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DEVELOPMENT OF MATHEMATICAL SUPPORT FOR ADAPTIVE CONTROL FOR THE INTELLIGENT GRIPPER OF THE COLLABORATIVE ROBOT MANIPULATOR

Abstract. The relevance of this study is due to the growing demands for intelligent robotic systems capable of safe interaction with humans in a collaborative work environment. It is especially important to provide adaptive control of grippers, which allows manipulators to accurately and delicately grasp objects of various shapes, masses, and stiffness. The subject of the research is the process of controlling a gripper as part of a collaborative robot manipulator, and the topic is the development of effective mathematical software for adapting control parameters in real time. The aim of the work is to improve the accuracy, reliability, and flexibility of the intelligent gripper by integrating Sensor Fusion and Neuro-PID control methods. In the course of the study, methods of mathematical modeling, sensor information processing, and numerical error analysis based on experimental data were used. The developed model takes into account the symmetry of the applied forces and ensures stable control of the gripping force, as evidenced by the results of experiments on controlling the asymmetric error and the control signal. The analysis showed that the deviations of the gripping error remain within ±0.2 N, and the control signal has smoothed dynamics without sharp impulses, which provides an adaptive response to external changes. The conclusions confirm the feasibility of the proposed approach to improve the control efficiency of robotic grippers. The scope of the results includes industrial collaborative robots, automated warehousing systems, manipulation of delicate objects, and biomedical robotic systems where high accuracy and adaptability of interaction is required.

Keywords: adaptive control; intelligent gripper; collaborative robot manipulator; Sensor Fusion; Neuro-PID controller; gripping force; strain gauges; ultrasonic sensor; multisensory system; safe interaction with objects.

Introduction

Formulation of the problem. In the context of the development of the Industry 5.0 concept, which involves the deep integration of human-centered technologies, intelligent systems, and flexible robotic solutions, research aimed at increasing the adaptability and safety of interaction between humans and collaborative robots is becoming increasingly important [1–3]. One of the critical components of such robotic systems is an intelligent gripper that provides direct physical contact with objects of various shapes, structures, and rigidities [4–6]. The ability of such a device to fine-tune the gripping force, taking into account contact conditions, object properties, and a changing environment, is crucial for the efficient and safe performance of manipulation tasks in flexible production systems [7–10]. The problem arises of creating mathematical software that allows to implement adaptive gripper control with dynamic force balancing on each claw of the device, while taking into account sensor data [11–14]. The use of Sensor Fusion methods allows synthesizing accurate force estimates based on multi-source information, while the Neuro-PID controller provides flexible adjustment of control parameters in real time based on changing external conditions [15–18]. The study aims to formalize mathematical models and algorithms for adaptive control that meet the safety, accuracy, and efficiency requirements of new generation systems operating in the Industry 5.0 paradigm.

Analysis of recent research and publications. The work presented in [19] investigates recent advances in planning and controlling collaborative robots, in particular in the context of integrating these systems into complex production processes. The authors proposed methods of adaptive planning and control that reduce energy consumption and increase the accuracy of manipulator movements, which can be useful for adaptive control of grippers. However, from the point of view of developing mathematical support for adaptive control for grippers, the proposed methods cannot be directly applied due to the lack of consideration of the specific characteristics of grippers and the need for integration with other robotic systems.

Study [20] proposes a new model of infinitely precise robust control for manipulators, which is widely used to ensure stability in unstable conditions. This method allows for improved control over manipulator trajectories even under strong dynamic oscillations, which is useful for precise operations with grippers. However, the method needs to be adapted to specific working conditions, as it was developed for general manipulation systems that do not take into account the features of collaborative use.

Paper [21] considers trajectory control using robotic observers for manipulators with brushless DC motors, which reduces errors in real-time trajectory tracking. The proposed solution improves the accuracy and stability of movements, which is important for integration into systems where grip accuracy is critical. However, this method can be limited in environments where additional variables need to be taken into account, such as the response to different loads when working with different materials.

