ABSTRACT

of the dissertation for the degree of "Doctor of Philosophy" (Ph.D.) in the specialty 8D07101 - "Automation and Control"

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Title: “APPLICATION OF METHODS OF ADAPTIVE CONTROL OF A ROBOTIC ARM FOR ADDITIVE MANUFACTURING OF MEDICAL COATINGS”

The main idea of the research: the dissertation is devoted to the synthesis of adaptive control algorithms for a robotic manipulator for additive manufacturing of medical coatings. The research is aimed at improving the accuracy and speed of the movement of the robot’s working tool (plasma torch) along a given 3D trajectory, which is a key condition for ensuring the uniformity and quality of the applied coating.

The following approaches are proposed and substantiated in the work:

- an adaptive control method for a sequential manipulator with force control, based on the Computed Torque Control (CTC) method;
- application of the inverse dynamics method (compensation of object dynamics and disturbances) to the problem of trajectory control;
- a new method for automatic trajectory generation of a robot manipulator based on a 3D surface model, constructed using vector fields on triangular meshes.

The developed methods have been validated both by means of mathematical modeling and through experimental studies on a robotic microplasma spraying station. The obtained results demonstrate improved control accuracy and robustness to disturbances compared with conventional solutions.

Keywords: sequential robot manipulator, adaptive control, inverse dynamics, trajectory control, additive manufacturing, microplasma spraying of coating.

The relevance of the research. In the current development of robotic systems, special attention is paid to the automation of technological processes of additive manufacturing, in particular the deposition of coatings on medical implants. The use of robotic manipulators as actuators makes it possible to achieve high-precision and reproducible processing of complex surfaces based on a pre-constructed 3D model. This opens up opportunities for the layer-by-layer formation of functional coatings with predetermined properties, which are in demand in medicine and bioengineering.

At the same time, a key challenge remains the control of the motion of a multi-link robotic manipulator to ensure fast and accurate trajectory tracking of the tool along complex surfaces. Control algorithms applied in industrial controllers are, as a rule, limited to proportional-derivative or linear regulators of the positions of individual links, which reduces efficiency at high speeds and does not take into account system dynamics and disturbances. Modern manufacturing requires more

flexible and adaptive control methods that make it possible to synthesize tool trajectories without detailed decomposition by links and at the same time compensate for nonlinear effects.

In this dissertation, new adaptive control methods are proposed, based on the application of inverse dynamics and computed torque control, as well as a method for automatic trajectory generation of the manipulator tool according to 3D scanning data of the object. These approaches improve the accuracy and speed of tool motion, as well as the overall productivity of the coating deposition process.

The dissertation was carried out within the framework of a state-funded (grant) project of the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan, No. AP19679327 “Machine learning methods in the tasks of automatic control and inertial navigation of mobile robots” under the priority “Information, communication and space technologies,” sub-priority “Intelligent robotic systems”.

The object of the research is a robotic manipulator with a programmable control unit and the technological process of additive manufacturing of medical coatings implemented by the robot.

The subject of the research is the application of adaptive control methods to the problems of controlling the motion of the end-effector of a multi-link robotic manipulator performing the deposition of medical coatings.

The research goal is to develop adaptive control algorithms for a robotic manipulator that ensure sufficiently high speed and accuracy of the tool motion along a given trajectory in the process of additive manufacturing of medical coatings.

Research objectives:

1. To study modern approaches to the design of robust and adaptive trajectory control systems for manipulators. To investigate the possibility of modifying the most promising trajectory control methods for manipulators in order to improve their robustness or to create adaptive methods based on them.
2. To analyze the features of robotic manipulators as control objects and to identify uncertainty factors that affect the quality of control and trajectory tracking.
3. To synthesize an adaptive algorithm of trajectory control for a manipulator, robust to disturbances, based on the method of compensation of system dynamics and disturbances.
4. To carry out experimental studies of the performance characteristics of the most promising adaptive control methods for manipulators using computer modeling. To determine the degree of robustness of these methods to disturbances and uncertainties arising in practical applications.
5. To formulate the problems of trajectory planning of a manipulator used for additive deposition of medical coatings. To analyze the problem of automatic trajectory generation of the manipulator according to a 3D surface model and the given parameters of the coating deposition process.
6. To develop an algorithm for automatic trajectory generation of the end-effector of a robotic manipulator for application in a robotic system for medical coating deposition.

7. To perform modeling and experimental studies, and to investigate the effectiveness of the proposed approach.

The main research methods are methods of the theory of automatic control and linear algebra, mathematical computer modeling, testing of control algorithms in a simulator program and scanning techniques on model objects, full-scale experiment: 3D scanning and plasma processing of real scanning objects at a pilot production site with an assessment of the result in terms of requirements for the final product (coating).

Provisions to be defended:

1. An adaptive control method for a sequential manipulator with force control, developed on the basis of the Computed Torque Control (CTC) method.

2. The application of the inverse dynamics method (compensation of system dynamics and disturbances) to the problem of trajectory control of a sequential manipulator.

