Automation of Industrial Sites with Mechatronic Systems

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Abstract—**This paper describes developing an intelligent automated system of controlling an industrial robot manipulator, that allows producing items by plasma cutting according to a given 2D or 3D model of the product; carrying out product surface hardening treatment: coating application using microplasma method, and plasma irradiation modification of surfaces of complex shape products. The results are implemented at a pilot production site equipped with advanced laboratory and industrial complex for microplasma processing of materials on the basis of an industrial robot Kawasaki RS-010LA (Kawasaki Robotics, Japan). Testing technological solutions on the experimental production site with the quality control of products processed by new technologies was carried out.**

Index Terms—**industrial robot manipulator; mechanical testing; plasma processing; robot programming; software development**

I. Introduction

In order to accurately perform plasma-based operations, such as spraying of coatings, as well as cutting, one needs to precisely observe a number of technological parameters, such as the distance from the plasma system nozzle to the surface of a workpiece, the nozzle movement speed, etc. throughout the entire processing period. The violation of these parameters against the permissible limits can result not only in rejected product, but also in a short circuit or some other accident. When the robot actions are programmed according to a given geometrical model of a workpiece being processed, the deformity of the real object from the model often involves the non-observance of processing technological parameters and hence its undesirable consequences. This issue is particularly critical concerning bulky objects, when relatively small errors of geometric parameters and object positioning go with inadmissibly high absolute deviations of the distances between the mounted on the manipulator tools and the object surface. Pre-scanning the surface of an object may radically solve these problems.

A modern robot manipulator is an instrument that allows setting spatial position and orientation of any tool with high accuracy and precision. In case a vision system element (camera or projector) or a distance sensor is used as a tool, the robot manipulator can be a great basis for engineering a surface scanning system. Currently, industrial robot based 3D-scanners are used in quality control systems, automatic packing lines, and assembly systems; and their application over time has been steadily expanding.

It should be noted that the tasks associated with the construction of 3D-scanning systems on the basis of robot manipulators are of considerable interest, both practical and theoretical in nature; and research stimulated by these objectives is conducted by both research units of companies, specializing in the production of control and measuring devices and automation means of production, and representatives of the academic community [1]-[8]. Because our main ideas for developing an intelligent automated system of controlling an industrial robot manipulator are focused on scanning techniques, we give a brief overview of commonly used technologies of non-contact scanning and related research.

Non-contact scanners can be divided into active, i.e. generating scanning radiation (electromagnetic or ultrasound waves) and receiving radiation reflected from a scanned object, and passive, i.e. receiving natural light dispersed on an object. Active scanners, in their turn, by the principle of measurements are divided into time-of-flight, triangulation and structured light scanners. Time-of-flight scanners are based on a laser or ultrasonic rangefinder determining a distance to an object according to the transport signal delay. In laser triangulation scanners the beam reflected from an object is received by a digital camera. When the relative position of the source and the camera is known, the distance to the scanned surface is found by the image obtained at the camera matrix. Currently variations of this method have been implemented, in particular, the methods, which use a narrow strip of light for scanning received by a pair of cameras [6]. In their essence, these methods belong to the group of methods of binocular machine vision. The groups of methods that use structured light technology include methods in which the projector rays illuminating the scanned area of an object form a geometric structure with known parameters. The projector rays form a characteristic pattern on the scanning surface (often in the form of strips or grid), and image analysis in receiving chambers allows calculating the coordinates of points located on the illuminated narrow lines. By the form the initial scan results are presented, methods are divided into two groups: in the methods of the first group (point scan methods) primary data is represented by the set of

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coordinates of a discrete set of surface points, called "point cloud"; in the methods of the second group, the result of scanning is a set of contours of the scanned surface.

