the direction in which the robot i should be pushed to increase the distance from the person.

Robot-to-robot safety pseudopotential:

$$V_{i,j}(t) = \alpha_r \left(\frac{1}{d_{i,j}(t) - d_{\min}^{(t)}} \right)^2 \ , \quad i \neq j \ , \quad (17)$$

where: $\alpha_r > 0$ – collision avoidance coefficient between robots. Total safety potential for the robot i:

$$V_i^{safe} = V_{i,h} + \sum_{j=1, j\neq i}^{N} V_{i,j} \ . \quad (18)$$

Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 2 (36) ISSN 2522-9818 (print)
Innovative technologies and scientific solutions for industries. 2026. No. 2 (36) ISSN 2524-2296 (online)

Conversion of security forces into τ_i^{safe}, repulsive force in the workspace:

$$F_i^{safe} = -\nabla_{p_i} V_i^{safe} \ . \quad (19)$$

Let's make a projection (19) into the joint space:

$$\tau_i^{safe} = J_i^{\mathsf{T}}(q_i) F_i^{safe} \ . \quad (20)$$

Let us interpret Model (20) as follows: if the robot gets too close to a human or another robot, $\|\nabla V\|$ grows, it generates a large pushing moment τ_i^{safe} that corrects its motion to a safe trajectory. That is, Model 3 will be the full dynamic control.

As a result, for each robot i, we have a system of classical second-order differential equations for q_i; to perform numerical modeling, the following steps are proposed:

1. Let's calculate $x_i = f_i(q_i)$ and $J_i(q_i)$.

2. Calculate errors $e_i = x_i - x^*$, $e_{ij} = x_i - x_j$.

3. Calculate the virtual control in the problem space

$$u_i = -K_p e_i - K_c \sum_{j=1}^{N} a_{ij}(x_i - x_j) - K_d \dot{x}_i + \ddot{x}^* \ .$$

4. Find the desired joint acceleration $\ddot{q}_i^{dec} = J_i^{\dagger}(q_i) u_i$.

5. Get the synchronizing moment

$$\tau_i^{sync} = M_i(q_i)\ddot{q}_i^{dec} + C_i(q_i, \dot{q}_i)\dot{q}_i + g_i(q_i) \ .$$

6. Count $\tau_i^{safe} = J_i^{\mathsf{T}} F_i^{safe}$, where

$$F_i^{safe} = -\nabla_{p_i}\left(V_{i,h} + \sum_{j \neq i} V_{i,j}\right).$$

7. Substitute into the dynamic model

$$\ddot{q}_i = M_i^{-1}(q_i)\left(\tau_i^{sync} + \tau_i^{safe} + \tau_i - C_i(q_i, \dot{q}_i) - g_i(q_i)\right).$$

5. Development of a program for modeling the fusion of data from sensors of a collaborative robot and analysis of the results obtained

Purpose of the modeling:

1. To investigate the synchronization of a group $N = 3$ of collaborative planar manipulators (2 DOF each) in a shared workspace with a human.

2. Analyze how a consensus control law in the task space (effector position) with damping and backward projection via the Jacobian matrix ensures: tracking of a common desired coordination trajectory $x^*(t)$ among robots; maintenance of safe robot↔robot and robot↔human distances based on potential safety fields.

Modeling parameters:

– total modeling duration $T = 20$ s; integration step $dt = 0.002$ s; RK4 integrator;

– number of robots $N = 3$;

– manipulator geometry (all identical): link lengths $l_1 = 0.6$ m, $l_2 = 0.4$ m;

– inertial parameters: $m_1 = 2.0$ kg; $m_2 = 1.0$ kg; $I_1 = 0.05\ \text{kg/m}^2$; $I_2 = 0.02\ \text{kg/m}^2$; $g = 9.81\ \text{m/s}^2$;

– parameters of the spatial synchronization law: $K_p = 18$, $K_c = 10$, $K_d = 3.5$;

– projection into joint space $J^{\dagger}$ (regularized pseudo-inverse) with damping 10–4;

– safety (potential fields): robot↔human threshold $d_{\min}^{(h)} = 0.5$ m, coefficient $\alpha_h = 20$; robot↔robot threshold $d_{\min}^{(r)} = 0.35$ m, coefficient $\alpha_r = 0.12$; for critically small distances – saturation of the repulsive force.

Modeling input data:

– initial states in the joint space (for generating initial configurations):

robot 1: $q = [0.0, 0.5]$, $\dot{q} = [0, 0]$,

robot 2: $q = [0.6, -0.3]$, $\dot{q} = [0, 0]$;

robot 3: $q = [-0.6, 0.3]$ $q = [-0.6, 0.3]$, $\dot{q} = [0, 0]$.

