ABSTRACT

thesis for the degree of Doctor of Philosophy (PhD)
on speciality 8D07104 - "Instrumentation engineering"
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DEVELOPMENT OF AN AUTOMATED MANIPULATOR CONTROL SYSTEM USING MACHINE VISION

Relevance of the work. With the accelerated development of modern technology, the importance of automated systems and robotics is increasing. Automation of manipulator control using machine vision is an important research area that extends the scope of applications, from industrial production to medicine and security.

In such a context, the development of low-cost, versatile and accessible robotic solutions is crucial. In this thesis, the development of a manipulator platform is a reflection of progress in this direction. Printing the robot elements on a 3D printer and using low-cost electronic components provide affordable and efficient solutions for small-scale manufacturing and research environments. The control system algorithms are designed so that the robot kinematics and trajectory planning can run on low-performance microcontrollers, extending the scope of the application. Thus, this work has great potential for automating small-scale manufacturing processes and creating experimental laboratory benches used in research work. The relevance of this thesis lies in increasing the availability of new technologies and stimulating innovative growth in the SME sectors.

This research also opens new possibilities for future developments of automated systems, especially in the area of complex data processing and improving the ability of machine vision to analyze information. The relevance of this topic is also due to the wide range of research in the field of artificial intelligence and robotics, which play an important role in the development of modern innovative technologies.

The aim of the work is to develop a low-cost sorting manifold platform and its automated control system with machine vision.

The objectives of the study are:

1. A review of state-of-the-art manifolds, their control systems, machine vision platforms and trajectory planning approaches;

2. Solving the kinematics of the selected type of manipulator and modeling with trajectory planning;

3. Selection of control system components and implementation of kinematics and trajectory planning algorithms on microcontroller, training of machine vision debugging board;

4. Conduct experiments with the developed system, compare the results with the model and improve;

5. To compare the performance and cost of the manipulator with solutions in the market.

The objects of research or development are the electronic control system and kinematic and trajectory algorithms.

The subject of research – low-cost manipulator platform with machine vision, kinematic modeling, development of trajectory control algorithms and implementation techniques on low-cost microcontrollers.

Methodological basis of scientific research:

1. Literature review: existing research, publications on modern robotic systems, kinematics, control algorithms and microcontroller applications were studied.

2. Computer modeling and simulation: computer modeling tools and simulation programs were used to study the manipulator kinematics and approaches to trajectory planning: Matlab Simulink, Matlab Simscape Multibody, Solidworks, Python Matplotlib, Python scipy.Signal, Solidworks, Fusion 360.

3. Prototyping: developed a physical model of the manipulator using 3D printing technology.

4. Software: control algorithms for the manipulator were developed and implemented on microcontrollers.

5. Experimental tests: experimental tests were conducted to evaluate the performance of the control system on the assembled manipulator.

Scientific novelty:

The work presents new software and hardware solutions in the realization of integrated control system of manipulator c machine vision.

In the work a new hybrid method of planning the trajectory of the manipulator motion is developed. The hybrid method allows to optimize accuracy and efficiency due to trajectory planning both in the task space and in the space of kinematic pairs within one operation.

Practical significance and results:

The practical significance of the study is revealed by the integration of machine vision into the manipulator control system, a method that allows research and experimentation in scientific laboratories, as well as the automation of various sorting and assembly operations at small manufacturing enterprises.

The main points put forward for defense are:

1. Manipulator, model of its kinematics and trajectory planning method.

2. Scheme of the manipulator control system, algorithm and trained model of machine vision for object recognition.

3. Manipulator and prototype of its control system.

4. Experimental verification of the manipulator.

Approbation of the research results. The main results of the work were discussed at the 1st International Scientific and Technical Conference:

“IEEE International Symposium on Multiple-Valued Logic. Online ACESYRI workshop - 2021” (May 25-27, Online).

Publications, doctoral student's contribution to their publication and approbation of the work.

The main findings of the work are presented in 4 publications, including 1 article in a journal included in the SCOPUS database (percentile 36%), 3 articles in publications recommended by the Committee for Quality Assurance in Science and Higher Education of the Republic of Kazakhstan.

The doctoral student made the main contribution to all publications on the development of the research concept, development of methodology, data collection and analysis, visualization of results, writing the main texts of articles and ensuring their scientific justification. In addition, the doctoral student performed important technical and analytical tasks in the work, such as software development, modeling and experimentation.

Scope and structure of the work. The dissertation consists of an introduction, four chapters, a conclusion, a list of used sources and appendices. The scope of the dissertation consists of a reference list of 117 titles, 108 pages of typewritten text, 6 tables, 80 figures, and 1 appendix.

