ABSTRACT

The dissertation work of Momynkulov Zeinel Zeinullauly
«Development of deep reinforcement learning models for controlling a robotic manipulator in industrial applications», submitted for the degree of Doctor of Philosophy (PhD) in the program 8D06105 – "Data Science"

Relevance

Modern industrial enterprises are characterized by a high degree of automation, however, a significant proportion of manual labor remains in many technological processes, especially in areas with increased risk. Such zones include operations associated with high temperatures, toxic substances, increased noise, vibrations, and the risk of mechanical damage. Working in such conditions poses a threat to human health and life. As a result, it increases the likelihood of occupational injuries and requires additional safety costs. In this regard, one of the key tasks of modern industry is to minimize human involvement in dangerous and heavy production processes. An effective solution to this problem is the introduction of robotic manipulators capable of performing a wide range of operations without direct human involvement. The use of robots can significantly reduce the level of production risks, increase the stability of operations and ensure the continuity of the technological process. In addition to improving security, the introduction of robotic systems has significant economic benefits. Automation of processes allows you to reduce labor costs, reduce costs associated with work injuries and equipment downtime. In addition to this, increase productivity due to round-the-clock work and high repeatability of actions. Robotic manipulators provide more accurate and stable tasks, which is especially important in high-precision manufacturing processes such as welding and marking various objects. However, traditional approaches to robot control based on hard-coded algorithms and pre-programmed trajectories have limited flexibility. In real production conditions, uncertainties often arise: changes in the position of objects, the need to adapt to new tasks. In such situations, classical management methods require complex reconfiguration and do not provide sufficient adaptability. In recent years, a promising direction has been the use of deep learning methods with reinforcement, allowing robots to independently learn effective management strategies based on interaction with the environment. Such methods make it possible to take into account complex dynamic processes and adapt to changing conditions, which is especially important for working in real industrial scenarios. An additional advantage is the ability to integrate with computer vision techniques, which allows robots to navigate in space and perform tasks without precise pre-configuration. Thus, the development of intelligent control systems for robotic manipulators capable of operating effectively in dangerous and dynamically changing conditions is an urgent task. Solving this problem will not only increase the level of industrial safety, but also provide significant economic benefits by increasing the efficiency, reliability and autonomy of technological processes.

The main **purpose** of the dissertation research is to develop an intelligent control system for a robotic arm based on deep reinforcement learning methods that ensures adaptive and highly accurate performance of industrial tasks in a given environment.

To achieve this goal, it was necessary to solve the following **tasks**:

1) to analyze modern methods of deep reinforcement learning used to control robotic arms in industrial applications;

2) to develop a virtual simulation environment that reproduces typical industrial tasks (welding and marking);

3) create a space of states and actions for the robotic arm, including joint parameters, object positions, and target states.;

4) develop a reward function that takes into account the accuracy of the task, trajectory efficiency, collision avoidance, and control stability;

5) Implement and train reinforcement learning deep learning models for manipulator control;

6) to conduct an experimental study of trained models in a simulation environment with an assessment of control quality based on metrics of accuracy, execution time and stability;

7) optimize the architecture of the model and learning parameters to improve the efficiency and generalizing ability of the system;

8) to validate the developed approach in real or near-real conditions, including integration with industrial robotic equipment or a digital twin;

The object of the research is robotic manipulators used in industrial automation tasks (moving, capturing and processing objects).

The subject of the research is methods and algorithms of intelligent control of robotic manipulators, providing adaptive trajectory planning, accurate positioning and effective task execution in dynamic industrial environments based on deep reinforcement learning and optimization approaches.

The methodological basis of the work is the development and research of a hybrid control system for a robotic arm that combines reinforcement learning and predictive control methods. The study analyzes modern approaches to managing robotic systems, including classical trajectory planning methods, optimal control algorithms, and deep reinforcement learning methods. To simulate the dynamics of the manipulator and build trajectories, kinematic and geometric models of movement in three-dimensional space were used, taking into account the limitations on speed, acceleration and the working area of the robot. Deep learning algorithms with DDPG and TD3 reinforcement have been used for adaptive management and decision-making. As well as hierarchical and multi-level management schemes. The experimental part of the study was implemented in a simulation environment designed to reproduce scenarios of robotic manipulation. To test the effectiveness of the developed approaches, the tasks of arc welding and industrial marking were used, requiring high positioning accuracy and smooth movement. The evaluation of the effectiveness of the developed models was carried out on the basis of experimental studies using metrics of the average absolute error, maximum trajectory deviation, acceleration indicators, stability of movement and success of the task. A comparative analysis of the results allowed us to determine the influence of MPC parameters and reinforcement learning algorithms on the quality of control of a robotic arm in industrial applications.