In [22], an improved neuro-adaptive PID control strategy for robotic manipulators was proposed to achieve high accuracy and stability in automation tasks. This method can be effective for controlling adaptive grippers because it takes into account the constant changes in the working environment. However, the challenge lies in the difficulty of integrating this strategy with existing automation systems, which requires additional calibration and adjustment to the specific conditions of the gripper.

Study [23] compares traditional thermal and intelligent controllers combined with neural networks to regulate robotic manipulators. This approach can be useful for adaptive control of gripper mechanisms, as it allows taking into account thermal changes that can affect the stability of operation. However, this method needs to be improved for use in the context of collaborative robots, as thermal effects are not always the main problem in gripper control, and other factors such as mechanical vibrations and changes in load may be more critical.

In [24], a model based on a PD neural network was presented to control a manipulator for sealing cracks in pipes. This study demonstrates how neural networks can help in realizing precise manipulator movements, which is also an important aspect for grippers of collaborative robots. However, this approach does not take into account the specific needs for highlighting the details of adaptive gripper control, which requires additional improvements.

Study [25] reviews the use of external sensors to detect people in environments with robot participation. Given the need for integration with security systems, this approach can be useful for collaborative robots, but it is not focused on direct control of the trajectory of gripping devices, which is important for specific adaptive control.

The proposal for synergistic grasping analysis in [26] uses multi-sensor gloves to study object grasping. This method may be interesting for the development of adaptive control of gripping devices, as it allows for more accurate measurement of gripping forces. However, practical application in real-world settings may be limited by the difficulty of integrating such devices into collaborative robot systems.

Paper [27] considers the real-time generation of movements for manipulators in complex dynamic environments. This improves the adaptability of the system under changing circumstances, which can be useful for grippers under uncertainty. However, this approach requires further research in terms of integration with other sensors and control mechanisms to achieve high accuracy of adaptive control.

Deep learning for real-time planning of manipulator trajectories proposed in [28] is a promising direction for the development of adaptive manipulator control systems. At the same time, this approach requires a significant amount of data to train models, which may be a limitation for use in real-world applications.

Study [29] considers motion planning and impedance control for two-handed material handling tasks. This can be useful for the development of adaptive control methods for grippers, as it allows for real-time consideration of forces and loads. However, it should be borne in mind that for collaborative robots, further improvements to the algorithms may be required to ensure greater motion accuracy.

Taking into account all the studies presented, it can be concluded that the availability of various approaches to adaptive control in robotic systems has significant potential to improve the accuracy and efficiency of collaborative robots. However, in order to develop mathematical support for adaptive control of intelligent grippers for collaborative robots, it is necessary to take into account the specifics of such systems, including integration with various sensors, safety mechanisms, and high accuracy requirements, which makes this study relevant.

Formulation of the purpose of the article (statement of the task). The aim of the article is to develop mathematical support for the implementation of adaptive control of the intelligent gripper of a collaborative robot manipulator using the Sensor Fusion method and the Neuro-PID controller in order to ensure uniform distribution of the gripping force on each gripper and safe interaction with objects of different rigidity under conditions of incomplete or fuzzy information.

To achieve this goal, the following tasks need to be solved:

- to build a mathematical model of the dynamics of the gripping force, taking into account the influence of sensor data from strain gauges and an ultrasonic sensor;
- develop a data integration model (Sensor Fusion) to generate a generalized assessment of contact exposure;
- design a Neuro-PID controller for adaptive control of compression force based on feedback from a multisensor system;
- simulate and experimentally test the functioning of the adaptive control system on the model of an intelligent gripper.