Main content of the work

In the field of technological advancement, the importance of automated systems and robotics is constantly increasing [1-8]. The thesis delves into this developing field with a focus on the development of an automated control system for manipulators using machine vision. This research spans from industrial manufacturing to medicine and security, demonstrating the application of robotic technology. The essence of the work is to increase the accessibility of robotics, making complex solutions accessible to small industrial and research organisations through the use of cost-effective components and 3D printing technologies.

Automating the control of manipulators using machine vision not only improves efficiency but also enhances capabilities. The thesis outlines a comprehensive approach of manipulators from analysing existing technologies and their control systems to the practical implementation of a manipulator platform. This initiative reflects the drive for innovation by offering a way to integrate advanced robotics into sectors previously considered impractical due to cost and complexity constraints.

The first section begins by analysing the current state of the art of manipulators and their control systems. This section is important because it lays the foundation for understanding the dynamics of the robotic manipulator market and the technological advances that have shaped their evolution. The global market for industrial robotic manipulators is wide and diverse, and their applications include assembly [9], welding [10], painting [11], healthcare [12], agriculture [13], and others. The analysis provides a classification of manipulators based on mechanical structure, control methods, applications and levels of autonomy to provide a holistic picture. A detailed analysis of state-of-the-art manipulator control systems and their applications is presented in a review study [14].

A significant part of this analysis is designed to understand the types of manipulators such as articulated, SCARA, Cartesian and parallel (delta), each with its own advantages and disadvantages and suitable for specific tasks.

Furthermore, the thesis emphasises the role of machine vision in enhancing the capabilities of manipulators. Machine vision allows robots to perceive the environment, make informed decisions and perform tasks more accurately and adapted to the environment.

The second part of the thesis deals with crucial aspects of robot manipulator design: kinematics and trajectory planning, modelling. It plays a crucial role in bridging the gap between the theoretical principles of robotics and their practical application, Laying the foundation for an automated control system combined with machine vision.

Kinematics studies motion without considering the forces that cause it, which plays a very important role in understanding and designing robotic manipulators. The analysis of kinematics includes forward and inverse kinematics. Forward kinematics involves determining the position of the working body by considering the parameters of the kinematic couples of the robot. On the contrary, inverse kinematics allows finding the parameters of the pair necessary to achieve the desired position of the implement.

The parallel (delta) manipulator (Fig. 1), characterised by its parallel structure and high-speed manipulation capabilities, presents unique challenges and opportunities in kinematic analysis.

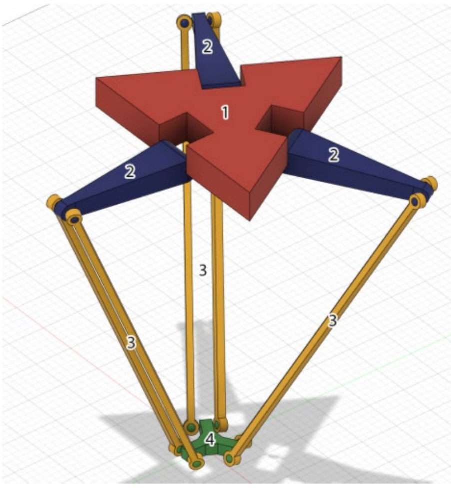

Figure 1 – Parallel (delta) manipulator

The delta manipulator consists of two triangular platforms, one of which is stationary (1) and the other is movable and is a working organ (4). The platforms are interconnected by three kinematic chains, each of which consists of two links - active (2) and passive arm (3). The kinematic model of the delta manipulator is based on its geometric and algebraic relations, which simplifies the calculation of the position of the working body in three-dimensional space. This model allows accurate prediction of the robot's movements and performs various operations, this is very important to ensure its high accuracy.

Trajectory planning is the process of determining the path that the robot's working body follows to move from one point to another, ensuring smooth and efficient motion. Trajectory planning for a parallel (delta) robot involves not only the spatial path but also the timing of each motion, taking into account the robot's speed, acceleration and braking capabilities.

The thesis investigates different trajectory planning methods, including two-point, linear and circular trajectories, as well as interpolation methods such as splines or polynomial functions. The choice of trajectory planning method depends on the specific application and requirements, such as the need for continuous motion, minimal bounce, or precise control of implement velocity and acceleration.

