ABSTRACT

of the thesis for the degree "Doctor of Philosophy" (PhD) in the specialty 6D070200 - "Automation and Control"

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INTELLIGENT ROBOTIC SYSTEM FOR PLASMA PROCESSING OF PRODUCTS WITH COMPLEX SHAPE

General characteristics of the research: the thesis is devoted to the automation of the control system of an industrial robot-manipulator with a working tool attached to it, which sequentially performs 3D scanning and plasma cutting or surface treatment (spraying of coatings), while planning the trajectory and generating the robot arm motion program is performed according to scan data. Thus, intelligent control of the movement of the working tool of the robot manipulator is realized when performing plasma cutting and spraying operations, since the programmed trajectory of the manipulator is not set in advance, but is formed by the robot control system based on information about the current state of the external environment, that is, according to the 3D model of the processed surface, reconstructed according to the results of 3D scanning.

Keywords: industrial robot manipulator, contactless distance sensors, 3D scanning, segmentation, automatic trajectory planning, robot manipulator program generation, plasma spraying of coatings.

The relevance of the research. A modern robot-manipulator can be considered as a means that allows precisely setting the spatial position and orientation of an arbitrary tool and moving it with controlled kinematic parameters along a given trajectory. Nowadays, the field of application of industrial robot-manipulators is steadily expanding; manipulators are used in automatic packaging lines, assembly systems, for automated painting processes, for the automation of plasma cutting or for the automation of plasma spraying of coatings. In this regard, the problems of planning and control of the trajectory of robotic manipulators are of significant independent interest, both practical and theoretical. The research stimulated by these problems is carried out both by researchers at manufacturing automation or robotics companies and by academic researchers. Currently, the use of robotic manipulators in automobile and mechanical engineering is limited to large-scale production, because each transition to a new type of product requires complex calibration procedures in order to achieve compliance with the original model embedded in the robot at the stage of its production. Therefore, the problem of automatic generation of the program code of a robot-manipulator according to a product model specified by CAD means is in the focus of attention of scientists and developers of robotic systems. The practical implementation of such a robotic system could allow cost-effective production or processing of small-scale and piece parts using a robotic arm. The study was carried out according to the priority "Information,

telecommunication and space technologies, scientific research in the field of natural sciences", within the framework of the project with grant funding from the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan for 2018-2029 No. AR05130525 "The intelligent robotic system for plasma processing and cutting of large-sized products with complex shape"

The main idea of the research is to develop an intelligent automated control system for an industrial robot manipulator, which allows the robot arm to move along a given 3D trajectory - a model of a product that the robot will cut or process with plasma. A distinctive feature of the proposed system is the preliminary 3D scanning of the surface of the workpiece to be processed, followed by automatic generation of the robot manipulator program code, which takes into account the data of the 3D scanning of the processing object, previously carried out by means of distance sensors mounted on the robot manipulator, which will allow the use of workpieces with varying in a wide range of geometric parameters and to process large-sized products, the geometric parameters of which are determined with low accuracy, or products with deviations from a given shape.

The object of research is an intelligent control system for an industrial robot manipulator.

The subject of the research is the automation of a control system for an industrial robot-manipulator by developing a scheme of a robotic system for 3D scanning, followed by planning the trajectory and generating a program for the movement of the robot-manipulator based on the scan data.

The research goal: development of an intelligent automated control system for an industrial robot manipulator that allows plasma cutting of parts with complex shape and/or processing of their surfaces with plasma according to a given 3D model of the product, while preliminary 3D scanning of the processed surface and generation of a motion program using a 3D model the product is carried out by the same robotic arm.

Research objectives:

1) develop a scheme for a 3D scanning system with a laser triangulation distance sensor mounted on a robotic arm and a surface segmentation algorithm to reconstruct an analytical surface model;

2) develop an algorithm for automatic planning of the trajectory of the working tool of the robot manipulator and software designed to interact with the robot operator;

3) implement the generation of a robot manipulator program for its movement along a planned trajectory;

4) conduct a production test of an industrial product processed by plasma with the use of the developed intelligent robotic system for plasma spraying and cutting.

The main research methods: methods of the theory of automatic control, mathematical computer modeling, and the field experiment: testing the scanning technique on model objects and the implementation of robotic plasma surface

treatment with the movement of the robot manipulator along the generated trajectory, followed by production testing of the industrial product.