The analysis of publications [7]-[9], whose topics are related to the development of systems for 3D-scanning based on robot manipulators, and the analysis of solutions presented in the market, it is possible to come to a definite conclusion: the developers of such systems use only methods of the second group [7], [8]. The systems of 3D-scanning, where robotic manipulators are applied, use either laser triangulation scanners [9], or optical scanners that are implemented on the basis of machine vision systems (in particular, the system using structured light technology). Currently, a number of manufacturers of optical measuring equipment are producing 3D-scanners specially designed for systems using a robot manipulator to move the scanner in space. The analysis of the market suggests that they all use methods of machine vision for scanning, i.e., include multiple cameras, and software allowing for the reconstruction of 3D-scenes, located in the working area of the camera system. As an example, let us note the series of MetraSCAN 3D-optical 3D-scanners produced by Creaform Inc. Machine vision systems require much less time for scanning than point scan systems, that require manipulator passing all the scanning points; in addition, point scanning systems are of little use for scanning objects, the surface of which cannot be described by a smooth function – e.g. polyhedra. On the other hand, the point scanning systems of the same accuracy will always be much cheaper and easier to setup and maintain than the corresponding machine vision system. For any optical scanner, the necessary conditions for achieving high measurement accuracy are a high resolution image sensor and a high quality optical system. Machine vision systems require additional expensive hardware and specific software. At the same time, distance sensors for building a fairly accurate scanning system are cheap and easy to use.

The fundamental difference between our ideas from existing analogues is that we propose to generate a robot program by a 3D-model of the object to be processed, obtained in the result of scanning, using an industrial robot as a key component of the scanning system.

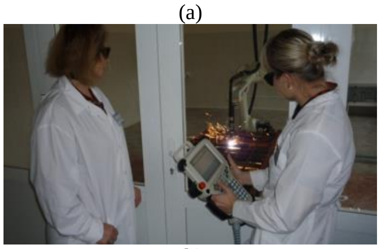
The aim of this work was the development of a method of segmentation of the point cloud obtained at the stage of rough scanning of the surface, namely the algorithms of image segmentation and segmentation of the surface based on the calculation of the local geometric properties of the surface.

II. Experiment

A. Equipment

The research was carried out at a pilot production site established on the basis of D. Serikbayev East Kazakhstan State Technical University with advanced laboratory and industrial complex for microplasma processing of materials on the basis of an industrial robot Kawasaki RS-010LA (Kawasaki Robotics, Japan) (Fig. 1).

(a)



(b)

Figure 1. General view of the robot manipulator with the machine for microplasma spraying of coatings (a) and with the surface plasma cutting machine (b)

The robot consists of movable parts with six degrees of freedom for moving the equipment installed therein according to a predetermined contour. It is controlled by E40F-A001 programmable controller. Kawasaki RS-010L.

Robot manipulator characteristics are the following: 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 robot's arm is equipped either by a device for air plasma cutting ("UPR") powered by a DC 120P.33 inverter power source produced by "NPP Tekhnotron" Ltd. (Russia) to work on plasma cutting, or a device for plasma deposition of powder or wire coatings ("MPN-004", produced by E.O. Paton Institute of Electric Welding, Ukraine). The assembling of the robot was carried out by "Innotech" Ltd, Kazakhstan.

New algorithms were applied for the plasma processing of products. The analysis of the structure and some properties of the samples processed using the new technology and the morphology of their surface shows good results, but they are not presented here, because they require separate representation in a specialized materials science printed edition.

The quality control of the processed surfaces was carried out at an engineering laboratory equipped with Transmission Electron Microscope JEM-2100 ("JEOL", Japan) with INCA Energy TEM 350 ("Oxford Instruments", Great Britain), Scanning Election Microscope by JSM-6390LV ("JEOL", Japan), X-ray diffractometer X'Pert PRO ("PANalytical", the Netherlands), M-691 Precision Ion Polishing System ("Gatan", USA), and LM-700 digital microhardness meter (LECO, Russia).

B. Methods

The proposed method is aimed at the development of a combined system for scanning with the division of a scan process into two phases: a rough scan phase and a refining phase. Rough scanning may be performed by a vision system, which uses a single camera mounted on the manipulator and a fixed structured light projector. During the rough scan phase, photography of an "illuminated" object from several points of space is being carried out (the orientation of the principal optical axis of the camera are known). The scanning system software produces a segmentation of the object surface and builds an approximate 3D model of the object based on the images obtained in the shooting process. Then a set of reference points is selected on the surface according to the segmentation results. Their spatial coordinates are known and a fairly accurate 3D model of the object that can be constructed. As soon as reference points are selected, the software generates the program for the manipulator to successively pass the reference points, performing surface scanning at each of the points.

