Development of an Experimental Robotic Complex for Direct Metal Deposition and Testing of Deposition Modes for Heat-Resistant Powder Material

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Abstract. The paper considers the issue of optimizing the movement of an industrial robot used in additive manufacturing in the technology of direct metal deposition of parts. The developed mathematical model that takes into account the joint work of a six-axis robot manipulator and a two-axis positioner is described. The algorithm for calculating the motion based on the relative position of two adjacent points of the working tool trajectory relative to the rotary axis of the positioner with a given accuracy is described. The simulation of processing is carried out both when working only with the manipulator, and when working together with a two-axis positioner, and control programs with recalculated coordinates and rotation angles of the positioner are obtained.

Introduction

The first industrial robots (IR) appeared in 1956 and were intended for the simplest manipulations of moving parts [1]. Due to the low rigidity and high inertia, as well as the low level of software development, it was not possible to use IR in more complex operations [2]. However, the further development of the industry allowed them to be used for welding [3, 4], coating [5], maintenance of machine tools and machines [6]. Currently, industrial robots are increasingly being used in medicine [7], as well as in the processing of materials. Such types of mechanical processing as milling [8, 9], polishing [10], as well as the use of robots in additive manufacturing, for example, in the technology of direct metal deposition of powder materials, are actively studied [11]. The use of direct metal deposition technology, in which controlled continuous multi-axis deposition of metal powder particles in the laser radiation field is carried out, provided by combining a gas-powder jet with a laser beam, is one of the progressive directions for the creation of aircraft engine parts [12-15].

Among the advantages of using modern industrial robots, we can highlight their high flexibility, which allows to quickly reconfigure production and ability to work out movements that are not available for traditional CNC machines due to of more degrees of freedom [2].

Despite the continuous improvement of the IR, the problems of rigidity and inertia are still inherent in robotic manipulators. In addition, there may be situations in which a robot singularity is observed - a phenomenon accompanied by the fact that the mathematical function used in the calculations of the IR's movement tends to infinity, which causes incorrect movements of the IR's links [16]. Therefore, most studies are aimed at optimizing the movements and improving the accuracy of the positioning of tool. Methods of programming sequential linearization were proposed, in which an approach was developed to ensure the smoothness of the trajectory over the entire path section [17] and a method for predicting the dynamics of the robot depending on its position [18]. The creation of NC-programs can be performed both by means of offline

programming, implying the use of various CAM systems, and through online programming, that is, programming the robot directly at the installation site via control panel[19].

In this paper to improve the accuracy of the positioning of tool the optimization of movement when processing axisymmetric and / or close-shaped parts is considered.

Description of the Method

The object of the study is a robotic complex of direct metal deposition (RCDMD) developed by the Institute of Laser and Welding Technologies (ILWT, St. Petersburg) [11]. RCDMD consists of a six-axis robot manipulator Fanuc Robot M-20iA_20M with mounted a additive head on it and a table for workpieces mounted on a tilt-and-turn device (a two-axis positioner Fanuc 2-axis Arc Positioner).

A IR can be considered as a set of rigid links connected in series, each of which is equipped with a servo drive. The robot has six rotational kinematic pairs. The two-axis positioner has two rotary joints J_7 and J_8 , which rotate around the B and C axes, respectively.

The task of kinematics is to describe the spatial position of the links of the mechanism. There are direct and inverse kinematics problems. The direct kinematics problems gives a decision about the position and orientation of the tool (in this work of the additive head), based on the given geometric parameters of the links and the vector of the attached angles.

The inverse problem gives a solution to the possible values of the attached angles that provide a given position of the tool and its orientation relative to the absolute coordinate system. In general, for a 6-axis robot equipped with a positioner, the mathematical model of kinematics for the inverse problem can be represented as:

$$\begin{cases} J_1 = J_1(x, y, z, i, j, k, \alpha_1, \theta_1, a_1, d_1, t); \\ J_2 = J_2(x, y, z, i, j, k, \alpha_2, \theta_2, a_2, d_2, t); \\ J_3 = J_3(x, y, z, i, j, k, \alpha_3, \theta_3, a_3, d_3, t); \\ J_4 = J_4(x, y, z, i, j, k, \alpha_4, \theta_4, a_4, d_4, t); \\ J_5 = J_5(x, y, z, i, j, k, \alpha_5, \theta_5, a_5, d_5, t); \\ J_6 = J_6(x, y, z, i, j, k, \alpha_6, \theta_6, a_6, d_6, t); \\ J_7 = J_7(x, y, z, i, j, k, \alpha_7, \theta_7, a_7, d_7, t); \\ J_8 = J_8(x, y, z, i, j, k, \alpha_8, \theta_8, a_8, d_8, t), \end{cases}$$

where x, y, z are Cartesian coordinates; i, j, k are the guiding orts of the tool axis; $\alpha_i, \theta_i, a_i, d_i$ are the parameters of the links; t is the time; α_i is the angular displacement – the angle by which the z_{i-1} axis should be rotated around the x_i axis so that it becomes co-directional with the z_i axis; θ_i is the connecting angle by which the x_{i-1} axis should be rotated around the z_{i-1} axis so that it becomes co-directional with the x_i axis; a_i is the linear displacement – the distance between the intersection the x_{i-1} axis with the x_i axis and the beginning of the i -th coordinate system, counted along the x_i axis; d_i is the distance between the intersection of the z_{i-1} axis with the x_i axis and the beginning of the $(i-1)$ -th coordinate system, calculated along the z_{i-1} axis. For rotational joints, the parameters α_i, a_i, d_i are constant values for each specific robot model that characterize the design of the links.