– desired group trajectory in the problem space $x^*(t)$: a circle of radius $R = 0.5$ m with angular velocity $w = 0.25$ rad/s and center $(0.4,\ 0.1)$;

– human trajectory $p_h(t)$: smooth motion along a line with slight oscillations in y (amplitude 0.2 m, frequency 0.15 rad/s with a fixed $x = 0.6$ m);

– model matrices/functions: $f(q)$, $J(q)$, $M(q)$, $C(q, \dot{q})$, $g(q)$, safety settings, and interaction graph A.

Constraints imposed on the model during the modeling process:

– spatial simplicity, i.e., a planar 2D model (we consider only the effector's (x, y) position; we do not model the tool's orientation);

– simplified dynamic terms, i.e., the model M, C, g is canonical for a 2-link manipulator; friction, backlash, transmission elasticity, and drive saturation are not taken into account;

– measurements are ideal; this is a modeling without noise, delays, or calibration errors; feedback uses "true" values $q, \dot{q}$;

ISSN 2522-9818 (print) Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 2 (36)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2026. No. 2 (36)

– collision/safety takes into account repulsion calculated at the end-effector (or a single control point); self-intersections of links and contacts across the entire manipulator geometry are not modeled;

– joint limits and torque/velocity constraints are not accounted for (no saturation/anti-windup);

– using a pseudo-inverse $J^{\dagger}$ with low damping can lead to errors near singular positions (singularities);

– potential safety fields may cause local minima (although consensus and damping reduce the risk of "getting stuck");

– the connection graph is static and fully connected; data transmission and communication delays are not accounted for.

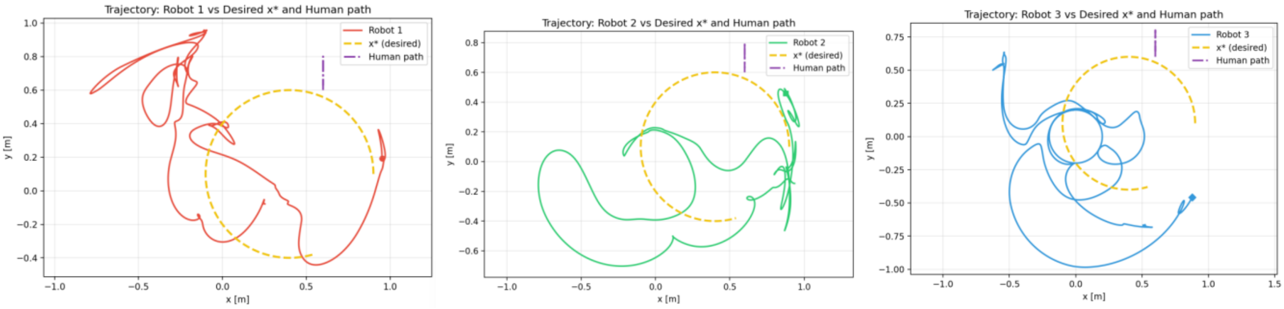
Hardware specifications for the study: Microsoft Surface Pro 9 with the following specifications: CPU: 10-core Intel Core i7-1255U (1.7–4.7 GHz), GPU: Iris Xe Graphics, RAM: 16 GB, SSD: 512 GB.

Software: Windows 11 Pro (version 24H2), 64-bit operating system, x64-based processor.

PyCharm 2025.1.1.1 numerical modeling software development environment, Python 3.13.7 programming language [25–33].

The modeling results are presented in Figures 1–4.

The resulting trajectories (Fig. 1) confirm the effectiveness of the improved synchronization law; however, the accuracy of tracking the common target remains limited: the mean error e_i is approximately 0.59 m, the 95th percentile is approximately 0.91 m, and the final error remains at $\approx 0.58\text{ m}$; that is, steady-state conditions with an accuracy of 0.1 m are not achieved. Unlike the previous "filled circles", the trajectories have taken on a spiral-crescent shape with a smaller amplitude and a distinct tendency to move toward the area $x^*(t)$ which indicates an effect of enhanced damping in the problem space and at the joints, as well as a reduction in mutual "pulling" following the thinning of the interaction graph. At the same time, although safety metrics have improved on average, they remain critical during peak conditions: the minimum robot↔human distance drops to $\approx 0.085\text{ m}$ when the 5th percentile is $\approx 0.232\text{ m}$, the minimum robot↔robot distance drops to $\approx 0.006\text{ m}$ with a 5th percentile of $\approx 0.178\text{ m}$, which implies periodic breaches of the 0.50 m and 0.35 m safety barriers.



a) b) c)

Fig. 1. Trajectoty: Robot n vs Desired x^* and Human path: a) Robot 1; b) Robot 2; c) Robot 3