There are three stages of processing an image obtained by the camera in the algorithm for the vision system: 1) establishing a function module of the intensity gradient; 2) building a set of lines of this function level (structuring the system of level lines radically simplifies the task of finding correlation between the lines obtained in the processing of the two photos taken from different positions of a camera); 3) specification of the spatial coordinates of the scene points, whose images lie on these lines.

Implementing the proposed algorithm, unlike the common computer vision algorithms, does not require much computational power. Moreover, the algorithm of level lines is easily parallelized, which makes possible the implementation of the personal computer software processing system (using the CUDA system for efficient implementation of parallel algorithms).

III. Results and Discussion

As noted above, a key feature of the proposed method is to build 3D models of the machined surface based on the data of its pre-scanning, and further generating a program of a robot manipulator. In its turn, the surface scanning is divided into two stages – rough and fine. At the stage of rough scanning carried out using the technique of machine vision, a point cloud is generated; the coordinates of the points are determined with a sufficiently large instrumental error and jitter. The stage of rough scanning is required for the segmentation of the surface. The segmentation of the surface, in turn, is necessary to determine geometrically homogeneous areas of the surface and reference points within the area, which will be used for precision point scanning. Segmentation is a necessary process in many applications such as object recognition, modeling, compression, and so on. Although various segmentation methods have been proposed, segmentation of raw point clouds is still a challenging problem due to lack of the structures or the mathematical model of the input data, geometry shape complexity and noise (outliers). A good overview of the methods of segmentation and their comparative analysis can be found in the works [10], [11]. The methods of geometric segmentation can be classified by the method of surface approximation. At present, the most advanced methods are the methods of planar segmentation, which continue to develop [12, 13]. Among them, the methods based on the quadric fitting are much more flexible [14], [15]. It is known that surfaces with sharp kinks and bends represent the greatest difficulty for the development of adequate analytical 3D models, while the technique of approximation of smooth surfaces is elaborated in detail. Thus, the method of surface segmentation plays an important role in the proposed technology of surface treatment. Below we present a description and brief discussion of the proposed segmentation algorithm.

A. Algorithm

The algorithm of segmentation of the surface is given below based on the local calculation of the average and Gaussian curvature of the surface.

It is possible to distinguish four basic approaches to the problem of segmentation of the point cloud, namely the methods that use comparison of some parameters, namely the methods that use comparison of some parameter with predetermined thresholds, detecting the boundaries, the methods associated with the manipulation of areas, and hybrid methods. In the threshold methods it is postulated that each point in the cloud belongs to only one class defined by the range of the function values calculated in each point cloud. Such methods ignore the information about the structure of the surface as a whole and are heavily influenced by jitter. Methods of boundary detection are based on the assumption of the existence of sharp boundaries between areas of the surface, allowing the approximation of smooth functions. The main instrument for the implementation of the methods of this group is a gradient filter of any type. Typically, the methods of this kind suggest that the areas in which the gradient value is significant, transform into closed lines representing the boundaries separating geometrically homogeneous areas. Segmentation algorithms not based on the operations with the areas are built on the basis of one or another criterion of similarity between points on the surface (this criterion is often mathematically formulated as the introduction of a specific metric in the space of points). The general procedure, roughly speaking, is that a point is compared to the closest neighboring points. If the criterion of homogeneity is met, the point belongs to the same class as its neighbors. A key role in the practical applicability of the methods in this class is the choice of the homogeneity criterion. Hybrid methods combine one or more of the above mentioned basic methods.

For surface segmenting we suggest using the variation of the region growing algorithm, called Unseeded Region Growing Algorithm. Although this algorithm was proposed for the segmentation of images, its sufficient commonality allows using it for our purposes. The proposed procedure for the automatic segmentation of the surface is based on local analysis of the Gaussian and mean curvature of the surface obtained when constructing a nonparametric analytical model. Curvature scale space is a popular shape descriptor for still images and video. However, to date, using curvature to represent shape for 3D models has not been investigated as much as for image and video. Though some pioneering work on 3D shape representation and matching has been done [16, 17], the work on how to represent and match shapes for 3D surfaces while preserving both geometric and topological properties is still thin. In the proposed method, the point cloud is interpreted as a height map, i.e. it is assumed that the discrete function of two variables *Z* (*X*, *Y*) on a grid in the plane *X*-*Y* is preassigned.