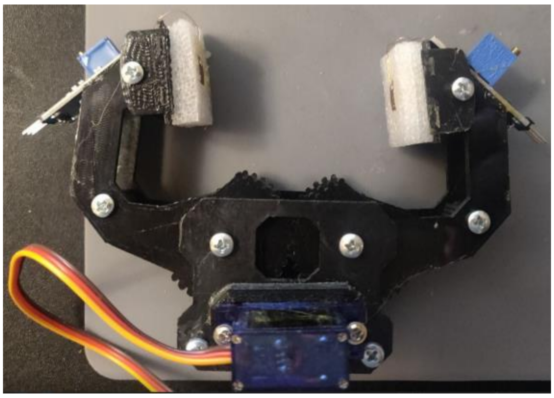
Main results

At the first step of developing a mathematical description of the adaptive control of the gripper for a collaborative manipulator using the Sensor Fusion method and the Neuro-PID controller, it is necessary to take into account the specifics of the hardware modules that will be used to obtain data: two BF350-3AA strain gauges [30], located on white pads on the jaw of the gripper; an HC-SR04 ultrasonic sensor [31,32] for determining the distance to the object; and an actuator: an SG90 servo motor [33] that controls the position of the claws, the general view of the experimental layout is shown in Fig. 1. As you can see from Fig. 1, each jaw is equipped with a BF350-3AA strain gauge, which makes it possible to measure the strain when it comes into contact with an object:

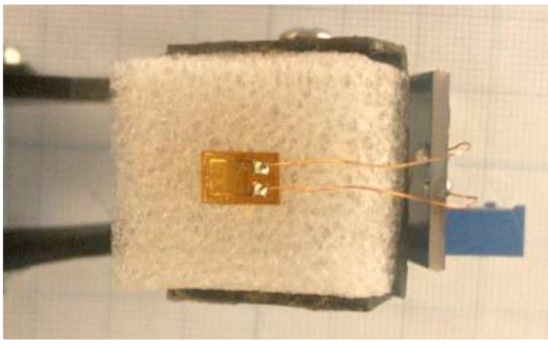
$$\varepsilon_i = \frac{V_{out,i}}{k \cdot V_{in}}, i = 1, 2; \tag{1}$$

$$F_i = E \cdot A \cdot \varepsilon_i = \underbrace{\left(E \cdot A / \left(k \cdot V_{in}\right)\right)}_{K_f} \cdot V_{out,i}, \tag{2}$$

where F_i – Strength on the left (F_1) and right sponge (F_2); $V_{out,i}$ is the output voltage of the load cell; V_{in} – bridge power supply (5V); E – modulus of elasticity of the pad material (polyurethane: ~10^6 Pa); A – contact area of the pad; K_f – generalized voltage-to-force conversion factor; k – the calibration factor of the sensor includes the Gauge Factor (GF).



a



b

Fig. 1. General view of the experimental model of the intelligent gripper of the collaborative robot man/pulator: a – top view; b – mounting of the BF350-3AA load cell on the gripper jaw

GF is the sensitivity factor of a strain gauge, which shows how much the electrical resistance of the strain gauge changes when it is stretched or compressed. Gauge Factor (GF) [34] is defined as:

$$GF = \frac{\Delta R / R}{\varepsilon_i}, \qquad (3)$$

where ΔR – change in strain gauge resistance; R – initial resistance; ε_i – mechanical deformation on the left (F_1) and right claws (F_2).

For example, for the BF350-3AA strain gauge, GF ≈ 2.0, which means that when stretched by 1% (i.e. $\varepsilon = 0.01$), the resistance will change by 2%.

Ultrasonic sensor HC-SR04 measures the distance to an object:

$$d = \frac{v_s \cdot t_{echo}}{2}, \qquad (4)$$

where v_s – the speed of sound (≈ 343 m/s); t_{echo} – the time between sending and receiving a pulse; d – distance to the object between the claws.

In the next step, using the Sensor Fusion model [35], we will merge the data from the sensors described in (1,3) to improve the accuracy of the compression force estimation, taking into account: direct force measurement (F_1, F_2) and approximation of the force from the object geometry through distance (d):

$$F_{est} = w_1 \cdot \left(\frac{F_1 + F_2}{2} \right) + w_2 \cdot f(d), \qquad (5)$$

where $w_1, w_2 \in [0,1]$, $w_1 + w_2 = 1$ – weighting coefficients; $f(d)$ – a heuristic function for estimating grip strength based on distance:

$$f(d) = K_d \cdot e^{-\alpha d}, \qquad (6)$$

where K_d – scaling factor (characterizes the "rigidity" of the grip); α – rate of force reduction with increase d.