Qualitatively, this is explained by the fact that the safety modulation coefficient γ_i effectively "stifles" consensus and accountability $x^*(t)$, in hazardous zones, causing phase shifts and local bypasses of the human body and adjacent effectors, but the single-point interaction model and the barrier potential, combined with the projection J^{T} still lag behind during rapid approaches and near singular configurations. Adaptively damped pseudo-inversion reduces disturbances on degenerate configurations; however, during moments of abrupt reprioritization between safety and synchronization, curvilinear loops arise, increasing the integral error. Strengthened dampers and saturation of velocities and accelerations prevented the "spinning up" of amplitudes, but limited maneuverability for precise trajectory entry, which again shifts the balance toward avoidance rather than tracking. Taken together, the results demonstrate that the introduced improvements stabilized the dynamics and reduced the characteristic orbits, but to achieve centimeter-level accuracy while simultaneously maintaining clearances, rigid geometric constraints are lacking in the control law itself. From the perspective of the synchronization model, this indicates the need to replace soft potentials with a goal-priority scheme using null-space or QP/CLF-CBF control, where safety is encoded as non-negative barrier conditions, and tracking $x^*(t)$ is performed within

Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 2 (36) *ISSN 2522-9818 (print)*
Innovative technologies and scientific solutions for industries. 2026. No. 2 (36) *ISSN 2524-2296 (online)*

the permissible range. Further improvements are expected from a multi-point contact model for safety and adaptation γ_i based on the rate of convergence, as well as subsequent filtering $\ddot{x}^*$ and fine-tuning the ratio $K_p : K_c : K_d$. Thus, the study confirms the effectiveness of the proposed coordination approach, but at the same time highlights the limitations of soft constraints in HRC scenarios and calls for the introduction of hard constraints to ensure safety while maintaining synchronization quality.

The resulting curve (Fig. 2) of the average tracking error demonstrates transient dynamics characteristic of synchronized collaborative manipulators, with a noticeable oscillatory mode. The initial increase to ≈ 0.85 m in the first $3-4$ s indicates a phase mismatch between the robots and a delay in the formation of a coordinated potential field. After 5 s, a gradual decrease in the error is observed, with amplitude oscillations of approximately ± 0.15 m around the mean value of 0.55 m. At the end of the modeling $(t \approx 20\text{ s})$, the average error is $\approx 0.38-0.40$ m, meaning the system is gradually approaching equilibrium, but the specified accuracy threshold of 0.05 m is not achieved. This means that the consensus law in the problem space effectively stabilizes the relative positions of the robots; however, due to the significant damping effect of the safety forces and the low weight of the component (K_c) Convergence slows down and residual phase desynchronization occurs. From the perspective of the synchronization model, this indicates partial coordination – the group coordinates without chaotic disturbances, but without fully adhering to a common trajectory, which requires a stronger prioritization of tracking over consensus and further strengthening of the adaptive components in the control law.

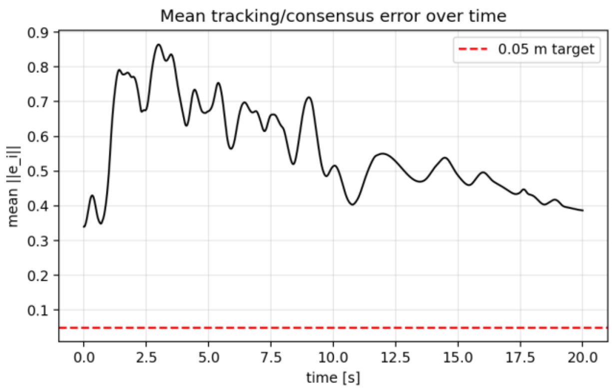


Fig. 2. Mean tracking/consensus error over time

The curve showing the minimum distance between agents (Fig. 3) reveals a brief transitional "dip" to approximately $0.13-0.15$ m at the start, after which the repulsive forces and the modulating safety factor quickly push the agents apart, and already from approximately $t \approx 0.7$ s the distance consistently exceeds the specified threshold $d_{\min}^{(r)} = 0.35$ m. Subsequently, fluctuations are observed in the range of $0.55-0.70$ m, with occasional local drops to approximately $0.40-0.45$ m during periods of active formation reconfiguration, and after $t \approx 10$ s. The metric stabilizes around $0.63-0.67$ m, with peaks reaching approximately 0.80 m. Qualitatively, this means that the sparse "ring" graph and enhanced damping have eliminated mutual "overlap", while adaptively damped pseudo-inversion has reduced risks near singularities, so the system maintains a safe margin in the quasi-stationary state. The initial non-compliance interval and rare close approaches are explained by competition between attraction to $x^*(t)$ and by mutual agreement, which are temporarily suspended γ_i in response to barrier fields. From the perspective of the synchronization model, this confirms the effectiveness of safety prioritization: the method ensures compliance with $d_{\min}^{(r)}$ in steady state, but to ensure stability throughout the transition process, it is advisable to increase the barrier (higher CBF conditions) and introduce multi-point repulsion along the links.

