Development of the Robotic Microplasma Spraying Technology for Applying Biocompatible Coatings in the Manufacture of Medical Products

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***Abstract* - The paper describes the algorithms and software development for a robotic technology of microplasma spraying of powder and wire materials for applying biocompatible coatings for medical implants and instruments. The authors observe the challenges and prospects of the development and implementation of the robotic technology for manufacturing medical products.**

I. Introduction

The multi-purpose methods of Thermal Coating Spraying have become popular all over the world lately [1, 2]. One of the major methods of gas-thermal deposition of coatings is plasma spraying. The micro plasma spraying (MPS) method is characterized by a small diameter of a spraying spot (1 ... 8 mm) and low (up to 2 kW) power of plasma, which results in low flow of heat into the substrate [3-5]. These characteristics are very attractive for the deposition of coatings with high accuracy, in particular for applying biocompatible coatings in the manufacture of medical implants.

However, the treatment of surfaces of complex configuration presents a challenge for the implementation of the thermal spraying technology and requires automated manipulations of the plasma source and/or the substrate along with robotic control for appropriate treatment of a surface [1, 2].

At present, robot manipulators are widely used in metallurgical industry, automotive industry and mechanical engineering, allowing to automate the plasma processing. However, they are used only for large-scale production, because every transition to a new product requires complex calibration procedures to achieve compliance with the model set in the robot previously. Thus, the problem of automatic code generation of a robot program for the model specified by means of CAD is in the limelight of researchers and developers of robotic systems [6-8].

The main prerequisites for the development of the research were the analysis of technical issues arising from the industrial robot application for coating by plasma jets, and the desire to expand the scope of tasks solved by the application of an industrial robot. The authors of this paper have carried out a work in the field of application of automated plasma methods of biocompatible or protective coating deposition, described in papers [9-11] and protected by certificates of intellectual property [12, 13]. There is a need to develop methods of plasma coating to create medical products. There is some successful research in the technology development of biocompatible coatings microplasma spraying of biomedical application onto different types of implants conducted by scientists of E. O. Paton Institute of Electric Welding, National Academy of Science of Ukraine [4, 5], which is in close relationship with the present research, because we have used the technological equipment for microplasma spraying developed at E. O. Paton Institute of Electric Welding (IEW), namely the MP-004 microplasmotron mounted on the arm of Kawasaki industrial robot. Currently, on the basis of D. Serikbayev East Kazakhstan State Technical University (EKSTU) there is a robot-manned floor for microplasma materials processing, it allows testing new technological solutions to use biocompatible coatings for medical purposes with high (precision) accuracy. In order to obtain coatings with the desired structure and properties, it is very important to provide accurate modes of deposition and modification of coatings by plasma.

As noted by several researchers [1, 2], the main disadvantages of the coatings achieved by using gas-thermal methods are their high porosity and occasional poor adhesion to the substrate. Porosity can be useful at times, as in the case of ensuring reliable fixation of orthopedic implants into bones on account of the intergrowth into the pores of the bone tissue, etc., but in this case it needs to be controlled.

The aim of this work was to develop a robotic micro plasma spraying technology for applying biocompatible coatings in the manufacture of medical products.

II. EXPERIMENT

A. Equipment and Materials

Within the activities of modern technologies development by D. Serikbayev EKSTU an experimental laboratory industrial complex for plasma treatment of materials based on an industrial robot has been established. Kawasaki RS-010LA (Kawasaki Robotics, Japan) industrial robot is a device consisting of moving parts with six degrees of freedom to move according to a predetermined track. It is controlled by a E40F-A001 programmable controller. MP-004 microplasmotron for applying the powder or wire coating produced by E. O. Paton IEW, Ukraine is mounted on the robot arm. The assembly of the system has been carried out by Innotech LLP, Kazakhstan.

Kawasaki RS-010LA robot manipulator characteristics:

- Number of degrees of freedom - 6;
- Positioning accuracy – 0.06 mm;
- Maximal linear speed - 13100 mm/s;
- Engagement zone - 1925 mm;
- Working load capacity - 10 kg.

The study has dealt with the starting materials for coating deposition: powders, wires and resulting coatings obtained by means of microplasma spraying, as well as substrates (in most cases 3 steel substrates treated by sandblasting were used). The range of materials in the study was broad enough to ensure the mastering of technological processes for different materials. Co-based and hydroxyapatite powders as well as Titanium wires have been used as the main materials for working out the microplasma spraying processes of biocompatible materials.