It is also necessary to develop a mathematical representation of the asymmetry of the gripping force, which is necessary for quantitative analysis and subsequent compensation of the uneven distribution of forces on the working surfaces of the gripping device of a collaborative robot. Force asymmetry occurs due to design inaccuracies, object heterogeneity, variations in sensor characteristics, or mechanical gaps in servos, and can lead to undesirable consequences such as object damage, object loss, or reduced manipulation accuracy [36].

Formalizing this asymmetry in the form of a mathematical expression allows us to build an error function that describes the difference between the forces acting on both sides of the gripper. This approach is key to the implementation of adaptive control algorithms, as it allows the Neuro-PID controller to respond in a timely manner to the detected imbalanced action [37–40]. In addition, the introduction of a mathematical model of asymmetry is critical in the implementation of the Sensor Fusion concept, as it ensures the integration of multisensory information taking into account the spatial distribution of force at the contact points. Thus, the mathematical representation of the gripping force asymmetry not only improves control accuracy, but also ensures safe and reliable interaction between a collaborative robot and a human in a variable production environment.

To ensure equal force on both jaws:

$$\Delta F = F_1 - F_2, \qquad (7)$$

where ΔF – the difference in force on the left and right claws, subject to $\Delta F \to 0$; F_1 – force on the left jaw of the gripper; F_2 – force on the right jaw of the gripper.

Let's determine the asymmetry error:

$$e_\Delta(t) = F_1(t) - F_2(t), \qquad (8)$$

where $e_\Delta(t)$ – gripping force asymmetry error at a point in time t. Characterizes the difference between the forces generated by the two claws of the gripper. If this value is not equal to zero, there is an imbalance that can affect the quality of gripping or the safety of the object [41]. This error is used as an input variable for the adaptive control system, in particular the Neuro-PID controller, to automatically equalize the forces;

$F_1(t)$ is the force generated by the first claw of the gripping device at the moment of time t, obtained from a strain gauge placed on the corresponding working surface;

$F_2(t)$ - the force generated by the second claw of the gripper at the same time *t*, also obtained from another load cell. Together with $F_1(t)$, it determines the balance of forces in the gripper system.

Equation 8 allows us to detect and quantify gripping imbalance, which is critical to ensure symmetrical action on the object and safe operation in human collaboration, and this error will also be controlled by a separate regulator.

To control the asymmetry error of the gripping force $e_\Delta(t)$ at the time t, it is proposed to use a Neuro-PID controller due to the need to ensure high accuracy and adaptability of the control of the gripping force of the intelligent gripper of a collaborative robot. The traditional PID controller works well in conditions with stable and predictable parameters of the control object, but under conditions of variable load, incomplete information about the object's dynamics, the influence of external factors, and high requirements for the safety of interaction with humans, its effectiveness decreases. The Neuro-PID controller, unlike the classical PID controller, combines the capabilities of a neural network and feedback control, which allows the controller coefficients to be automatically adapted to current conditions in real time. As a result, the system can effectively respond to asymmetries in gripping force, compensate for sensor errors, and change in shape or stiffness of the object to be gripped. In addition, integration with Sensor Fusion methods allows the Neuro-PID controller to take into account multi-source information from load cells and an ultrasonic sensor, which provides a more complete understanding of the system state and increases control reliability.

The classic PID control of the gripping force is described:

$$e(t) = F_{t\arg et} - F_{est}(t)\,, \tag{9}$$

where $e(t)$ – control error at a given time t, which determines the difference between the target (desired) value of the gripping force and the actual (estimated) force applied by the gripper. The error is the main input variable for the PID controller, which generates the corresponding control signal for the servomotor; $F_{t\arg et}$ – the target (desired) gripping force value, which is determined depending on the type of object, its weight, stiffness, or safety requirements. This value is set by the operator, predefined from the object database, or calculated automatically by a high-level system; $F_{est}(t)$ – is the estimated value of the gripping force at the moment of time t, which is determined by processing data from strain gauges (BF350-3AA).