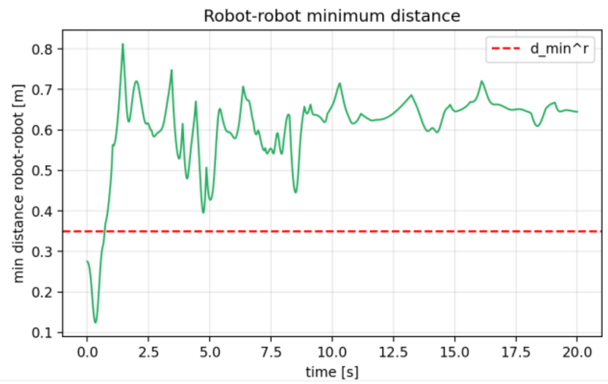


Fig. 3. Robot-robot minimum distance

The graph of the minimum "robot–human" distance (Fig. 4) shows a brief dangerous transition phase: in the first ≈ 2.3 seconds, the metric drops to $\approx 0.30-0.32$ m, which is below the threshold $d_{\min}^{(h)} = 0.50$ m. After the activation of the barrier forces and the reduction of γ_i.

The curve rises sharply above the threshold and subsequently remains within the safe zone, with typical fluctuations ranging from 0.70 to 0.95 m and occasional peaks reaching approximately 1.1 m. The average quasi-stationary value is approximately 0.80 m, indicating

a stable "social distance" around a person and an effective reorientation of priorities in favor of safety. The oscillatory profile is explained by a compromise between pull to $x^*(t)$ by consensus and barrier repulsion: when a human trajectory passes closer to the working contour, γ_i suppresses tracking by causing the robots to bypass the human with phase shifts. From the perspective of the synchronization model, this indicates that soft potentials remain functional after the transition; however, the initial failure highlights the need for stronger guarantees at the moment of launch (reinforcement of α_h, initial safety buffer (or CBF/predictive component) to ensure compliance $d_{\min}^{(h)}$ over the entire time interval.

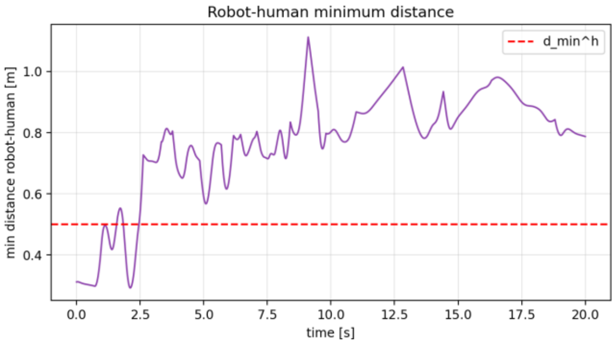


Fig. 4. Robot-human minimum distance

6. Conclusions

As a result of the study, a decentralized mathematical model for synchronizing the operation of collaborative robots in HRC scenarios, which combines consensus control in the task space with potential safety fields and projection via the pseudo-inverse Jacobian matrix, as confirmed by the results of numerical modelings for a group of three two-link manipulators. Quantitative analysis showed that the average tracking error of the common trajectory in steady-state operation decreased to 0.38 – 0.40 m, while the initial transient oscillations with peaks of up to 0.85 – 0.90 m gradually decay due to the action of damping and the consensus term, indicating the achievement of asymptotic motion coordination among the robots. The minimum distances between the robots, following a brief initial deviation, stabilize in the range of 0.60 – 0.70 m, which exceeds the specified safety threshold of 0.35 m, while the "robot–human" distance in quasi-steady-state mode is maintained at approximately 0.80 m against a standard of 0.50 m, which qualitatively confirms the effectiveness of potential barriers in steady-state mode. At the same time, recorded dangerous drops in the initial sections of the trajectory to 0.30 – 0.32 m for human-robot interaction and to 0.13 – 0.15 m for robot-robot interaction indicate the limitations of "soft" potential fields in transient modes and during rapid approaches. A qualitative analysis of the trajectory shapes revealed a decrease in the amplitude of oscillations and a transition from chaotic orbits to spiral-smoothed contours, indicating the stabilization of group dynamics; however, phase shifts caused by the trade-off between tracking and safety remain a source of integral error. The results obtained demonstrate the effectiveness of the proposed model for synchronization tasks in shared space with a human, but simultaneously reveal the need to implement strict barrier constraints such as Control Barrier Functions or CLF–CBF/QP control to ensure compliance with safe distances throughout the entire time interval. Further research should focus on integrating human motion prediction, a multi-point contact model along the manipulator links, and experimental validation of the model on a physical test bench, which will allow for increasing synchronization accuracy to the centimeter level while simultaneously ensuring formal safety guarantees in real-world HRC scenarios.