In each point the surface is modeled by a second-order polynomial by the local coordinates. The calculation of the coefficients of the approximating polynomial is carried out by considering a selected number of neighboring points lying within a circle of a given radius, for the application of the method of least squares. The main advantage of the nonparametric approach is its commonality: a priori assumptions about the local geometry of the surface are not introduced, and, moreover, the analytical model of the surface is not proposed.

Let us consider the approximation of the surface in the local neighborhood of an arbitrary point P with the coordinates (x_k, y_m, z_{km}) of type (1)

$$z_{ij} = c_0 + c_1 \cdot u + c_2 \cdot v + \frac{1}{2} \cdot c_3 \cdot u^2 + c_4 \cdot u \cdot v + \frac{1}{2} \cdot c_5 \cdot v^2 + \varepsilon_{ij} \cdot \quad (1)$$

Such approximation can be considered as the period of decomposition into a Taylor series of the function $Z(u, v)$ in the vicinity of a point (x_k, y_m). Here with equations (2 – 9) are correct

$$c_0 = z_{km} \quad (2)$$

$$c_1 = \left(\frac{\partial Z}{\partial u}\right)_P \quad (3)$$

$$c_2 = \frac{\partial Z}{\partial v} \quad (4)$$

$$c_3 = \frac{\partial^2 Z}{\partial v^2} \quad (5)$$

$$c_4 = \frac{\partial^2 Z}{\partial u \partial v} \quad (6)$$

$$c_5 = \frac{\partial^2 Z}{\partial v^2} \quad (7)$$

$$u = x_i - x_k \quad (8)$$

$$v = x_j - x_m \quad (9)$$

The calculations of coefficients c_0, c_1, …, c_5 of local approximation of type (1) are made by methods of the regression analysis according to the coordinate values of the points neighboring with P. More precisely, we specify some value of radius r (selected empirically) and consider the set of points for which the following inequality is satisfied (10)

$$d_{ij} \le r \quad (10)$$

where d_{ij} is the distance between the point with the coordinates (x_i, y_j, z_{ij}) and point P, which is defined according to (10)

$$d_{ij} = \sqrt{(x_k - x_i)^2 + (y_m - y_j)^2} \quad (11)$$

B. Calculation

The calculation of the average and Gaussian curvature of the surface is given below.

Consider the surface given by

$$\vec{r} = \vec{r}(x_1, x_2) \quad (12)$$

Total differential $\partial\vec{r}$ of the radius vector $\vec{r}$ of the surface point is represented as a linear differential form:

$$\partial\vec{r} = \vec{r}_1 \cdot dx_1 + \vec{r}_2 \cdot dx_2) \quad (13)$$

The scalar square of this form represents the scalar quadratic differential form with the property of invariance.

$$\partial\vec{r}^{\,2} = \vec{r}_x^{\,2} \cdot dx_1^2 + 2 \cdot \left(\vec{r}_x, \vec{r}_y\right) \cdot dx_1 \cdot dx_2 + \vec{r}_y^{\,2} \cdot dx_2^2) \quad (14)$$

This quadratic form is called the first quadratic form of surface. In expanded form the first quadratic form is usually written as

$$E \cdot dx^2 + 2 \cdot F \cdot dx \cdot dy + G \cdot dy^2 \quad (15)$$

The coefficients *E*, *F*, and *G* of the first quadratic form are defined by equation (3). In the future we will use the representation of the first quadratic form in standard form:

$$I(u,v) = (u^1, u^2) \cdot \begin{pmatrix} E & F \\ F & G \end{pmatrix} \cdot \begin{pmatrix} v^1 \\ v^2 \end{pmatrix} \quad (16)$$

Note that the matrix of the first quadratic form in regular points of the surface is positively defined. The coefficients of the first quadratic form are calculated using the coefficients c_0, c_1, …, c_5 of the approximating polynomial (1) by formulas (17)-(18).