Scientific novelty of the work:

1) A specialized simulation for training a robotic manipulator was developed, including a variety of industrial scenarios (grasping, moving, and sorting objects) close to real-world operating conditions.

2) A model architecture was proposed that considers additional environmental factors, such as object position uncertainty, sensor data noise, and dynamic variability. This improved the resilience of the trained model to changing conditions and ensured better generalization.

3) A deep reinforcement learning model for manipulator control was developed, enabling simultaneous solutions of problems of positioning, grasping, and moving objects, taking into account kinematic and dynamic constraints.

4) A control system for a collaborative robot for various industrial applications was integrated.

Scientific contribution:

1) A simulation environment for training a robotic manipulator was developed and implemented. It covers a wide range of industrial scenarios, such as grasping, moving, and sorting objects, taking into account the constraints of kinematics, dynamics, and contact interactions, ensuring a high degree of approximation to real-world operating conditions.

2) A comprehensive approach to modeling the training environment was developed, taking into account the uncertainty of object positions, the presence of sensor noise, and the variability of dynamic parameters. This significantly increased the stability and robustness of the trained models to external influences and changing conditions.

3) A deep reinforcement learning model for controlling a robotic manipulator was developed and experimentally validated. This model effectively solves a range of problems involving positioning, grasping, and moving objects in a continuous state and action space.

4) A comparative analysis of the effectiveness of various control strategies and learning parameters was conducted, including the influence of the reward function structure, environmental parameters, and learning algorithms. This allowed us to identify optimal configurations for achieving high control accuracy and stability.

5) An approach for integrating the developed model into a collaborative robot control system, designed for various industrial applications, is proposed, confirming the practical applicability and scalability of the developed solutions.

6) Experimental results were obtained demonstrating increased positioning accuracy, reduced control errors, and improved trajectory smoothness compared to baseline approaches, confirming the effectiveness of the proposed methods.

Scientific statements submitted for protection:

1) The developed simulation environment for training a robotic arm, which provides simulation of industrial scenarios (capture, movement and sorting of objects), taking into account kinematic and dynamic constraints close to real operating conditions.

2) The architecture of the deep learning model with reinforcement, which takes into account the uncertainty of the position of objects, the noise of sensory data and the variability of the dynamics of the system, which ensures stable control and high generalizing ability in changing conditions.

3) The developed control model of a robotic arm based on reinforcement learning, which makes it possible to effectively solve a set of tasks of positioning, capturing and moving objects in a continuous space of states and actions.

4) The proposed approach to the integration of reinforcement learning algorithms into a collaborative robot control system, providing adaptive performance of various industrial tasks and the possibility of practical application of the developed methods.

The scientific novelty of the research lies in the development of a specialized simulation environment for training a robotic arm, including a wide range of industrial scenarios such as capturing, moving and sorting objects in conditions close to real production processes. As part of the study, the architecture of the control model was proposed, taking into account additional environmental factors, which made it possible to increase the stability of control algorithms to changing conditions. A deep learning model with reinforcement has also been developed to control a robotic arm, providing simultaneous solutions to the tasks of positioning, capturing and moving objects, taking into account the kinematic and dynamic limitations of the robotic system. Additionally, a collaborative robot control system is integrated, focused on performing various industrial tasks. Including assembly, marking and arc welding operations. The proposed approach provides improved control accuracy, adaptability, and stability of the robotic system compared to classical control methods and traditional machine learning algorithms.