The trapezoidal trajectory planning method was used in this work. The trapezoidal path planning method is a mixture of two methods, parabolic and linear, hence it is also called Linear Section with Parabolic Blends (LSPB). A trapezoidal trajectory consists of three phases, a phase with constant positive acceleration (acceleration phase), a phase with constant velocity and a phase with constant negative acceleration (deceleration phase) [15]. The three phases are respectively characterised by the following formulae:

$$1)\qquad \begin{cases} q_a(t) = q_0 + \frac{v_{const}}{2T_a} t^2 \\ \dot{q}_a(t) = \frac{v_{const}}{T_a} t \\ \ddot{q}_a(t) = \frac{v_{const}}{T_a}, \end{cases}$$

$$2)\qquad \begin{cases} q_b(t) = q_0 - \frac{v_{const} T_a}{2} + v_{const} t \\ \dot{q}_b(t) = v_{const} \\ \ddot{q}_b(t) = 0, \end{cases}$$

$$3)\qquad \begin{cases} q_c(t) = q_1 - \frac{v_{const}}{2T_a} (T - t)^2 \\ \dot{q}_c(t) = \frac{v_{const}}{T_a} (T - t) \\ \ddot{q}_c(t) = \frac{v_{const}}{T_a}, \end{cases}$$

where q_a, q_b, q_c – position functions;

q_0, q_1 – initial and final positions;

v_{const} – value of constant velocity;

T_a – duration of constant acceleration/deceleration;

T – duration of motion.

One of the main contributions of this section is the development and implementation of trajectory planning algorithms combined with the kinematic structure of the delta manipulator. These algorithms take into account the physical constraints and usability of the robot, optimising the trajectory for speed, efficiency and accuracy. Trajectory planning is also integrated with the robot control system, providing real-time corrections based on sensor feedback and machine vision, further enhancing robot performance and adaptability.

A significant part of the section is devoted to 3D modelling and simulation of its kinematics and trajectory planning method. Using software tools such as MATLAB Simulink, SolidWorks and Fuison 360, the thesis proposes a comprehensive model that allows visualisation and analysis of the manipulator movements. Figure 2 shows a schematic of the model assembled in Matlab Simulink software.

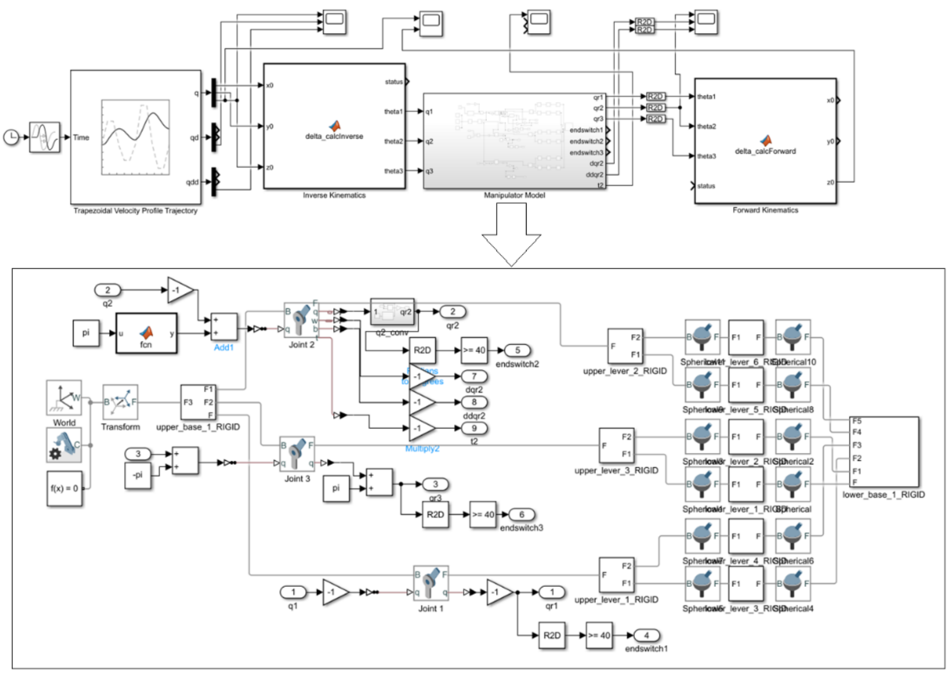

Figure 2 – Schematic in Matlab Simulink programme

3D modelling and computer simulation serve many purposes: they provide a virtual platform for testing and debugging kinematic models and trajectory planning algorithms, help identify potential problems and optimisations before physical implementation and provide interactive tools.

To validate the theoretical models and computational algorithms, the thesis shows a series of experiments with a physical prototype delta manipulator. These experiments are designed to verify the accuracy, efficiency and reliability of the kinematic models and trajectory planning methods under real-world conditions.