$$\begin{aligned} E &= c_3 \Big/ \sqrt{1 + c_1^2 + c_1^2} \\ F &= c_4 \Big/ \sqrt{1 + c_1^2 + c_1^2} \\ G &= c_5 \Big/ \sqrt{1 + c_1^2 + c_1^2} \end{aligned} \quad (17)$$

Using $\vec{m}(x, y)$ we shall denote such a normal to a regular surface at the point $\vec{r}(x, y)$ that $\left(\vec{m}, \vec{r}_x, \vec{r}_y\right)$ a positively oriented frame in R^3. Vector $\vec{m}$ is found explicitly by

$$\vec{m} = \frac{\left[\vec{r}_x, \vec{r}_y\right]}{\left|\left[\vec{r}_x, \vec{r}_y\right]\right|} \quad (18)$$

Let $\vec{r}_{jk}$ be defined by the formula (19)

$$\vec{r}_{jk} = \frac{\partial^2 \vec{r}}{\partial x_j \partial x_k} \quad (19)$$

The second quadratic form is a symmetric bilinear form Π determined by

$$\prod(u,v) = (u^1, u^2) \cdot \begin{pmatrix} L & M \\ M & N \end{pmatrix} \cdot \begin{pmatrix} v^1 \\ v^2 \end{pmatrix} \quad (20)$$

$$L = (\vec{r}_{11}, \vec{m}) \quad (21)$$

$$M = (\vec{r}_{12}, \vec{m}) \quad (22)$$

$$N = (\vec{r}_{22}, \vec{m}) \quad (23)$$

The coefficients of the second quadratic form are associated with the coefficients of the approximating polynomial by

$$L = 1 + c_1^2 \quad (24)$$

$$M = c_1 \cdot c_2 \quad (25)$$

$$N = 1 + c_2^2 \quad (26)$$

The fundamental role of the second quadratic form in the definition of the local surface geometry is that it allows you to determine the curvature of the given curve belonging to the surface. Let $\vec{v}$ be the tangent vector to the surface at the point $\vec{r}(u^1, u^2)$ and $\vec{m}$ be the vector of normal at the same point. Through the point $\vec{r}(u^1, u^2)$ we shall pass a two-dimensional plane, spanned over vectors $\vec{m}$ and $\vec{v}$. The intersection of this plane and the surface – the curve γ is called a normal section that meets the point $\vec{r}(u^1, u^2)$ and tangent vector $\vec{v}$. Then the curvature of the normal section γ is determined by the formula.

$$k = \frac{\prod(u, v)}{I(v, v)} \quad (27)$$

In the tangent plane, we can choose a basis $\vec{e}_1\vec{e}_2$ in which the forms of I and Π at the same time are diagonalized. The directions of vectors $\vec{e}_1$ and $\vec{e}_2$ are called principal directions, and they are unequivocally determined if $k_1 \neq k_2$.The values of k_1 and k_2 of normal curvatures along the principal directions are called the principal curvatures. They are the extreme values for the normal curvatures at the point, which follows from Euler's formula (28), where φ is the angle between vectors $\vec{e}_1$ and $\vec{v}$.

$$\frac{\prod(v, v)}{I(v, v)} = k_1 \cdot \cos^2 \varphi + k_2 \cdot \sin^2 \varphi \quad (28)$$

The product of the principal curvatures at the point is called the Gaussian curvature of the surface at this point:

$$K = k_1 \cdot k_2 = \frac{(L \cdot N - M^2)}{(E \cdot G - F^2)} \quad (29)$$

The sum of the main curvatures at the point is called the average curvature of the surface at this point:

$$H = \frac{1}{2} \cdot (k_1 + k_2) \quad (30)$$

Thus, for each point, the four local curvature values K, H, k_1 and k_2 can be automatically obtained as the functions of the coefficients of the approximating polynomial. In addition, such curvatures are invariant with respect to the adopted reference system, which represents a very important property in analyzing the surface shape.

IV. Conclusion

The method of the segmentation of the point cloud obtained at the stage of rough scanning of the surface, namely the algorithms of image segmentation and segmentation of the surface based on the calculation of the local geometric properties of the surface was proposed to develop an intelligent automated system of controlling an industrial robot manipulator, which allows a robot arm to move along a given 3D trajectory.

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

Testing technological solutions on the experimental production site with the quality control of products processed by new technologies was carried out.

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