B. Methods

The technologies of plasma spraying of coatings require accurate adhering to the number of technological parameters (the distance from the plasma system nozzle to the surface of a workpiece, the nozzle movement speed, etc.) during the entire processing time. Exceeding these parameters beyond the permissible limits can lead not only to rejected products, but also to an accident (a short circuit). In cases when the robot program is generated according to a given geometrical model of a processed workpiece or part, the deflection of the shape of the real object from the model often leads to the violation of technological parameters of processing with all its undesirable consequences. This problem is particularly acute in the case of large-sized objects, including medical implants or instruments, when small relative errors of geometric parameters and object positioning correspond to unallowably high absolute deviations of the distances between the tool mounted on the manipulator and the object surface. The radical method of solving these problems is pre-scanning the surface of an object

A modern robot manipulator can be considered as a means of allowing setting spatial position and orientation of an arbitrary tool with high precision and accuracy. If a distance sensor or a vision system element (camera or projector) is used as a tool, the robot manipulator can be an excellent basis for establishing a system of surface scanning.

The basic idea of the proposed method - the development of a combined system for scanning with the split of scan process into two phases: a rough scan phase and a refining phase. For rough scanning a vision system, that uses a single camera mounted on the manipulator and a fixed structured light projector is supposed to be used. During the rough scan phase, photography of an “illuminated” object from several points of space is performed (with the known orientation of the principal optical axis of the camera). By the images obtained in the shooting process, the software of the scanning system produces a segmentation of the object surface and builds an approximate 3D model of the object. According to the segmentation results, a set of reference points is selected on the surface; and if we know their spatial coordinates, we will be able to construct a 3D model of the object. After selecting reference points, the software generates the program of the manipulator which successively passes the reference points performing surface scanning at each point.

The vision system will be built on the original algorithm, implemented in three stages processing the image obtained by the camera: 1) building a function module of the intensity gradient; 2) constructing a set of lines of this function level (the structuring of the system of level lines radically simplifies the task of finding correlation between the lines obtained in the processing of the two photos taken at different camera positions); 3) calculating spatial coordinates of the scene points, whose images lie on these lines.

The implementation of the proposed algorithm, in contrast to the common computer vision algorithms, does not require much computational power. Besides, the algorithm of level lines is easily parallelized and makes it possible to set up the software processing system on a personal computer (when using the CUDA system for efficient implementation of parallel algorithms).

Thus, we are developing an intelligent automated system of controlling an industrial robot manipulator, which allows a robot arm to move along a given 3D trajectory, a model of the product that the robot will be treating with plasma. A distinctive feature of the proposed system is pre-3D scanning the surface of the rough workpiece or the workpiece in process. We are planning to implement automatic generation of a robot-manipulator program code, taking into account the data of the 3D scanning of an object to be processed, previously held by means of distance sensors mounted on the robot manipulator. This will allow to use workpieces varying in a wide range of geometric parameters and processing products, whose geometrical parameters are determined with low accuracy or products with deviations from a predetermined shape.

III. RESULTS AND DISCUSSIONS

At D. Serikbayev EKSTU the prototypes of coatings from Titanium - wires and Co-based and hydroxyapatite powders have been produced using the robotic complex for microplasma deposition. The parameters for additional processing of coatings by a plasma jet were selected on the basis of mathematical modeling of the temperature fields arising in the "coating-substrate" system when heated by a travelling plasma source [12]. The experience of getting coating from powders and wire of a range of alloys with the use of this complex was successful; the results were published in [9-11].

To solve the problem of providing the desired trajectory of the plasma source, we have developed the software which converts the drawings made in AutoCAD and Compass to the robot controller by selecting the graphics primitives (line, arc, etc.) from the drawings and transferring them into the commands for the robot arm movement [13]. However, we suppose that this method is unsatisfactory for plasma treatment of the large-sized implants and medical instruments surface, because a 3D model of the surface to be processed is needed to move the robot arm with plasma source accurately during the plasma processing. Currently we are developing an intelligent automated system of controlling an industrial robot manipulator, which allows carrying out product surface hardening treatment: coating application using a microplasma method, and plasma irradiation modification of surfaces of complex shape products. Preliminary 3D scanning of the surface is being processed and generation of the program code is carried out by the same robot manipulator.

As it seems to us, two main categories can be distinguished in the methods of machine binocular vision developed to date: methods based on the detection of image features [14, 15] and methods based on minimizing the energy function [16-18]. Most of the methods of the first group are associated with the so-called problem of edge detection. Edge detection includes a variety of mathematical methods that aim at identifying points in a digital image at which the image brightness changes sharply or, more formally, has discontinuities. The points at which image brightness changes sharply are typically organized into a set of curved line segments termed edges. It should be noted that the methods of the first group find the correspondence between some points of two images. For the methods of the first group it is not necessary to find a correspondence between all the pixels of two images, as well as to find the disparity function that minimizes the so-called energy function.