The practical significance of the thesis is a trained and optimized control model of a robotic arm based on deep reinforcement learning, capable of performing the tasks of capturing, moving and sorting objects with high accuracy and stability. The developed simulation environment makes it possible to effectively train models in conditions close to real ones, which significantly reduces the cost of experimental debugging and minimizes risks during implementation. Additionally, the integration of the developed algorithms into the collaborative robot control system has been implemented, which makes it possible to use them for a wide range of industrial operations. The practical implementation of the research results demonstrates that the proposed methods make it possible to increase the level of automation of production processes, reduce dependence on manual labor and increase the accuracy of technological operations. Thus, the developed methods and software tools have a high degree of readiness for implementation and are of significant interest for industrial applications.

The theoretical significance of the thesis lies in the development and adaptation of deep learning methods with reinforcement for the tasks of controlling robotic manipulators in industrial operation. Unlike most existing approaches, which focus either on classical control methods or on the isolated use of reinforcement learning algorithms, this study expands the scientific and methodological base by integrating continuous reinforcement learning methods, taking into account the kinematic and dynamic limitations of robotic systems. A significant contribution is the formalization of the manipulator control task as a multi-criteria optimization task that takes into account parameters such as positioning accuracy, smoothness of trajectory and resistance to external disturbances. This forms the theoretical basis for building intelligent control systems capable of operating in complex and uncertain industrial environments.

Approbation of the dissertation work

The main results of the work were presented and reported at the following scientific events and seminars of the Department of Mathematical and Computer Modeling of JSC IITU (2024–2026) and Asia Metropolitan University, Malaysia (2026). Four publications on the dissertation topic have been published, including two in a top-rated scientific journal indexed by Scopus; two in international conference proceedings; one in domestic conference proceedings; and one in the journals of the Science and Higher Education Quality Assurance Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

1) Momynkulov, Z., Tursynova, A., Olzhayev, O., Ikramov, A., Ibrayev, S., & Omarov, B. (2025). Three-Dimensional trajectory planning for robotic manipulators using model predictive

control and point cloud optimization. Computer Modeling in Engineering & Sciences, 145(1), 891–918. https://doi.org/10.32604/cmes.2025.068615. Quartile – Q2, percentile 73, citescore 4.4, DOI: https://doi.org/10.32604/cmes.2025.068615

2) Momynkulov, Z., Ibrayev, S., Suliman, A., Tenizbayev, Y., & Omarov, B. (2026). Pareto-Optimized model predictive control for dynamically feasible Three-Dimensional trajectory generation in robotic manipulators. International Journal of Advanced Computer Science and Applications, 17(5). Quartile – Q2, percentile 52, citescore 2.7, DOI: https://doi.org/10.14569/ijacsa.2026.0170527.

3) S. Ibrayev, B. Omarov, A. Ibrayeva, and Z. Momynkulov, “DeePSurNET-NSGA II: Deep Surrogate Model-Assisted Multi-Objective Evolutionary Algorithm for enhancing leg linkage in walking robots,” Computers, Materials & Continua/Computers, Materials & Continua (Print), vol. 81, no. 1, pp. 229–249, Jan. 2024. Quartile – Q1, percentile 86, citescore 6.1, DOI: https://doi.org/10.32604/cmc.2024.053075.

4) Zeinel Momynkulov, Azhar Tursynova, Olzhas Olzhayev, Akhanseri Ikramov, Sayat Ibrayev, Amandyk Tuleshov, Batyrkhan Omarov. Pareto-Optimized Model Predictive Control for Real-Time 3D Trajectory Planning of Collaborative Robots. In Proceedings of PAMDAS 2025 - International conference on Physical Asset Management and Data Science, 17-18 Jul. 2025, Coimbra, Portugal

5) Zeinel Momynkulov, Azhar Tursynova, Olzhas Olzhayev, Akhanseri Ikramov, Sayat Ibrayev, Amandyk Tuleshov, Batyrkhan Omarov. Trajectory Optimization for Collaborative Robots via the Deep Deterministic Policy Gradient Algorithm. In Proceedings of PAMDAS 2025 - International conference on Physical Asset Management and Data Science, 17-18 Jul. 2025, Coimbra, Portugal.

6) Z. Momynkulov & B. Omarov (2025). DDPG for Trajectory Generation. 10th International Conference on Digital Technologies in Education, Science and Industry (DTESI), 19-20 Nov. 2025, Almaty, Kazakhstan.