The results of these experiments are carefully analysed by comparing theoretical predictions with actual data. This analysis not only validates the kinematic models and trajectory planning algorithms, but also indicates areas of improvement and optimisation. Experimental validation is an important step in bridging the gap between theory and practice, ensuring that the developed models and algorithms can be used effectively to create an automated delta manipulator control system.

The third part of the thesis focuses on the physical model, structure and algorithms of the manipulator control system. This section includes the design of the manipulator, the hardware components of its control system, the control algorithm and the integration of machine vision into the system.

The report begins with the assembly of the manipulator itself. This part of the section describes considerations for the mechanical design, material selection, assembly processes, and the physical structure and motion capabilities of the manipulator.

The control system hardware includes demonstration and assembly of the electronic components that control the motion of the robot. The control system consists of a microcontroller, motor drivers, power supply, and connection modules that allow the manipulator to receive commands and start its motors accordingly.

Figure 3 shows the electronic schematic of the manipulator control system. Since the objective of the work was to create a low cost and affordable control system, a low cost and simple Arduino Uno development board was used as the basis for the control system. The Arduino Uno board is now equipped with an outdated 8-bit microcontroller, but nevertheless its processing power is sufficient to calculate the trapezoidal motion path and kinematics.

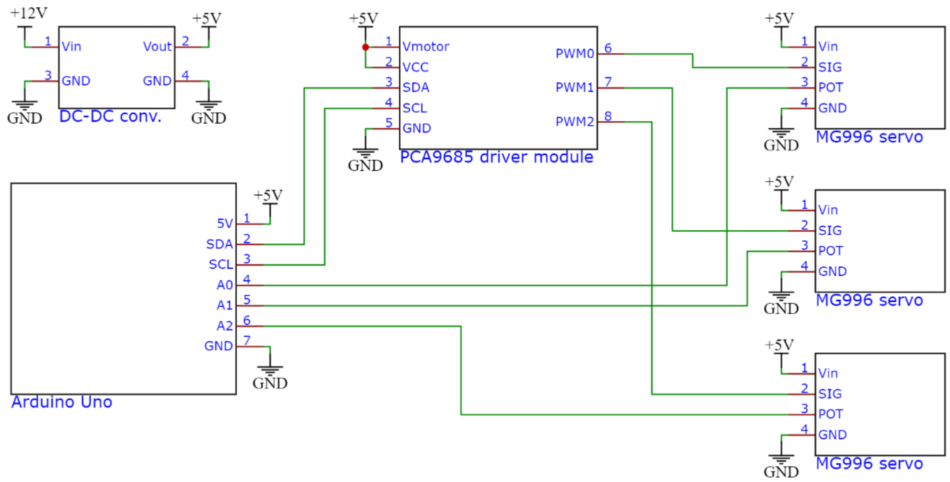

Figure 3 – Schematic diagram of the delta manipulator control system [16]

Servo drives have only three contacts (Vin, Signal and GND), which means that they do not allow the shaft position to be determined during operation. In order to determine the shaft position of the servos, they have been improved during operation. Each servo has a potentiometer that the integrated servo controller uses to determine the shaft position, so the signal only had to be output from the middle contact of each potentiometer. The structure diagram of the modernised servo drive is shown in Figure 4.

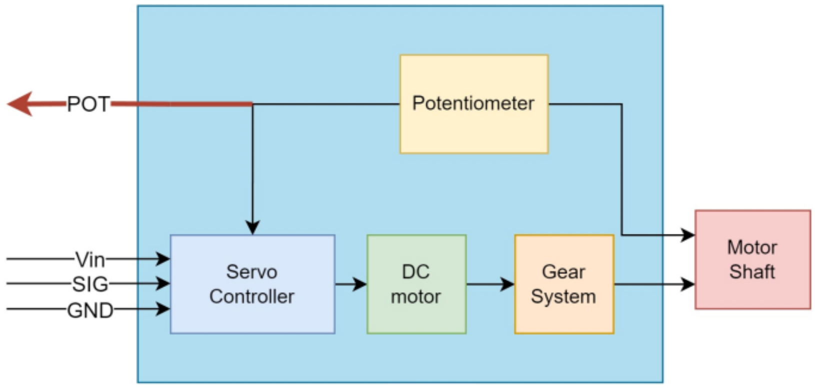

Figure 4 – Structural diagrams of modernised servo drive [16]

The manipulator control algorithm is crucial for translating necessary tasks into specific motions. This part of the section describes the logical and computational methods used to guide the robot's actions, such as moving to specified positions, handling objects, or performing tasks with precision. In this paper, an algorithm and a programme are developed in which two modes of trapezoidal trajectory planning are implemented: trajectory modes in joint space and task space.