The method proposed by us is based on finding the correspondence between the curves (contour level curves of modulo of gradient of intensity function) and has some common features with the methods of both the first and second groups.

A black and white image can be considered as a discretization of a continuous function of two arguments *I(x,y) (Intensity function)*. In image processing, so-called gradient image processing technique is widely used, based on the numerical calculation of the intensity function gradient. Typically, the magnitude of the gradient vector *F (x,y)* (1) and its direction are calculated separately as a discrete convolution of the image matrix with one of the specially designed convolution kernels. In our experiments we use the so-called Sobel kernel.

$$F(x,y)=\sqrt{\left(\frac{\partial I}{\partial x}\right)^2+\left(\frac{\partial I}{\partial y}\right)^2} \quad (1)$$

The proposed algorithm is based on finding the correspondence between the level contour curves of two functions of intensity gradient modulo F_1 and F_2 (for the left and right images correspondingly). On the set of level curves of the function, we can introduce a partial order relation, which we denote by the symbol $\preccurlyeq$. We assume that $s_1 \preccurlyeq s_2$ if the curve s_1 lies inside the region bounded by the curve s_2. As a consequence, set of level lines can be represented by a tree, as shown schematically in Fig 1.

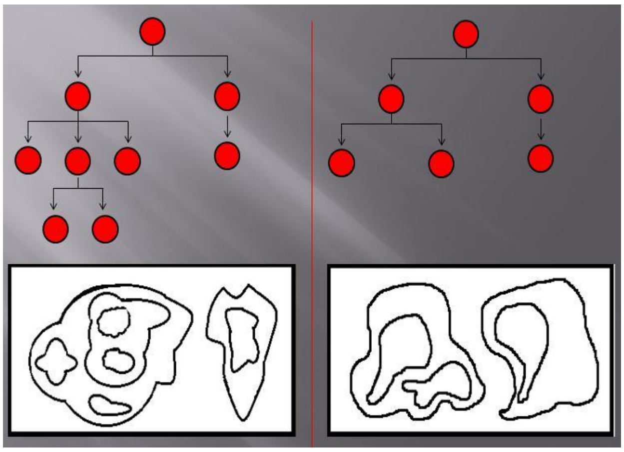

Figure 1. Level Tree

One of the leading ideas of the proposed method is the use of a hierarchical structure of level lines (given by a level tree) to simplify the task of finding a correspondence between the level lines of the functions F_1 and F_2. In fact, after constructing the level tree, the problem of finding the correspondences between isolines of functions F_1 and F_2 reduces to the problem of identifying isolines that are descendants of a single tree node. Obviously, to implement the methods of this kind, an effective algorithm for constructing isolines is needed. Such algorithms are used both in computer graphics and in image processing, and these algorithms still continue to be improved [19-20].

We have developed an algorithm for constructing the contour curves of the function of two variables that improve modification of the marching triangles classical algorithm. The original Marching Triangle algorithm does not specify any boundary edges processing sequence. It defines only a single pass into the edge list to process all boundary edges with the procedure steps including the estimation of a new potential triangle and its sphere test mesh. According to the implemented data structures and the method to add new edges in the edge list, the edge processing sequence can be different from each other. The resulting mesh from the Marching Triangle depends on the edge processing sequence and it can be different if the sequence is changed. The algorithm developed by us is free from these restrictions and allows parallelization.

Currently, we are developing an algorithm that allows us to identify many isolines. We have developed an effective algorithm for finding a numerical measure of the geometric proximity of two domains bounded by a polygon. The developed method is based on minimization of the energy function, for calculation of which the above-mentioned measure of geometrical proximity of spatial regions is used.

IV. CONCLUSION

Coatings from biocompatible materials deposited by the microplasma according to recommended modes onto steel substrates have been obtained. It is shown that the microplasma spraying method allows applying a wide range of materials: hydroxyapatite, Co-based powders, Titanium – wires. Successful deposition of biocompatible coatings with sustained characteristics on parts of complex shape, which are endoprostheses, requires steady travelling of the plasma source along the sprayed surface of the product. For this purpose, it becomes necessary to equip the deposition unit with a robot manipulator and to develop an intelligent automated system of controlling an industrial robot manipulator, which allows a robot arm to move along a given 3D trajectory.

Multi-view 3D – Reconstruction algorithm has been developed to scan an object quickly. The algorithm is based on finding the correspondence between the isolines of the images intensity gradient functions.

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