Conflict of interest

The authors declare that they have no conflicts of interest, including financial, personal, authorial, or any other nature, that could influence the research or the results published in this article.

Funding

Funding was provided as part of the state research project "Hardware and software complex for detection and neutralization of explosive objects based on intelligent robotic platforms" at the Department of Computer-Integrated Technologies, Automation, Robotics, and Security Engineering (KITARBI), Kharkiv National University of Radio Electronics.

Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 2 (36) *ISSN 2522-9818 (print)*
Innovative technologies and scientific solutions for industries. 2026. No. 2 (36) *ISSN 2524-2296 (online)*

Data availability

The manuscript has no associated data

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies to write this paper.

References

1. Mourtzis, D. (2023), "The Metaverse in Industry 5.0: A human-centric approach towards personalized value creation", Encyclopedia, Vol. 3, No. 3, pp. 1105–1120. DOI: https://doi.org/10.3390/encyclopedia3030080
2. Goh, C.S. and Chong, H.Y. (2023), "Opportunities in the sustainable built environment: Perspectives on human-centric approaches", Energies, Vol. 16, No. 3, Article 1301. DOI: https://doi.org/10.3390/en16031301
3. Lyashenko, V., Tahseen, A.J.A., Yevsieiev, V. and Maksymova, S. (2023), "Automated Monitoring and Visualization System in Production", International Research Journal of Multidisciplinary Technovation, Vol. 5, No. 6, pp. 09–18. DOI: https://doi.org/10.54392/irjmt2362
4. Borboni, A., Reddy, K.V.V., Elamvazuthi, I., Al-Quraishi, M.S., Natarajan, E. and Azhar Ali, S.S. (2023), "The expanding role of artificial intelligence in collaborative robots for industrial applications: A systematic review of recent works", Machines, Vol. 11, No. 1, Article 111. DOI: https://doi.org/10.3390/machines11010111
5. Hameed, A., Ordys, A., Możaryn, J. and Sibilska-Mroziewicz, A. (2023), "Control system design and methods for collaborative robots", Applied Sciences, Vol. 13, No. 1, Article 675. DOI: https://doi.org/10.3390/app13010675
6. Bortnikova, V., Yevsieiev, V., Beskorovainyi, V., Nevliudov, I., Botsman, I. and Maksymova, S. (2019), "Structural parameters influence on a soft robotic manipulator finger bend angle simulation", In: 2019 IEEE 15th International Conference on the Experience of Designing and Application of CAD Systems (CADSM), IEEE, pp. 35–38. DOI: https://doi.org/10.1109/CADSM.2019.8779300
7. Keshvarparast, A., Battini, D., Battaia, O. and Pirayesh, A. (2024), "Collaborative robots in manufacturing and assembly systems: Literature review and future research agenda", Journal of Intelligent Manufacturing, Vol. 35, No. 5, pp. 2065–2118. DOI: https://doi.org/10.1007/s10845-023-02137-w
8. Khan, Q.W., Khan, A.N., Rizwan, A., Ahmad, R., Khan, S. and Kim, D.H. (2023), "Decentralized machine learning training: A survey on synchronization, consolidation, and topologies", IEEE Access, Vol. 11, pp. 68031–68050. DOI: https://doi.org/10.1109/ACCESS.2023.3284976
9. Miao, X., Shi, Y., Yang, Z., Cui, B. and Jia, Z. (2023), "Sdpipe: A semi-decentralized framework for heterogeneity-aware pipeline-parallel training", Proceedings of the VLDB Endowment, Vol. 16, No. 9, pp. 2354–2363. DOI: https://doi.org/10.14778/3598581.3598604
10. Semeraro, F., Griffiths, A. and Cangelosi, A. (2023), "Human–robot collaboration and machine learning: A systematic review of recent research", Robotics and Computer-Integrated Manufacturing, Vol. 79, Article 102432. DOI: https://doi.org/10.1016/j.rcim.2022.102432
11. Li, W., Hu, Y., Zhou, Y. and Pham, D.T. (2024), "Safe human–robot collaboration for industrial settings: A survey", Journal of Intelligent Manufacturing, Vol. 35, No. 5, pp. 2235–2261. DOI: https://doi.org/10.1007/s10845-023-02159-4
12. De Simone, V., Di Pasquale, V., Giubileo, V. and Miranda, S. (2022), "Human-robot collaboration: An analysis of worker's performance", Procedia Computer Science, Vol. 200, pp. 1540–1549. DOI: https://doi.org/10.1016/j.procs.2022.01.355
13. Al-Sharo, Y., Abu-Jassar, A., Lyashenko, V., Yevsieiev, V. and Maksymova, S. (2023), "A Robo-hand prototype design gripping device within the framework of sustainable development", Indian Journal of Engineering, Vol. 20, No. 54, Article e37ije1673. DOI: https://doi.org/10.54905/disssi.v20i54.e37ije1673
14. Rybalskii, I., Kruusamäe, K., Singh, A.K. and Schlund, S. (2024), "An Augmented Reality Interface for Safer Human-Robot Interaction in Manufacturing", IFAC-PapersOnLine, Vol. 58, No. 19, pp. 581–585. DOI: https://doi.org/10.1016/j.ifacol.2024.09.275
15. Kóczi, D. and Sárosi, J. (2025), "Safety Engineering for Humanoid Robots in Everyday Life-Scoping Review", Electronics, Vol. 14, No. 23, Article 4734. DOI: https://doi.org/10.3390/electronics14234734
16. Pawlewski, P. (2024), "Scientific and Practical Challenges for the Development of a New Approach to the Simulation of Remanufacturing", Sustainability, Vol. 16, No. 9, Article 3857. DOI: https://doi.org/10.3390/su16093857
17. Ye, H., Song, Y., Lam, J. and Ioannou, P.A. (2025), "Decentralized Prescribed-Time Control of Robotic Arm-Finger Systems for Grasping and Moving Tasks", IEEE Transactions on Cybernetics, Vol. 55, No. 9, pp. 4386–4399. DOI: https://doi.org/10.1109/TCYB.2025.3586153
18. Zhang, M., Guo, J. and Zhang, Z. (2025), "A Distributed Slack Barrier Recurrent Neural Network for Multiple Redundant Manipulators Collaborative System in Obstacles Environment", IEEE Transactions on Systems, Man, and Cybernetics: Systems, Vol. 55, No. 9, pp. 6299–6311. DOI: https://doi.org/10.1109/TSMC.2025.3578566
19. Agarwal, S., Alonso-Mora, J. and Sun, S. (2025), "Decentralized Real-Time Planning for Multi-UAV Cooperative Manipulation via Imitation Learning", arXiv preprint, arXiv:2510.17143. DOI: https://doi.org/10.48550/arXiv.2510.17143