7) Z.Z. Momynkulov, O. M. Olzhayev, A. T. Tursynova, A. K. Tuleshov, & S. M. Ibrayev. (2025). CONSTRUCTION AND GENERATION OF OPTIMAL TRAJECTORIES USING THE DDPG REINFORCEMENT LEARNING ALGORITHM. Science and Technology of Kazakhstan, №4, 2025.

8) Momynkulov Z. Z., Tursynova A. T., Olzhaev O. M., Ibraev S. M., Tuleshov A. K., Omarov B. S., Musilimov Zh. A., Ikramov A. Z., Tuenbaev M. K. Patent for utility model “Method for visual tracking and collision prevention of a collaborative robot manipulator” No. 11903 dated March 13, 2026.

The relationship of this work with other scientific research works.

This dissertation was completed under the grant funding program of the Ministry of Higher Education of the Republic of Kazakhstan:

- "Development of Robots, Scientific, Technical, and Software Support for Flexible Robotics and Industrial Automation (RPA) of Automotive Industrial Enterprises in Kazakhstan Based on Artificial Intelligence" (2024-2026, No. BR24992947). The study aligns with the strategic development priorities of the Republic of Kazakhstan and contributes to the implementation of the Concept for the Development of Artificial Intelligence for 2024-2029 in terms of developing domestic intelligent technologies, robotic systems, and machine learning methods for industrial automation. The developed deep reinforcement learning models and hybrid approaches to control robotic manipulators are aimed at increasing the level of autonomy, precision, and safety of industrial processes. The proposed control methods contribute to the development of national scientific and technical potential in the field of artificial intelligence, intelligent robotics, and the digital transformation of Kazakhstan's industry.

Dissertation summary

This dissertation examines the development of an intelligent control system for robotic manipulators based on a hybrid approach combining reinforcement learning and predictive control.

The first section substantiates the relevance of robot control automation in the context of the transition to Industry 4.0 and 5.0, formulates the purpose and objectives of the study, and defines the scientific novelty and practical significance of the proposed approach.

The second section provides a comprehensive literature review covering the development of robot control systems, the macroeconomic aspects of robotics, and modern trends such as embodied intelligence and fundamental models. Attention is paid to the integration of large language models into robotics, as well as the application of deep reinforcement learning to control and optimization problems. Methods for trajectory planning, navigation, and spatial perception are considered, including approaches based on MPC and DRL. Robotic assembly and manipulation tasks are also analyzed, as well as issues of collaborative robotics and safety. A discussion of the economic benefits of autonomous systems in industrial applications is also included.

The third section describes the research methodology in detail. It presents the concept of hybrid control, in which high-level planning is performed using reinforcement learning methods, and low-level control is implemented through Model Predictive Control. The separation of control levels and the mathematical foundations of MPC are discussed, including the formalization of the objective function and constraints. The DDPG and TD3 algorithms, along with their extensions, such as hierarchical learning and multi-layer architectures, are analyzed in detail. The 3D trajectory generation problem is formulated, with boundary conditions, evaluation metrics, and parameter optimization methods, including Pareto front analysis, specified.

Section four presents the experimental results. The effectiveness of MPC is analyzed under various optimization criteria, including error and acceleration minimization. The results of reinforcement learning and their behavior in a simulation environment are discussed. A comprehensive analysis of the obtained data is performed, including a comparison of various approaches and an assessment of the system's robustness. The application of the developed methods to practical problems, such as arc welding and marking, is also demonstrated, taking into account the actual technical characteristics of robots.

Section five summarizes the work. The achievement of the stated goal is confirmed, the main scientific and practical results are presented, and conclusions are drawn regarding the potential of applying hybrid RL and MPC methods to industrial robotics problems. The potential for further development of the system towards increased autonomy, expansion of the scope of application, and integration with real robotic platforms is noted.

Author's contribution. All key results described in the dissertation were developed and compiled by the author. Furthermore, the author created the main research findings, analyses, models, and programs, and the conclusions are based on the results obtained from the PhD student's work and research.

Structure and scope. The dissertation consists of a title page, table of contents, notations and abbreviations, five sections, and a list of 150 references. The total length of the dissertation is 121 pages, including 44 illustrations and 19 tables.