ABSTRACT

of the dissertation for the degree of "Doctor of Philosophy" (Ph.D.) in the specialty 6D070200 - "Automation and Control"

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Title: "SYNTHESIS OF THE AUTOMATIC CONTROL SYSTEM FOR MOVING OF A ROBOT MANIPULATOR FOR 3D-SCANNING OF OBJECTS WITH COMPLEX GEOMETRIC SHAPE"

The main idea of the research: the dissertation work is devoted to the synthesis of an automatic control system for moving of a robot manipulator for 3D-scanning of objects with complex geometric shape, then plasma spraying of coatings on the surface of these objects is carried out using the same robot manipulator. To control a robot performing a technological operation of plasma spraying of coatings, it is necessary to use a ready-made or create a new specific model of the robot's trajectory and set it in a form understandable to the robot. In the dissertation work, it is proposed to pre-conduct a robotic scanning of the object using distance sensors mounted on the robot and, according to the scanning data, obtain a 3D-model of the object, along which the robot arm with a plasmatron attached to it will then move. Trajectory planning of the movement of the working tool of the robot manipulator, performing the procedure of scanning the object sequentially, and then processing it with a plasma jet, as well as ensuring the coordinated movement of the manipulator joints in both of these processes, which includes the coordination of speeds and accelerations of various joints, are the main control tasks in this research. These control tasks are solved at two levels. At the first level, the control is implemented by synthesizing the control system of the robot joints using the methods of the theory of automatic control. At the second level, control is implemented by programming the robot controller, for which control algorithms are developed for the robot performing the 3D-scanning procedure, followed by trajectory planning and automatic generation of the robot movement program based on the 3D-model built as a result of scanning.

Keywords: synthesis of the control system, 3D-scanning, 3D-object models, robot manipulator working tool, contactless distance sensors, trajectory planning, plasma spraying of coatings.

The relevance of the research. A lot of research has been devoted to solving the problem of controlling the movement of a robot manipulator and planning its trajectory recently, one of the most relevant areas is the use of a robot manipulator as a basic component of a 3D-scanning system in order to reconstruct a geometrical model of a product processed by a robot. 3D-scanners based on industrial robots are used in quality control systems, automatic packaging lines, assembly systems, etc., the scope of their application is steadily expanding over time. Currently, robotic manipulators have begun to be used for plasma spraying of coatings in experimental production sites and laboratories, but the industrial

introduction of robotic plasma spraying technologies is difficult due to the challenges associated with both the specifics of the spraying process (for example, the use of thermal plasma spraying technologies for medicine is an innovative task that requires precision accuracy of processes in relation to biocompatible materials) and with the control of robotic manipulators.

Development and testing of a new method for synthesizing the automatic control system for moving of a robot manipulator for 3D-scanning of objects of complex geometric shape, combined with the use of new 3D-reconstruction algorithms – models of scanned objects and planning the robot's trajectory will allow creating a robotic 3D-scanning system of objects of complex geometric shape for the subsequent execution of technological operations of plasma spraying coatings with the movement of the plasmatron along the reconstructed 3D-model of the object with precision compliance with key parameters such as linear velocity and distance to the surface of the object, which will give advantages over existing solutions.

The topic of the dissertation corresponds to the priority direction of science in the field of ICT and the State program "Digital Kazakhstan". The dissertation work was carried out within the framework of the project No. AR05130525 "Intelligent robotic system for plasma processing and cutting of large-sized products of complex shape" with grant funding from the Committee of Science of the Ministry of Education and Science of the Republic of Kazakhstan for 2018-2020, according to the priority "Information, telecommunications and space technologies, scientific research in the field of natural sciences" (the project leader Dr. Prof. Alontseva D.L.)

The object of the research is the automatic control system for moving of the industrial robot manipulator that performs sequentially 3D-scanning operations and plasma spraying of coatings on the surface of scanned objects.

The subject of the research is the synthesis of the automatic control system for moving of the industrial robot manipulator for 3D-scanning of objects of complex geometric shape and the development of control algorithms for an industrial robot manipulator that performs sequentially 3D-scanning operations and plasma spraying of coatings on the surface of scanned objects.

The research goal: synthesis of a 3D-scanning system based on a robot manipulator and contactless distance sensors installed on the robot and testing of a robotic 3D-scanning system on model and real objects.

Research objectives:

1) Analysis of the current state of the problems of the development and use of robotic scanning systems and the synthesis of control systems based on a review of open literature, taking into account the specifics of the processes of plasma processing of industrial products, which are preceded by 3D-scanning.

2) Development of a methodology for the synthesis of an automatic control system for a robot manipulator based on an algorithm for compensating the dynamics of the object and disturbances and development of software designed to control the robot in accordance with the selected parameters of the automatic control system.

3) Development of algorithms for controlling a robot manipulator performing the procedure of 3D-scanning for the surface of an industrial product.

4) Testing of the developed 3D-scanning system based on a robot manipulator and contactless distance sensors installed on the robot on model and real objects.