20. Ma, D., Zhang, C., Xu, Q. and Zhou, G. (2026), "Large and small-scale models' fusion-driven proactive robotic manipulation control for human-robot collaborative assembly in industry 5.0", Robotics and Computer-Integrated Manufacturing, Vol. 97, Article 103078. DOI: https://doi.org/10.1016/j.rcim.2025.103078
21. Ding, P., Zhang, J., Zheng, P., Zhang, P., Fei, B. and Xu, Z. (2025), "Dynamic scenario-enhanced diverse human motion prediction network for proactive human–robot collaboration in customized assembly tasks", Journal of Intelligent Manufacturing, Vol. 36, No. 7, pp. 4593–4612. DOI: https://doi.org/10.1007/s10845-024-02462-8
22. Loy, W.W., Donovan, J., Rittenbruch, M. and Belek Fialho Teixeira, M. (2025), "Exploring AR-enabled human–robot collaboration (HRC) system for exploratory collaborative assembly tasks", Construction Robotics, Vol. 9, No. 2, Article 19. DOI: https://doi.org/10.1007/s41693-025-00165-x
23. Rahman, S.M. (2025), "Assessment and Benchmark Metrics for Human-Robot Collaborative Object Manipulation Tasks", In: 2025 IEEE International Conference on Robotics and Technologies for Industrial Automation (ROBOTHIA), IEEE, pp. 1–6. DOI: https://doi.org/10.1109/ROBOTHIA63806.2025.10986742
24. Lin, P., Zeng, N., Li, Q. and Nübel, K. (2025), "A Review of Human–Robot Collaboration Safety in Construction", Systems, Vol. 13, No. 10, Article 856. DOI: https://doi.org/10.3390/systems13100856
25. Syed Khalid, M., Yevsieiev, V., Nevliudov, I., Lyashenko, V., Alharbi, A.R. and Rajeh, W. (2022), "HMI Development Automation with GUI Elements for Object-Oriented Programming Languages Implementation", International Journal of Engineering Trends and Technology, Vol. 70, No. 1, pp. 139–145. DOI: https://doi.org/10.14445/22315381/IJETT-V70I1P215
26. Nevliudov, I., Yevsieiev, V., Maksymova, S., Gopejenko, V. and Kosenko, V. (2025), "Development of mathematical support for adaptive control for the intelligent gripper of the collaborative robot manipulator", Advanced Information Systems, Vol. 9, No. 3, pp. 57–65. DOI: https://doi.org/10.20998/2522-9052.2025.3.07
27. Twist, L., Zhang, J.M., Harman, M., Syme, D., Noppen, J. and Nauck, D. (2025), "LLMs Love Python: A Study of LLMs' Bias for Programming Languages and Libraries", arXiv preprint, arXiv:2503.17181. DOI: https://doi.org/10.48550/arXiv.2503.17181
28. Kuchuk, H., Kosenko, N., Kuchuk, N., Gopejenko, V. and Kosenko, V. (2026), "Adaptive Resource Allocation Method for the Mobile Fog Layer of High-Density Industrial Internet of Things in Industry 5.0 Networks", Innovative Technologies and Scientific Solutions for Industries, Vol. 1, No. 35, pp. 65–78. DOI: https://doi.org/10.30837/2522-9818.2026.1.065
29. Monteiro, W.R. and Meza, G.R. (2026), "Practical Optimization Examples with Python", In: A Practical Guide to Optimization in Engineering and Data Science, Springer, Cham, pp. 261–324. DOI: https://doi.org/10.1007/978-3-032-04633-8_7
30. Nevliudov, I., Yevsieiev, V., Maksymova, S., Demska, N., Kolesnyk, K. and Miliutina, O. (2022), "Object Recognition for a Humanoid Robot Based on a Microcontroller", In: 2022 IEEE XVIII International Conference on the Perspective Technologies and Methods in MEMS Design (MEMSTECH), IEEE, pp. 61–64. DOI: https://doi.org/10.1109/MEMSTECH55132.2022.10002906
31. Bezkorovainyi, V., Binkovska, A., Noskov, V., Gopejenko, V. and Kosenko, V. (2025), "Adaptation of logistics network structures in emergency situations", Advanced Information Systems, Vol. 9, No. 4, pp. 39–50. DOI: https://doi.org/10.20998/2522-9052.2025.4.06
32. Nevliudov, I., Yevsieiev, V., Maksymova, S. and Filippenko, I. (2020), "Development of an architectural-logical model to automate the management of the process of creating complex cyber-physical industrial systems", Eastern-European Journal of Enterprise Technologies, Vol. 4, No. 3(106), pp. 44–52. DOI: https://doi.org/10.15587/1729-4061.2020.210761
33. Yevsieiev, V., Nevliudov, I., Maksymova, S., Omarov, M. and Klymenko, O. (2023), "Conveyor Belt Object Identification: Mathematical, Algorithmic, and Software Support", Applied Mathematics & Information Sciences, Vol. 17, No. 6, pp. 1073–1088. DOI: https://doi.org/10.18576/amis/170615