Scientific provisions submitted for defense:

1) a scheme of a 3D scanning system with a laser triangulation distance sensor mounted on a robotic arm and a segmentation algorithm used to reconstruct an analytical surface model;

2) automatic planning of the trajectory of the working tool and generation of the program for the movement of the robot-manipulator along the planned trajectory.

The scientific novelty of the research is that for the first time:

- a scheme for 3D scanning by a laser triangulation distance sensor mounted on a robot manipulator was developed. The scheme includes a Kawasaki industrial robot manipulator with a distance sensor installed on it, a robot manipulator controller, a personal computer and a distance sensor, both connected to the robot manipulator controller via an RS232 serial interface. The Kawasaki robotic arm allows high-precision positioning of the working tool, due to which this scheme makes it possible to implement a 3D scanning system with a high resolution and accuracy, relatively inexpensive for the achieved characteristics;

- an original algorithm for the surface segmentation procedure with the reconstruction of an analytical surface model has been developed The algorithm is based on the application of a local parametric model and the subsequent combination of local surface areas with a homogeneous geometric structure, which allows, without a priori assumptions about the geometric structure of the surface, to reconstruct an analytical 3D model of a surface with a complex shape;

- an algorithm for controlling a robot-manipulator has been developed, in which the automatic planning of the trajectory and the generation of a program for the movement of the robot-manipulator is carried out according to the data of 3D scanning of the surface of the product being processed by the robot. The trajectory planning algorithm is based on the choice of the starting segment of the trajectory as a geodesic line on the surface, the direction of which is chosen according to the criteria described in the thesis. Automatic planning of the trajectory with the subsequent generation of the program of movement of the robot arm with the working tool attached to it allows to ensure uniformity of the thickness of the plasma coating (or plasma cut) over the entire surface.

Scientific and practical significance of the research. The combination of theoretical and experimental results of the research allowed developing the scientific foundations of robotic technology for plasma cutting and processing of large-sized products with complex shape. A computer program has been registered, which makes it possible to interact with a human - a robot operator during the 3D scanning process, as well as to recognize and analyze images obtained as a result of scanning. A production test report for an industrial product processed using the new technology was received, which confirmed the increase in the service life of the jaw crusher plate with a plasma coating of the worn surface. The new algorithms for controlling a robot manipulator, a segmentation

algorithm and a robotic 3D scanning scheme developed in the dissertation are of interest to a wide range of researchers in the field of automation and control, in particular, in the field of intelligent control of a robot manipulator. The results of the thesis can be used to optimize the technology of plasma cutting and processing of products in order to improve the performance of the processed products and cost-effectively produce robotic plasma spraying of coatings on parts or products of complex shape, as well as plasma cutting of large-sized small-scale and piece products

Approbation of the research. The main results of the Ph.D. thesis were presented and discussed at 5 international conferences:

1) 12th International Symposium on Applied Informatics and Related Areas, November 2017, Székesfehérvár, Hungary;

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

3) IV International scientific and technical conference of undergraduate, graduate students and young scientists called “Creativity of youth for the innovative development of Kazakhstan” April 12-13, 2018, Ust-Kamenogorsk, Kazakhstan;

4) International Conference “Computational and Information Technologies in Science, Engineering and Education” (CITech–2018), September 25-28, 2018, Ust-Kamenogorsk, Kazakhstan;

5) "Global Science And Innovations 2018: Central Asia", 2018, Astana, Kazakhstan.

Publications. 16 papers were published on the topic of the thesis, of which:

4 articles in journals recommended by the Education and Science Control Committee of the Ministry of Education and Science of the Republic of Kazakhstan

1) Alontseva D. L., Russakova A.V. Krasavin A. L., Prokhorenkova N.V., Kadyroldina A. T. Development of technology for microplasma deposition of biocompatible coatings for the manufacture of medical products // Bulletin of D. Serikbayev EKSTU, No 3, 2017. - P. 65-71, in Russian.

2) Alontseva D. L., Krasavin A. L., Shadrin G. K., Kadyroldina A. T. Kussaiyn-Murat A. T. Development of a control system for an industrial robot manipulator to do 3D surface scanning // Bulletin of D. Serikbayev EKSTU, No 1, 2019. - P. 81-87, in Russian.