Control signal to the servo drive (SG90):

$$u(t) = K_p(t)e(t) + K_i(t)\int e(t)dt + K_d(t)\frac{de(t)}{dt}\,, \tag{10}$$

But, K_p, K_i, K_d – variables adapted by a neural network, then:

$$K_p(t) = NN_p([e(t), \dot{e}(t), \Delta F])\,; \tag{11}$$

$$K_i(t) = NN_i([e(t), \int e(t), \Delta F])\,; \tag{12}$$

$$K_d(t) = NN_d([\dot{e}(t), \Delta F])\,, \tag{13}$$

where $e(t)$ – the error between the desired and actual grip strength; $\dot{e}(t)$ – rate of change of the error (derivative of the error); ΔF – asymmetry of the gripping force between the two claws; $\int e(t)$ – time error integral, which takes into account the long-term deviation of the system from the desired gripping force, allows you to take into account constant or slow shifts, for example, due to object deformation or material creep.

Thus, all three coefficients $K_p(t), K_i(t), K_d(t)$ are determined in real time using adaptive neural networks, taking into account the state of error and symmetry of the gripping force, which allows flexible and accurate control of the intelligent gripper of a collaborative robot in accordance with the requirements of safety and efficiency in Industry 5.0 [42–46].

The servo control model (SG90) is a system with limited position control:

$$\theta(t) = \theta_0 + u(t)\,, \tag{14}$$

where θ – jaw opening angle (controls compression); $u(t)$ – control signal from the Neuro-PID; θ_0 – initial value (open claw).

Based on model 14, the following conclusions can be drawn: a decrease in $\theta \rightarrow$ to a decrease in $d \rightarrow$ and an increase in F_1, F_2.

To control the asymmetry (force balancing), it is proposed to use a separate angle correction controller (or an additional microservo drive) to compensate for the asymmetry of the gripping force between the two "claws" (jaws) of the intelligent gripper, which is especially important when interacting with delicate or non-standard objects, can be implemented as:

$$u_\Delta(t) = K_\Delta \cdot (F_1 - F_2)\,, \tag{15}$$

where $u_\Delta(t)$ – Angle compensation or micro-positioning control signal used to adjust an additional actuator, such as a micro-servo drive, which adjusts the position of one of the jaws to equalize the compression force; K_Δ – asymmetry gain, which determines how strongly the regulator will respond to the difference between the forces applied by the two claws. The value of K_Δ is selected taking into account the design features of the mechanism and the requirements for accuracy and stability; F_1 and F_2 are the gripping forces measured on the first and second jaws of the gripper, respectively, using strain gauges.

Thus, the regulator (15) allows for local compensation of the asymmetry of the gripping force by adjusting the position of one of the gripping elements, ensuring uniform distribution of forces and increasing the reliability and safety of collaborative interaction with a person.

The developed mathematical description of the adaptive control of the gripper for a collaborative manipulator using the Sensor Fusion method and a Neuro-PID controller provides significantly higher accuracy and stability of the gripping force compared to classical PID or fixed-parameter controllers. By integrating data from strain gauges and an ultrasonic sensor in real time, a more complete picture of physical interaction with the object is achieved, allowing for dynamic adaptation of control actions. The Neuro-PID controller, in turn, compensates for nonlinearities and changes in gripping characteristics under variable loads and complex object geometries, which is not available to traditional controllers. Compared to algorithms with predefined parameters or hard-coded logic rules, the proposed approach provides adaptability, smoothness, and safety, which is critical for human interaction in Industry 5.0.

Experimental studies and analysis of the results

To verify the correctness and adequacy of the developed mathematical support for adaptive control of the intelligent gripper of the collaborative robot manipulator, it is proposed to conduct two experiments:

- stabilization of grip strength (first experiment).

Objective: to test the ability of the system to maintain the target gripping force (2N) on both jaws of the gripper with a static object.

Conditions: gripping an object with a known rigidity. The system regulates the force through a servo motor using a Neuro-PID controller.

Evaluation: Analyzing the discrepancy between F_1, F_2 and the target force, as well as the capture asymmetry ($e_\Delta(t)$).

- reaction to an obstacle (second experiment)

Objective: to evaluate the response of the adaptive controller when the force on one of the claws is reduced (simulating an external impact or displacement of an object).