Main research methods: 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).

Scientific provisions submitted for defense:

1) The synthesis of the automatic control system for moving in a given direction of a tool and a joint of the robot manipulator based on an algorithm for compensating the dynamics of an object and disturbances;

2) The results of development and testing on model and real objects of a new 3D scanning system based on a robotic arm and non-contact distance sensors installed on the robot.

The scientific novelty of the work lies in the fact that for the first time:

1) The synthesis of the automatic control system for moving in the given direction of the tool and the joint of the robot-manipulator was performed based on the algorithm for compensating the dynamics of the object and disturbances;

2) A control algorithm has been developed that provides the generation of a program for the movement of the industrial robot manipulator Kawasaki performing a 3D-scanning procedure with a contactless laser distance sensor with the specified parameters of the scanning process (step, speed, accuracy of the trajectory);

3) A set of results of testing on model and real objects of the automatic control system for moving of the industrial robot manipulator performing the tasks of 3D-scanning of objects of complex geometric shape with subsequent plasma spraying of their surface, which has advantages in the accuracy of technological processes compared to existing solutions, has been obtained.

Publications. A total of 14 papers have been published on the topic of the dissertation, of them: 4 articles in journals recommended by the Committee of the Republic of Kazakhstan; 4 articles in international peer-reviewed journals indexed in the Scopus database and having a Cite Score percentile and (or) indexed in the data of the information company Web of Science Core Collection, Clarivate Analytics and (or) having a non-zero impact factor, 5 papers in the proceedings of international conferences and 1 certificate of state registration for the copyright object.

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, describing and discussing experimental results and in drawing conclusions, as well as in presenting and discussing scientific results at seminars and conferences.

The main results of the dissertation work were presented and discussed at 5 international conferences:

1) 11th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS), September 22-24, 2021, Krakow, Poland (online);

2) 14th International Symposium on Applied Informatics and Related Areas, November 14, 2019, Szekesfehervar, Hungary;

3) VIII International Scientific and Technical Conference of students, undergraduates and young scientists "Creativity of young for innovative development of Kazakhstan", April 8, 9, 2021, Ust-Kamenogorsk, Kazakhstan;

4) Communications in Computer and Information Science (CITech-2018), September 12-13, 2018, Ust-Kamenogorsk, Kazakhstan;

5) Global Science and Innovations 2018: Central Asia", December 7, 2018 Astana, Kazakhstan.

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

1. The universal algorithm for the synthesis of the control system of the control object by the method of compensation of the dynamics of the object and disturbances, applicable to single- and multidimensional control objects in which the number of controlled variables is equal to the number of control actions. The method underlying the algorithm is based on compensation of all external additive influences and dynamics of the control object with accuracy up to standard filters by means of an inverse mathematical model of this object. The analysis of successive steps of the algorithm makes it possible to identify the dynamic properties of the resulting system and the quality of signal compensation in the ideal case when the structure and parameters of the object are equal to their calculated values.

2) The control algorithm that provides the generation of a program for moving the Kawasaki industrial robot manipulator to perform a 3D-scanning procedure, which differs from the existing ones in that the generation of a program for moving the robot's working tool (non-contact distance sensor) is performed from a reference point and ensures the movement of the manipulator's working tool (laser distance sensor) along a given curved trajectory in a plane with the specified parameters of the scanning process (step, speed, accuracy of the trajectory);

3) The totality of the results of approbation on model and real objects of the automatic control system for the movement of a robot-manipulator that performs the tasks of 3D scanning of objects of complex geometric shapes with subsequent plasma spraying of their surface. The developed control system has advantages in the accuracy of the execution of technological processes in comparison with existing solutions.

The dissertation has practical significance:

- the results of the dissertation have been introduced into the educational process of D. Serikbayev EKTU in the educational program "Automation and control", are used for teaching the disciplines: "Nonlinear automatic control systems" and "Experimental statistical methods for constructing mathematical

models" (Act No. 30.11.21 on the introduction of research into the educational process);

- in "IE S.A. Abakumov", production tests of an industrial product (jaw crusher) were carried out, on the surface of which a coating was applied using a robot manipulator moving along a 3D-model of the product obtained as a result of preliminary 3D-scanning, confirming an increase in the service life of the jaw crusher plate with a plasma coating of the worn surface (Production test report ""IE S.A. Abakumov", Act No. 1 of 01.10.2020).

For implementation into practice, it is proposed: certificate of state registration for the copyright object No. 5803 dated October 15, 2019. Object type: computer program. The name of the object: "Calculation of the coefficients of the control algorithm of a single-joint robot manipulator" Authors: D.L. Alontseva, G.K. Shadrin, Kussaiyn-Murat A. T.

The structure and scope of the dissertation. The dissertation consists of an introduction, 4 sections, conclusions, conclusions, a list of 171 references, the dissertation is presented on 119 pages of computer text, includes 44 figures, 3 tables and 4 appendices.