Received (Надійшла) 25.01.2026
Accepted for publication (Прийнята до друку) 21.05.2026
Publication date (Дата публікації) 27.06.2026

Відомості про авторів / About the Authors

Невлюдов Ігор Шакирович – доктор технічних наук, професор, Харківський національний університет радіоелектроніки, завідувач кафедри комп'ютерно-інтегрованих технологій, автоматизації, робототехніки та безпекової інженерії, Харків, Україна;.

Igor Nevliudov – Doctor of Technical Sciences, Professor, Kharkiv National University of Radio Electronics, Head of the Computer-Integrated Technologies, Automation, Robotics and Safety Engineering Department, Kharkiv, Ukraine;
e-mail: igor.nevliudov@nure.ua
ORCID ID: https://orcid.org/0000-0002-9837-2309
Scopus Author ID: https://www.scopus.com/authid/detail.uri?authorId=57216434058

Євсєєв Владислав В'ячеславович – доктор технічних наук, професор, Харківський національний університет радіоелектроніки, професор кафедри комп'ютерно-інтегрованих технологій, автоматизації, робототехніки та безпекової інженерії, Харків, Україна;

Vladyslav Yevsieiev – Doctor of Technical Sciences, Professor, Kharkiv National University of Radio Electronics, Professor of the Computer-Integrated Technologies, Automation, Robotics and Safety Engineering Department, Kharkiv, Ukraine;

e-mail: vladyslav.yevsieiev@nure.ua

ORCID ID: https://orcid.org/0000-0002-2590-7085

Scopus Author ID: https://www.scopus.com/authid/detail.uri?authorId=57190568855

Максимова Світлана Святославівна – кандидат технічних наук, доцент, Харківський національний університет радіоелектроніки, доцент кафедри комп'ютерно-інтегрованих технологій, автоматизації, робототехніки та безпекової інженерії, Харків, Україна;

Svitlana Maksymova – Candidate of Technical Sciences, Associate Professor, Kharkiv National University of Radio Electronics, Associate Professor of the Computer-Integrated Technologies, Automation, Robotics and Safety Engineering Department, Kharkiv, Ukraine;

e-mail: svitlana.milyutina@nure.ua

ORCID ID: https://orcid.org/0000-0002-1375-9337

Scopus Author ID: https://www.scopus.com/authid/detail.uri?authorId=57199329065

Пащенко Олександр Сергійович – Харківський національний університет радіоелектроніки, здобувач вищої освіти ступеня доктора філософії кафедри комп'ютерно-інтегрованих технологій, автоматизації, робототехніки та безпекової інженерії, Харків, Україна;