3) Kadyroldina A. T. Kussaiyn-Murat A. T., Krasavin A. L., Prokhorenkova N.V. Development of an information system for a robot manipulator performing plasma processing of products of complex shape// Bulletin of D. Serikbayev EKSTU, No 3, 2020. – P.95-98, in Kazakh

4) Certificate of the Republic of Kazakhstan for the copyright object (computer program) “Laser strip highlighting program for digital images of 3D scanning objects” / Krasavin A.L., Alontseva D. L,, Kadyroldina A.T. - No. 5870 of October 17, 2019, in Russian;

7 articles in international peer-reviewed journals indexed in the Scopus database and having a CiteScore percentile and (or) indexed in the data of the Web of Science Core Collection, Clarivate Analytics and (or) having a non-zero impact factor

5) Shadrin G. K., Alontseva D. L., Kussaiyn-Murat A. T., Kadyroldina A. T., Ospanov O.B., Haidegger T. Application of Compensation Algorithms to Control the Movement of a Robot Manipulator// Acta Polytechnica Hungarica Vol. 17, No. 1, 2020, P. 191-214. DOI: 10.12700/APH.17.1.2020.1.1 Impact factor of the journal for 2018: 1.51 (Web of Science Core Collection, Clarivate Analytics), CiteScore 2020 in Scopus 75% (General Engineering) https://www.scopus.com/sourceid/19700173166

6) Alontseva D., Ghassemieh E., Voinarovych S., Kyslytsia O, Polovetskyi Y., Prokhorenkova N., Kadyroldina A. Manufacturing and characterisation of robot assisted microplasma multilayer coating of titanium implants: Biocompatible coatings for medical implants with improved density and crystallinity// Johnson Matthey Technology Review, Vol. 64, No 2, 2020. -P. 180-191. DOI: https://doi.org/10.1595/205651320X15737283268284 Impact factor of the journal for 2018: 1.296 (Web of Science Core Collection, Clarivate Analytics). CiteScore 2020 in Scopus 80% (Materials Science: Metals and Alloys) https://www.scopus.com/sourceid/21100443320

7) Alontseva D. L., Ghassemieh E., Krasavin A. L., Shadrin G. K., Kussaiyn-Murat A. T., Kadyroldina A. T. Development of Control System for Robotic Surface Tracking//International Journal of Mechanical Engineering and Robotics Research, Vol. 9, No. 2, February 2020. – P. 280-286. doi: 10.18178/ijmerr.9.2.280-28. CiteScore 2020 in Scopus 26% (Mechanical Engineering) https://www.scopus.com/sourceid/21100788860

8) Alontseva D. L., Ghassemieh E., Krasavin A. L., Kadyroldina A. T. Development of 3D Scanning System for Robotic Plasma Processing of Medical Products with Complex Geometries // Journal of Electronic Science and Technology. – 2020. – vol. 18(3). – pp. 212-222. doi: 10.1016/j.jnlest.2020.100057, CiteScore 11% (Engineering), https://www.scopus.com/sourceid/21100432792?origin=recordpage

9) Alontseva, D., Borisov Y., Voinarovych S., Kyslytsia O., Kolesnikova T., Prokhorenkova N., Kadyroldina A. Development of technology of microplasma spraying for the application of biocompatible coatings in the manufacture of medical implants// Przegląd Elektrotechniczny, Vol 94, No 7, 2018. -P.94-97 doi:10.15199/48.2018.07.23. CiteScore 21% (Electrical and Electronic Engineering), https://www.scopus.com/sourceid/18700

10) Darya L. Alontseva, Alexander L. Krasavin, Alyona V. Russakova, and Albina T. Kadyroldina Automation of Industrial Sites with Mechatronic Systems //International Journal of Electrical and Electronic Engineering & Telecommunications, Vol. 7, No. 4, pp. 146-151, October 2018. DOI: 10.18178/ijeetc.7.4.146-151 CiteScore 11% (Engineering), https://www.scopus.com/sourceid/21100838789

11) Alontseva D., Krasavin A., Kadyroldina A., Kussaiyn-Murat A. Segmentation Algorithm for Surface Reconstruction According to Data Provided by Laser-Based Scan Point // Communications in Computer and Information Science, vol 998, 2019. - pp, 1-10. https://doi.org/10.1007/978-3-030-12203-4_1. CiteScore 31 % (General Mathematics), https://www.scopus.com/sourceid/17700155007 (Conference paper)

5 papers have been published in the international conference's proceedings

12) Alontseva D.L., Krasavin A.L., Kadyroldina A.T., Kussaiyn-Murat A.T., Nurekenov D. M., Zhanuzakov Ye.T., Prokhorenkova N.V. Development of the microplasma spraying technology for applying biocompatible coatings// Proceedings of 12th International Symposium on Applied Informatics and Related Areas (AIS 2017), Székesfehérvár, Hungary, 2017, –P.45-48.