Conditions: at the moment of time $t = 5$ c, the mechanical displacement of the object is added.

Evaluation: speed and stability of symmetry restoration (minimizing $e_\Delta(t)$ and returning to $F_{t\arg et}$.

The results of the experiments are shown in Fig. 2, in the form of combined graphs.

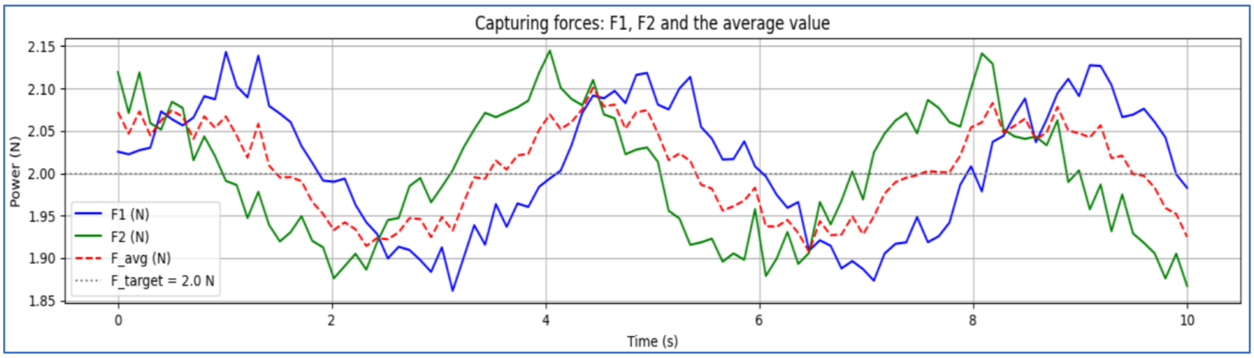


Fig. 2. Combined graph of grip strength: F_1, F_2 and average value (first experiment)

Based on the resulting graph (Fig. 2) showing the change in the gripping forces F_1 and F_2 over time, as well as their average value F_{avg}, we can conclude that the gripping device of the collaborative manipulator is stable and symmetrical. It is observed that both forces F_1 and F_2 have a sinusoidal character with minor fluctuations, which models the variability of the real environment, the influence of external factors, or micro-vibrations of the mechanisms.

The average force value F_{avg}, which is directly compared to the target force $F_{tavget} = 2.0$H, shows generally stable behavior and is close to the target value in most parts of the graph. This indicates the effectiveness of the Neuro-PID controller used to maintain the required level of grip force [46, 47].

Fluctuations between F_1 and F_2 within ± 0.1 N are acceptable and indicate a slight asymmetry that may be due to design or feedback features. The absence of sharp peaks or dips in the graph demonstrates that the system does not go beyond the limits of stability and that the adaptive control copes with the compensation of fluctuations. Reducing the deviation of the average gripping force from the set target confirms the accuracy of the implemented mathematical control model.

In the context of the first experiment, the results obtained indicate the correctness of the mathematical model of the adaptive controller, the adequacy of the use of sensor fusion, and the possibility of its further integration into practical tasks of controlling the grasping of objects of different rigidity and shape. This behavior of the system is encouraging for the next stages of the study, in particular in the context of testing on physical objects with uneven mass distribution.

Analysis of the graph (Fig. 2) of the gripper asymmetry error $e_\Delta(t) = F_1(t) - F_2(t)$ shows a dynamic change in the difference between the forces applied by both sides of the gripper.

A characteristic waveform is observed, indicating the periodic dominance of one of the gripper jaws, but the fluctuations remain within about ± 0.2 N. This indicates a relatively small asymmetry in the gripper operation, which does not exceed the acceptable level for most precision manipulation tasks. Importantly, the graph does not contain sharp jumps or a constant shift to one side, indicating a well-balanced system with dynamic deviation compensation. The fluctuations pass through the zero line, which confirms the operation of the balancing algorithm based on the asymmetric error. This confirms the effectiveness of using a separate controller to compensate for the asymmetry, in particular in the form of position or angle correction by the microservo drive. Combined with the results of the first experiment, where the average gripping force remained close to the target, we can conclude that the developed adaptive control approach not only provides the required level of gripping force but also dynamically corrects the asymmetry while maintaining system stability. Thus, the model effectively implements both general force control and local balancing, which is critical for working in a variable environment or when manipulating objects with uneven mass distribution.