Integrating machine vision into a control system means a significant advancement in robot capabilities. Machine vision allows the robot to "see" the environment, detect objects, and make decisions based on visual data. This section describes the board used and the training of the machine vision model. This machine vision allows the robot to perform tasks that require identification, sorting or precise manipulation based on visual cues. A detailed analysis of the use of machine vision in manipulator control systems is presented in [17]. Figure 5 shows the classification of objects as a result of training.

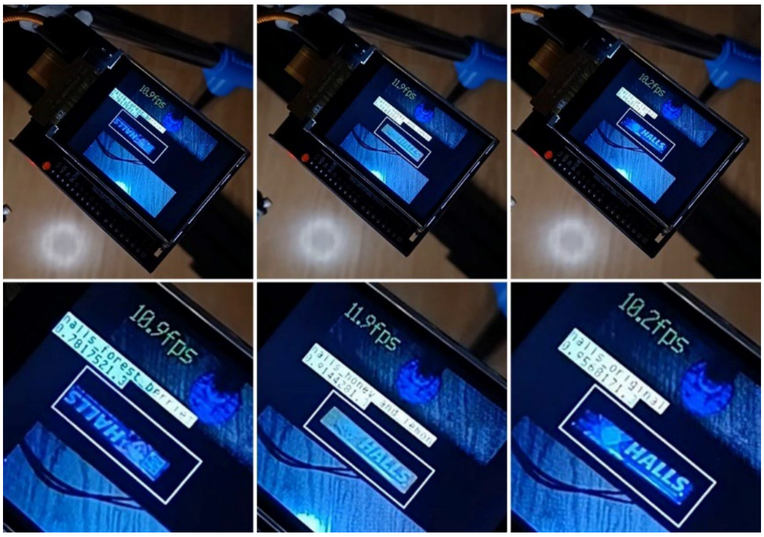

Figure 5 – Example of object classification [18]

The fourth part of the thesis is devoted to the testing and results achieved by conducting experiments with the manipulator. This section includes the experimental validation of the trajectory planning and kinematic algorithms, discussion of the results and conclusions from the results. The methods are described: experimental setup, procedures and analyses of the results, demonstrating the performance, accuracy and efficiency of the manipulator in various tasks.

During the experiments, the manipulator made movements between three points four times in a row:

$$P_0 \rightarrow P_1 \rightarrow P_0 \rightarrow P_2 \rightarrow P_0,$$
$$P_0(0, 0, -150),$$
$$P_1(50, 50, -250),$$
$$P_2(-50, -50, -250).$$

Trajectories between given points were calculated in task space and kinematic pairs. The duration of each movement was set to 0.5 seconds, totalling 2 seconds. The trajectories are shown in Figure 7.

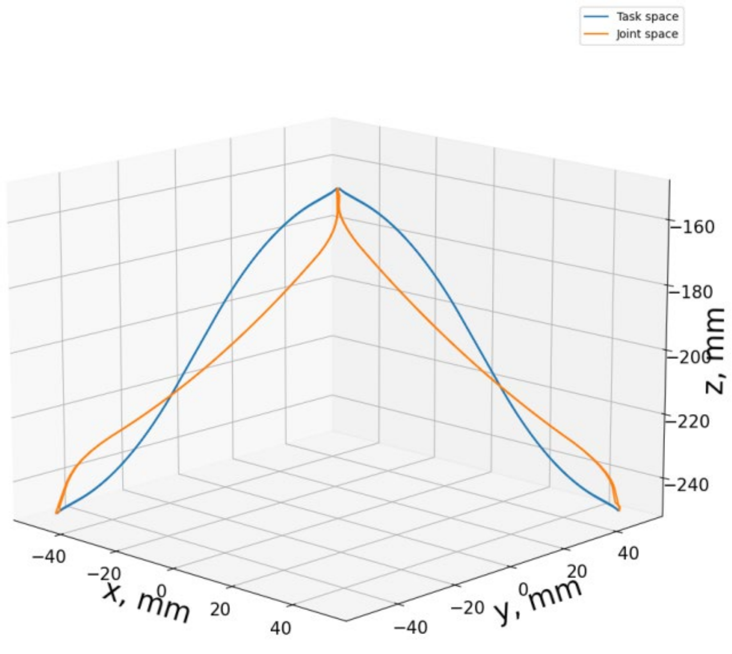

Figure 6 – Modelled trajectories: in task (blue line) and kinematic pairs (orange line) [16]

Figure 7 shows the angular and positional errors in trajectory planning in joint space. The average values of angular error were 0.093° and absolute error was 2.238 mm.