3. A method for automatic trajectory generation of a robotic manipulator for additive manufacturing of coatings, based on a new numerical method for constructing vector fields on surfaces defined by triangular meshes.

The scientific novelty of the work lies in the following:

For the first time, the method of trajectory control of sequential manipulators with force control, known as the inverse dynamics method, has been considered as a trajectory control method for a special class of flat systems. A general adaptive method of trajectory control for flat systems is proposed, which generalizes the Computed Torque Control method to a wide class of nonlinear control objects, including various types of manipulators. In this work, for the first time, a stability criterion against disturbances has been developed, which must be satisfied by the linear regulator included in the trajectory control scheme implementing the classical or generalized Computed Torque Control method.

For the first time, the method of compensation of system dynamics and disturbances has been applied to the control of a two-link planar sequential manipulator. A mathematical model of the two-link manipulator has been developed using Lagrange equations in the form of state equations with state-dependent parameters (SDC model). The adaptive nature of inverse dynamics methods has been substantiated in relation to the control of a nonlinear multivariable object — a sequential manipulator with flat input.

A new method for automatic trajectory generation of a robotic manipulator for additive coating deposition on surfaces based on their 3D model has been developed. For the first time, a new method for constructing vector fields with given properties on a triangular mesh representing the model of the processed surface is proposed, and its application to the procedure of automatic trajectory generation of the manipulator's tool for coating deposition has been implemented.

Publications. A total of **12** papers have been issued on the topic of the dissertation, including: **4** papers in journals recommended by the Committee; **4** papers in international peer-reviewed journals indexed in the Scopus database with CiteScore percentile and/or indexed in the Web of Science Core Collection

(Clarivate Analytics) and/or having a non-zero impact factor; **4** papers in the proceedings of international conferences; and 1 patent for a utility model.

The contribution to the preparation of each publication consisted in the analysis of data from open literature sources on the research topic, in the development and testing of models, in obtaining and describing experimental results, in preparing and discussing conclusions, as well as in presenting and discussing scientific results at seminars and conferences.

The main results of the dissertation work were reported and discussed at 6 international conferences:

1) ACDSA International Conference on Artificial Intelligence, Computer, Data Sciences and Applications, August 8, 2025, Antalya, Turkey (online).

2) 18th International Symposium on Applied Informatics and Related Areas, Joint event of the Hungarian Science Festival 2024, organized by Óbuda University, November 14, 2024, Székesfehérvár, Hungary.

3) International Conference "Engineering Education: Challenges, Trends, Best Practices (EE: CTBP)", October 4, 2024, Ust-Kamenogorsk, Kazakhstan.

4) 10th International Scientific and Technical Conference of Students, Master's and Young Scientists "Creativity of Youth for Innovative Development of Kazakhstan," dedicated to the 125th anniversary of Kanysh Satpayev, April 11–12, 2024, Ust-Kamenogorsk, Kazakhstan.

5) International Conference "Computational and Information Technologies in Science, Engineering and Education (CITech-2023)", October 2, 2023, Ust-Kamenogorsk, Kazakhstan.

6) 9th International Scientific and Technical Conference of Students, Master's and Young Scientists "Creativity of Youth for Innovative Development of Kazakhstan," dedicated to the 65th anniversary of the university, April 13–14, 2023, Ust-Kamenogorsk, Kazakhstan.

The main scientific results proved in the dissertation, as well as in articles on the research topic, include:

1. An adaptive control method for a sequential manipulator with force control, developed on the basis of the Computed Torque Control method. The sequential manipulator with force control is considered as a flat control system of a special type, whose output depends only on the system state vector. The Computed Torque Control method, also known as the inverse dynamics method of manipulators, is regarded as a particular case of the general trajectory control method of such a flat system.

2. Application of the inverse dynamics method (method of compensation of system dynamics and disturbances) to the problem of trajectory control of a sequential manipulator.

3. A method for automatic trajectory generation of a robotic manipulator for additive manufacturing of coatings, based on a new numerical method for constructing vector fields on surfaces defined by triangular meshes.

The dissertation has practical significance: the results of the research have been implemented in the educational process of D. Serikbayev East Kazakhstan Technical University in the educational program "Automation and Control", and

are used for teaching the course “Fundamentals of Optimal Control Theory” (Act of February 5, 2025, on the implementation of the research work into the educational process).

For implementation into practice, it is proposed: patent of the Republic of Kazakhstan No. 8714 dated December 15, 2023, for a utility model “Method of spraying multilayer coatings on titanium alloy implants” according to application 2023/0995.2 dated October 5, 2023 (authors: D.L. Alontseva, N.V. Prokhorenkova, A.L. Krasavin, **G.M. Nazenova**).

The structure and scope of the dissertation. The dissertation consists of an introduction, 5 chapters, conclusions, a general conclusion, and a list of 163 references. The dissertation is presented on 142 pages of computer text, includes 51 figures, 1 table, and 2 appendices.