The graph (Fig. 3) of the control signal of the Neuro-PID controller demonstrates the variable dynamics of the output signal $u(t)$, which is adaptively formed in response to the deviation of the gripping force from the target value.

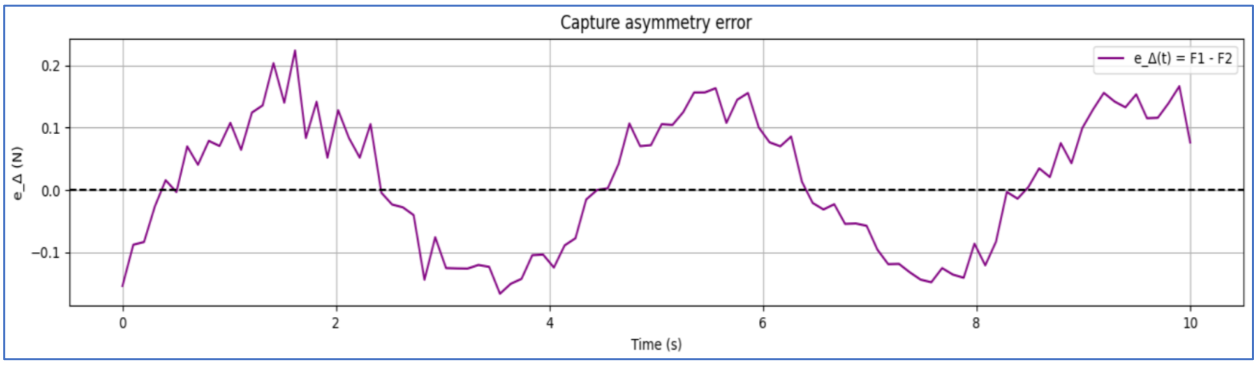


Fig. 3. Graph of gripper asymmetry error (second experiment)

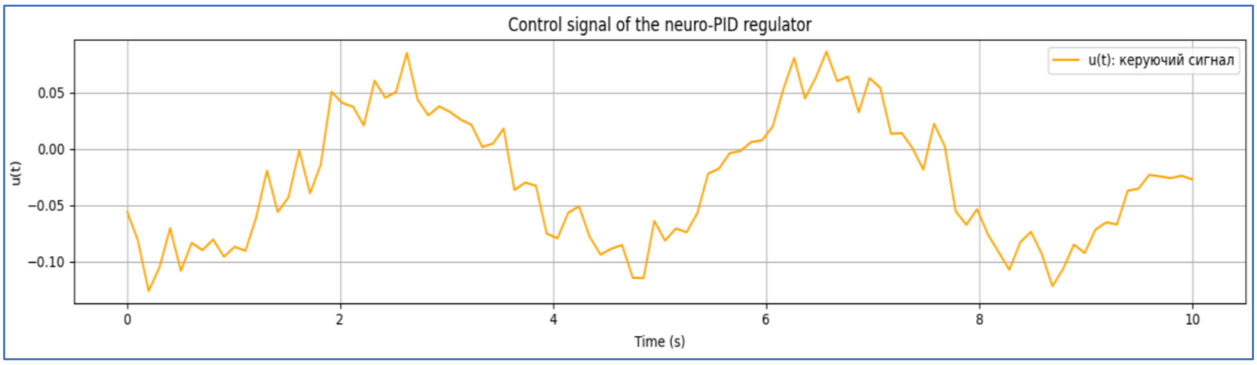


Fig. 3. Graph of the control signal of the Neuro-PID controller

Fluctuations in the control signal range from about – 0.12 to + 0.08, which indicates a moderate intensity of compensatory actions aimed at stabilizing the system. In the initial phase of the graph, there are noticeable fluctuations, which indicate the controller's response to initial inaccuracies or disturbances characteristic of the moment of object capture.