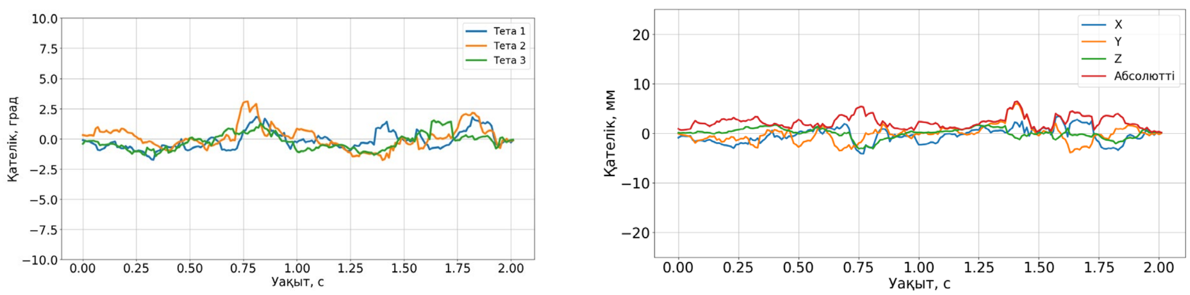

Figure 7 – Angular and positional errors in the joint space

Figure 8 shows the angular and positional errors in trajectory planning in task space. The mean values of angular error were 0.11° and absolute error was 2.199 mm.

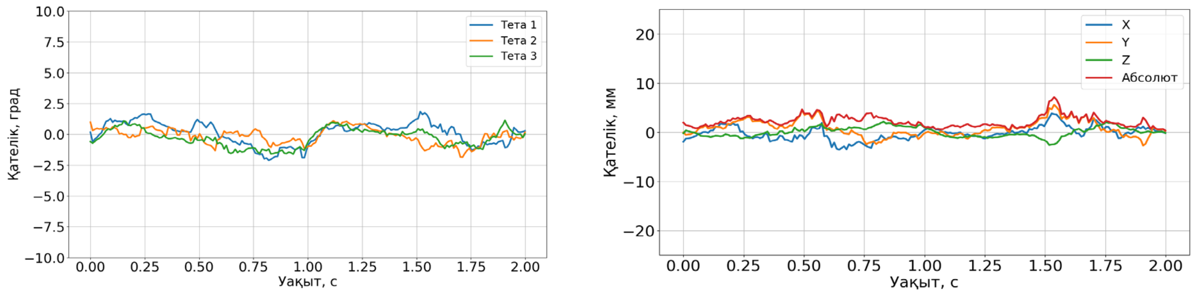

Figure 8 – Angular and positional errors in task space

It should be noted from these data that the angular error was higher for trajectory planning in task space, and the positioning error in the space of kinematic pairs.

Next, the same experiments were performed, but with payloads.

Figure 9 shows the angular and positional errors in trajectory planning in the space of kinematic pairs with payload. The average values of angular error were 0.104° (+12.1%) and absolute error was 2.832 mm (+26.5%).

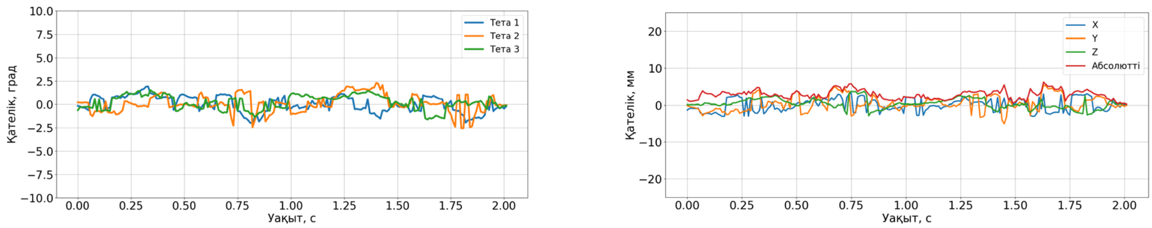

Figure 9 – Angular and positional errors in the space of kinematic pairs with payloads

Figure 10 shows the angular and positional errors in trajectory planning in payload task space. The mean values of angular error were 0.13° (+19.7%) and absolute error was 2.403 mm (+9.2%).