Oleksandr Pashchenko – Kharkiv National University of Radio Electronics, Postgraduate Student of the Computer-Integrated Technologies, Automation, Robotics and Safety Engineering Department, Kharkiv, Ukraine;

e-mail: oleksandr.pashchenko@nure.ua;

ORCID ID: https://orcid.org/0009-0003-5244-5925

Косенко Віктор Васильович – доктор технічних наук, професор, Національний університет «Полтавська політехніка імені Юрія Кондратюка», професор кафедри автоматики, електроніки та телекомунікацій, Полтава, Харківський національний університет радіоелектроніки, професор кафедри комп'ютерно-інтегрованих технологій, автоматизації, робототехніки та безпекової інженерії, Харків, Україна;

Viktor Kosenko – Doctor of Technical Sciences, Professor, National University "Yuri Kondratyuk Poltava Polytechnic", Professor of the Automation, Electronic and Telecommunication Department, Poltava, Kharkiv National University of Radio Electronics, Professor of the Computer Integrated Technologies, Automation, Robotics and Safety Engineering Department, Kharkiv, Ukraine;

e-mail: kosvict@gmail.com

ORCID ID: https://orcid.org/0000-0002-4905-8508

Scopus ID: https://www.scopus.com/authid/detail.uri?authorId=57190443921

РОЗРОБЛЕННЯ МОДЕЛІ СИНХРОНІЗАЦІЇ РОБОТИ КОЛАБОРАТИВНИХ РОБОТІВ-МАНІПУЛЯТОРІВ У HRC-СЦЕНАРІЯХ

У статті розглянуто задачу синхронізації роботи групи колаборативних роботів-маніпуляторів у спільному робочому просторі з людиною в умовах сучасних вимог людиноцентричного виробництва та концепції Індустрії 5.0. **Актуальність дослідження** зумовлена необхідністю забезпечення узгодженого руху декількох роботів за одночасного дотримання жорстких безпекових обмежень у HRC-сценаріях, де традиційні централізовані підходи не гарантують достатньої надійності та масштабованості. **Метою роботи** є розроблення математичної моделі синхронізованого керування колаборативними маніпуляторами з урахуванням взаємної узгодженості, відстеження спільної траєкторії та активного уникнення небезпечних зближень із людиною та між роботами. **Предметом дослідження** є децентралізовані закони синхронізації у просторі задачі з проєкцією в суглобовий простір та використанням потенціальних полів безпеки. **У роботі застосовано методи** математичного моделювання динаміки маніпуляторів на основі рівнянь

Ейлера–Лагранжа, методи консенсусного керування, псевдоінверсії матриці Якобі, чисельні методи інтегрування Рунге–Кутти четвертого порядку та методи аналізу безпекових метрик. **Завданнями дослідження** є формалізація законів консенсусного керування у просторі задачі, інтеграція потенціальних полів безпеки та чисельна валідація моделі для групи маніпуляторів у спільному робочому просторі. **Результати моделювання** для групи з трьох дволанкових планарних маніпуляторів показали формування узгоджених траєкторій зі зменшенням характерних коливань та стабілізацією динаміки, однак середня похибка відстеження спільної траєкторії залишається на рівні 0.38–0.40 м. Аналіз мінімальних дистанцій робот–робот і робот–людина підтвердив ефективність потенціальних бар’єрів у сталому режимі, проте виявив небезпечні провали на перехідних ділянках. **Зроблено висновок**, що запропонована модель забезпечує стабільну синхронізацію та базовий рівень безпеки, але для гарантованого дотримання зазорів у всьому часовому інтервалі доцільно перейти до жорстких бар’єрних обмежень типу CBF та задачно-пріоритетних схем керування.

Ключові слова: колаборативні роботизовані маніпулятори, синхронізація руху, сценарії взаємодії людини і робота (HRC), децентралізоване керування, алгоритм консенсусу, потенціальні поля безпеки, псевдообернена матриця Якобі, Індустрія 5.0.

Бібліографічні описи / Bibliographic descriptions

Невлюдов І. Ш., Євсєєв В. В., Максимова С. С., Пащенко О. С., Косенко В. В. Розроблення моделі синхронізації роботи колаборативних роботів-маніпуляторів у HRC-сценаріях. *Сучасний стан наукових досліджень та технологій в промисловості*. 2026. № 2 (36). С. 214–226. DOI: https://doi.org/10.30837/2522-9818.2026.2.214

Nevliudov, I., Yevsieiev, V., Maksymova, S., Pashchenko, O., Kosenko, V. (2026), "Development of a model for synchronizing the operation of collaborative robotic manipulators in HRC scenarios", *Innovative Technologies and Scientific Solutions for Industries*, No. 2 (36), P. 214–226. DOI: https://doi.org/10.30837/2522-9818.2026.2.214