Subsequently, the signal remains relatively stable with alternating positive and negative values, indicating the balancing nature of the controller's action.

It is important to note that there are no sharp impulses or jumps in the signal, which confirms the effective operation of the adaptive mechanism based on neural network prediction of the PID controller parameters.

The smoothness of the control signal changes avoids mechanical overloads of the actuators, which is an important factor in the system's durability. In the context of the results of the first experiment, it can be argued that the generated signal $u(t)$ provided the necessary level of stabilization of the gripping force and reduction of the control error.

Thus, the adaptive Neuro-PID controller effectively implements a control algorithm that combines accuracy and stability with the ability to respond to unstable external influences or changes in the object of manipulation [3].

Conclusions and directions for further research

As a result of the research and experimental modeling, the mathematical support for the adaptive control system of the intelligent gripper of the collaborative robot manipulator was developed. The methodology is based on a combined approach that combines the Sensor Fusion method for integrating data from several pressure and force sensors, as well as a Neuro-PID controller adapted for real time, which allows taking into account dynamic changes in the conditions of object grasping. The results of the first experiment showed that the average value of the gripping force is kept near the target level with acceptable deviations, which indicates the high accuracy of the developed controller.

The analysis of the gripping asymmetric error showed that the system effectively compensates for asymmetric forces arising during the gripping of irregularly shaped objects, keeping the error within ±0.2 N. The dynamics of the control signal confirmed the presence of a stable and controlled response of the system to disturbances, without sharp impulses or oscillations, which allows maintaining the structural integrity of the manipulator and the object itself.

Thus, the proposed mathematical software has proven its effectiveness in experimental testing, demonstrating the ability to adapt, precise control, and reduce gripping asymmetries.

As a result, it can be concluded that the constructed control model is suitable for implementation in robotic systems with high requirements for safety, accuracy, and adaptability.

The results of the study can be applied in production of collaborative robots for handling delicate or fragile objects, in automated packaging, sorting, and biomedical manipulation systems, where reliable and sensitive grip control is required.

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Розробка математичного забезпечення адаптивного керування інтелектуальним захватним пристроєм колаборативного робота маніпулятора

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Анотація. Актуальність проведеного дослідження обумовлена зростаючими вимогами до інтелектуальних роботизованих систем, здатних до безпечної взаємодії з людиною в умовах спільного робочого середовища. Особливо важливим є забезпечення адаптивного керування захватними пристроями, що дозволяє маніпуляторам здійснювати точне і делікатне захоплення об'єктів різної форми, маси та жорсткості. Предметом дослідження є процес керування захватним пристроєм у складі колаборативного робота-маніпулятора, а темою - розробка ефективного математичного забезпечення для адаптації параметрів керування в реальному часі. Метою роботи є підвищення точності, надійності та гнучкості функціонування інтелектуального захвату шляхом інтеграції методів Sensor Fusion та Neuro-PID регулювання. У процесі дослідження було використано методи математичного моделювання, обробки сенсорної інформації та чисельного аналізу похибок на основі даних з експериментів. Розроблена модель враховує симетрію прикладених зусиль та забезпечує стабільне регулювання сили захоплення, про що свідчать результати експериментів із контролю похибки асиметрії та керуючого сигналу. Аналіз показав, що відхилення похибки захоплення залишаються в межах ±0.2 Н, а керуючий сигнал має згладжену динаміку без різких імпульсів, що забезпечує адаптивну реакцію на зовнішні зміни. Висновки підтверджують доцільність запропонованого підходу для підвищення ефективності керування роботизованими захватами. Область застосування результатів включає індустріальні колаборативні роботи, системи автоматизованого складування, маніпуляції з делікатними об'єктами, а також біомедичні роботизовані комплекси, де необхідна висока точність і адаптивність взаємодії.

Ключові слова: адаптивне керування; інтелектуальний захоплювач; колаборативний робот-маніпулятор; Sensor Fusion; Neuro-PID-контролер; сила захоплення; тензодатчики; ультразвуковий датчик; мультисенсорна система; безпечна взаємодія з об'єктами.