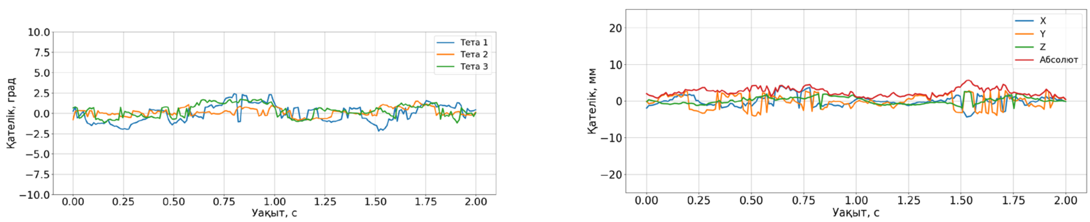

Figure 10 – Angular and positional errors in payload task space

As a result of experiments with payloads, the angular error was also higher in trajectory planning in the task space, and the positioning error in the space of kinematic pairs, but in this case this difference was more pronounced.

After analysing the obtained data and evaluating the advantages and disadvantages of both methods, a hybrid trajectory planning method was developed.

In the hybrid method, the trajectory in kinematic pair space is used during the movement section from the starting point to the load pick-up point and after the load placement (1,4), while the trajectory in task space is used during the load movement (2,3). The hybrid trajectory is shown in Figure 11.

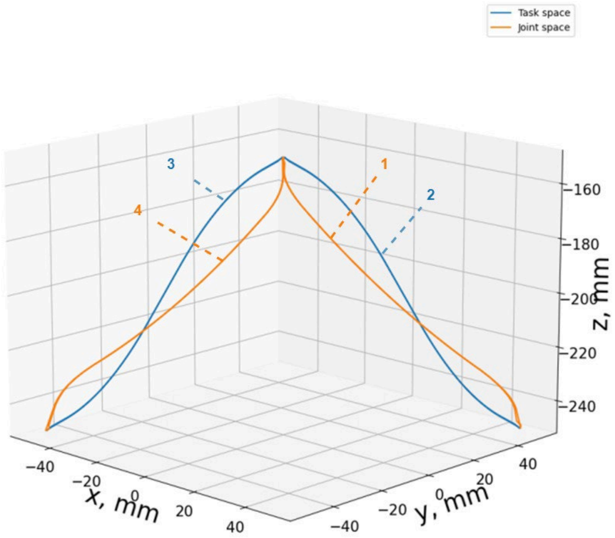

Figure 11 – 3D view of the hybrid trajectory

Figure 12 shows the angular and positional errors when using the hybrid payload trajectory. The average values of angular error were 0.113° and absolute error was 2.351 mm. Table 1 summarises the angular and positional errors of all the trajectory planning methods used.

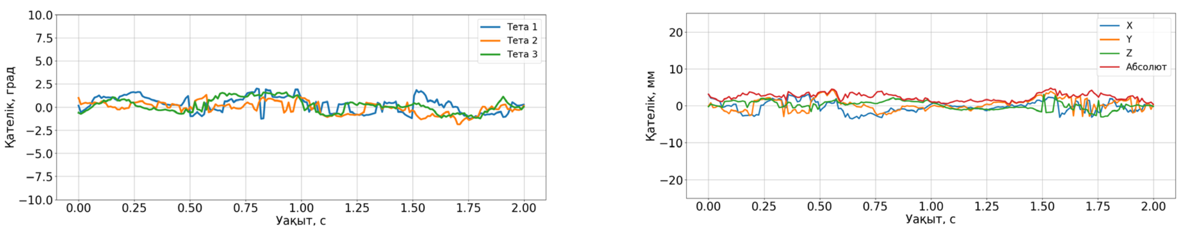

Figure 12 – Angular and positional errors of the hybrid trajectory

Table 1 – Comparison of experimental results

Trajectory space	Joint	Task	Joint (with payload)	Task (with payload)	Hybrid (with payload)
Angular error	0,093°	0,11°	0,104°	0,13°	0,113°
Position error	2,238 mm	2,199 mm	2,832 mm	2,403 mm	2,351 mm

Conclusion

The thesis describes that an automated robotic arm control system combined with machine vision has been developed and successfully tested. The work shows approaches to kinematic modelling, trajectory planning and the use of machine vision for dynamic object recognition and manipulation.

Experimental results validate the theoretical models and control algorithms, demonstrating the accuracy, efficiency and versatility of the manipulator in complex tasks.

The research contributes new methodologies for integrating machine vision with robotic manipulators, enhancing the manipulator's ability to interact intelligently and autonomously with the environment.

The developed system makes a significant contribution to the development of low-cost and accessible robotic systems that can be applied in small businesses, research laboratories and for training.

The thesis identifies areas for additional research and development such as improving the speed and accuracy of the manipulator, extending the range of tasks it can perform, and improving machine vision integration for more complex object recognition and interaction scenarios.