13) Kadyroldina A.T., Kussaiyn-Murat A., Beszedes B., Alontseva D., Krasavin A. Image Acquisition and Processing on Raspberry Pi in Matlab for 3D-Scanning. Proceedings of 14th International Symposium on Applied Informatics and Related Areas organized in the frame of Hungarian Science Festival 2019 by Óbuda University. Székesfehérvár, Hungary, November 14, 2019.- P.39-42.

14) Kadyroldina A. T., Alontseva D. L. 3D-scanning system for intelligent robotic plasma processing and cutting large volumes of complex shapes. GLOBAL SCIENCE AND INNOVATIONS 2018: CENTRAL ASIA» Astana, 2018 –P.341-344. in Kazakh

15) Alontseva D.L., Krasavin A.L., Kadyroldina A.T., Kusaiyn-Murat A.T. Development of a 3D scanning system for an intelligent robotic system for plasma processing and cutting of large-sized products of complex shape // Joint issue of scientific journals "Bulletin of D. Serikbayev EKSTU" and "Computing Technologies ", Volume 1, Part 1, D. Serikbayev EKSTU, Ust-Kamenogorsk. - ICT SB RAS Novosibirsk. - 2018. – P. 7-19, in Russian

16) Kadyroldina A. T., Kusaiyn-Murat A.T. Alontseva D. L. Intelligent robotic system for microplasma processing of complex medical implants // Proceedings of the IV International scientific and technical conference of undergraduate, graduate students and young scientists called "Creativity of youth for the innovative development of Kazakhstan" April 12th -13th, 2018, No IV, EKSTU, Ust-Kamenogorsk. - P.137-142. in Kazakh

The structure and scope of the thesis. The thesis consists of an introduction, 4 chapters, conclusions, a list of references containing 99 titles. The doctoral thesis is presented in 89 pages of typewritten text and contains 39 figures, 3 tables and 2 appendixes.

In the first chapter of the thesis, modern methods and equipment for 3D scanning were considered and the main technological processes of plasma spraying and cutting were analyzed from the point of view of automation. The relevance of the development of an intelligent robotic system for plasma cutting and surface treatment with the use of preliminary scanning of the processed surface was substantiated. The type of a distance sensor was selected for the 3D scanning. The need to develop a segmentation procedure for the reconstruction of a 3D surface model when scanning products of complex shape was substantiated.

The goal and objectives of the research were set and the provisions for the defense were formulated.

In the second chapter of the dissertation, the choice of the main equipment was justified and the research methods were described. The algorithms used for controlling a robot-manipulator for moving a plasma source along predetermined complex trajectories in a plane and for implementing 3D scanning of objects were briefly described. A new algorithm for recognizing scanned images and a computer program that implements it for interactive interaction with the robot operator was described, which allowed the operator during the 3D scanning process to set, test and save the parameters of the recognition process for further use in the process of automatic processing of 3D scanning data.

In the third chapter of the thesis, a scheme of a 3D scanning system with a laser triangulation distance sensor mounted on a robotic arm was presented; a segmentation algorithm for reconstructing an analytical surface model was described. The results of approbation of the developed scheme and the segmentation algorithm, such as test data for surface shape restoration were presented. Thus, the first submitted to the defense provision has been proved.

In the fourth chapter of the dissertation, the results of research on the automatic planning of the trajectory of the working tool and the generation of the program for the movement of the robotic arm along the planned trajectory were described, which confirmed the second position submitted for the defense. The theoretical basis was presented and new control algorithms were described, as well as the results of the practical application of the developed control algorithms in the development of technological solutions at the experimental robotic production site, the results of production tests of products processed using the new technology were presented.

In the final sections of the dissertation, the main results, conclusions and their significance have been presented, the scientific novelty, scientific and practical significance of the research have been described.