The ability of the manipulator to perform precise and repetitive actions guided by machine vision makes it a valuable tool to improve productivity, safety and quality in various sectors.

In conclusion, this paper developed an automatic control system for a parallel (delta) manipulator with machine vision. A review of the state of the art of manipulators, control systems, and machine vision solutions has been performed, resulting in a control system using a novel hybrid trajectory planning method.

List of references

1. Sotnik, S., & et al.. (2020). Some Features of Route Planning as the Basis in a Mobile Robot. International Journal of Emerging Trends in Engineering Research (IJETER), 8(5), 2074-2079.
2. Lyashenko, V., & Sotnik, S. (2020). Analysis of Basic Principles for Sensor System Design Process Mobile Robots. Journal La Multiapp, 1(4), 1-6.
3. Attar, H., & et al.. (2022). Zoomorphic Mobile Robot Development for Vertical Movement Based on the Geometrical Family Caterpillar. Computational Intelligence and Neuroscience, 2022, Article ID 3046116, https://doi.org/10.1155/2022/3046116.
4. Abu-Jassar, A. T., & et al.. (2021). Some Features of Classifiers Implementation for Object Recognition in Specialized Computer systems. TEM Journal, 10(4), 1645-1654.
5. Lyashenko, V., & Sotnik, S. (2021). Semantic Model Workspace Industrial Robot. International Journal of Academic Engineering Research (IJAER), 5(9), 40-48.
6. Baker, J. H., & et al.. (2021). Some interesting features of semantic model in Robotic Science. SSRG International Journal of Engineering Trends and Technology, 69(7), 38-44.
7. Matarneh, R., & et al.. (2019). Development of an Information Model for Industrial Robots Actuators. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 16(1), 61-67.
8. Al-Sharo, Y. M., & et al.. (2021). Neural Networks As A Tool For Pattern Recognition of Fasteners. International Journal of Engineering Trends and Technology, 69(10), 151-160.
9. Beltran-Hernandez, C.C.; Petit, D.; Ramirez-Alpizar, I.G.; Harada, K. Variable Compliance Control for Robotic Peg-in-Hole Assembly: A Deep-Reinforcement-Learning Approach. Appl. Sci. 2020, 10, 6923. https://doi.org/10.3390/app10196923
10. B. Hu, T. Wang, C. Chen, Y. Xu and L. Cheng, "Collision-free Path Planning For Welding Manipulator Via Deep Reinforcement Learning," 2022 27th International Conference on Automation and Computing (ICAC), Bristol, United Kingdom, 2022, pp. 1-6, doi: 10.1109/ICAC55051.2022.9911177.
11. Wang, J.; Yang, M.; Liang, F.; Feng, K.; Zhang, K.; Wang, Q. An Algorithm for Painting Large Objects Based on a Nine-Axis UR5 Robotic Manipulator. Appl. Sci. 2022, 12, 7219. https://doi.org/10.3390/app12147219
12. Zhang, D., Liu, J., Zhang, L. et al. Hamlyn CRM: a compact master manipulator for surgical robot remote control. Int J CARS 15, 503–514 (2020). https://doi.org/10.1007/s11548-019-02112-y
13. Chandana R. et al. A multipurpose agricultural robot for automatic ploughing, seeding and plant health monitoring //International Journal of Engineering Research & Technology (IJERT), IETE–Conference. – 2020. – T. 8. – C. 57-60.

14. Ayazbay A., Balbaev G., Orazaliyeva S. Manipulator control systems review // Vestnik KazATK. — 2023. — Vol. 124. — No. 1. — P. 245-253.
15. Biagiotti L., Melchiorri C. Trajectory planning for automatic machines and robots. — Berlin Heidelberg: Springer, 2008. — 514 p.
16. Ayazbay A.-A., Balabyev G., Orazaliyeva S., Gromaszek K., Zhauyt A. Trajectory Planning, Kinematics, and Experimental Validation of a 3D-Printed Delta Robot Manipulator // International Journal of Mechanical Engineering and Robotics Research. — 2024. — Vol. 13. — No. 1. — P. 113-125.
17. Ayazbay A., Balbayev G. Design of an automated control system of a delta manipulator with microcontroller based machine vision // Vestnik KazATK. — 2022. — Vol. 123. — No. 4. — P. 200-208.
18. Ayazbay A.E., Sergazin G.K., Orazalieva S.K., Baikenov B.S. Obuchenie modeli YOLO dlya raspoznavaniya ledentsov Halls s pomoshch'yu Maixduino // Vestnik KazATK. – 2024. – Vol. 130. – № 1.