There are many methods for solving the inverse problem of kinematics: the method of inverse transformations, direct geometric methods, a method based on nonlinear mathematical

programming. The last one has gained the greatest popularity, since with a large number of possible solutions, it is possible to impose restrictions that give an optimal solution [19].

First, the positioner rotation angles $J_7 = B$ and $J_8 = C$ are calculated. In this case, the optimization task is set, when the robot's movements are minimized and tool approach to the processing area is provided by the positioner. This method of setting the movement is explained by the presence of industrial robots with low (compared to conventional NC-machines) rigidity and high inertia of the joints. The essence of the method is that when processing axisymmetric (or close to such a shape) parts, the movement along a trajectory that has an axis of rotation that coincides or is close to the axis of rotation of the table is provided by the movement of the positioner. In this case, the robot will only make corrective movements. Figure 1 shows a diagram of the combined movement.

Fig. 1. Working travel due to combined movement of an additive head of a robot with rotation of a positioner table.

The initial data for the calculation are the coordinates of the start X_0 and end X_1 points of a trajectory, the coordinates of robot base O relative to the world coordinate system, the coordinates and direction of the axis of rotation of the table of the positioner O_c relative to the world, which are represented by vectors in the following form:

$$X_0 = \begin{bmatrix} x_0 \\ y_0 \\ z_0 \\ i_0 \\ j_0 \\ k_0 \end{bmatrix}; X_1 = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \\ i_1 \\ j_1 \\ k_1 \end{bmatrix}; O = \begin{bmatrix} x_o \\ y_o \\ z_o \\ 0 \\ 0 \\ 0 \end{bmatrix}; O_c = \begin{bmatrix} x_c \\ y_c \\ z_c \\ 0 \\ B \\ C \end{bmatrix},$$

where B, C are the angles of rotation of the axis of the positioner table.

First, the coordinates of the start and end points are converted to the positioner coordinate system:

$$X_{0C} = [M_Y] \cdot (X_0 - (O_c - O)) = \begin{bmatrix} x_{0C} \\ y_{0C} \\ z_{0C} \end{bmatrix},$$

$$X_{1C} = [M_Y] \cdot (X_1 - (O_c - O)) = \begin{bmatrix} x_{1C} \\ y_{1C} \\ z_{1C} \end{bmatrix},$$

$$\text{where } [M_Y] = \begin{bmatrix} \cos(p) & 0 & -\sin(p) \\ 0 & 1 & 0 \\ \sin(p) & 0 & \cos(p) \end{bmatrix} \text{ is the transformation matrix when rotated by an angle } p$$

relative to the Y axis of the positioner coordinate system, to which the positioner is to be rotated if the tool axis does not coincide with the Z axis.

Then the possible radii of rotation of the positioner relative to the Z axis are determined:

$$R_0 = \sqrt{x_{0C}^2 + y_{0C}^2};$$

$$R_1 = \sqrt{x_{1C}^2 + y_{1C}^2}.$$

The relative error is calculated and compared with the specified accuracy:

$$\delta = \left| 1 - \frac{R_0}{R_1} \right| \leq \delta_{\text{req}},$$

if the condition is not met, then the table rotation is not required, otherwise the calculation continues.

The guiding orts i_0, j_0, i_1, j_1 are located in the positioner's coordinate system.

Guide orts of the start point:

$$L_0 = \sqrt{x_{0C}^2 + y_{0C}^2 + z_{0C}^2};$$

$$i_0 = \frac{x_{0C}}{L_0}; j_0 = \frac{y_{0C}}{L_0}.$$

Guide orts of the end point:

$$L_1 = \sqrt{x_{1C}^2 + y_{1C}^2 + z_{1C}^2};$$

$$i_1 = \frac{x_{1C}}{L_1}; j_1 = \frac{y_{1C}}{L_1}.$$

The rotation angles are determined.

For the start point:

if $i_0 \geq 0$ and $j_0 \geq 0$, then 1 and 4 quadrants,

$$r_{C0} = \arctan\left(\frac{j_0}{i_0}\right) + \pi;$$

if $i_0 < 0$ and $j_0 \geq 0$, then quadrant 2,

$$r_{C0} = \arctan\left(\frac{j_0}{i_0}\right) + 2\pi;$$

if $i_0 < 0$ and $j_0 < 0$, then quadrant 3,

$$r_{C0} = \arctan\left(\frac{j_0}{i_0}\right).$$

For the end point:

if $i_1 \geq 0$ and $j_1 \geq 0$, then 1 and 4 quadrants,

$$r_{C1} = \arctan\left(\frac{j_1}{i_1}\right) + \pi;$$

if $i_1 < 0$ and $j_1 \geq 0$, then quadrant 2,

$$r_{C1} = \arctan\left(\frac{j_1}{i_1}\right) + 2\pi;$$

if $i_1 < 0$ and $j_1 < 0$, then quadrant 3,

$$r_{C1} = \arctan\left(\frac{j_1}{i_1}\right).$$

Next, the coordinates of the end point are calculated when the positioner table is rotated by an angle r_C relative to the Z axis:

$$X_{0C1} = M_z \cdot X_{1C},$$

where M_z – is the transformation matrix when rotated by an angle $(r_{C1} - r_{C0})$ relative to the Z axis,

$$M_z = \begin{bmatrix} \cos(r_{C1} - r_{C0}) & \sin(r_{C1} - r_{C0}) & 0 \\ -\sin(r_{C1} - r_{C0}) & \cos(r_{C1} - r_{C0}) & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

Then the coordinates of the robot tool movements are calculated to compensate for the displacements when the positioner table is rotated.

$$X_{1C1} = [M_y]^{-1} \cdot X_{0C1} + \left(\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} - \begin{bmatrix} x_o \\ y_o \\ z_o \end{bmatrix} \right) = \begin{bmatrix} x_{1C1} \\ y_{1C1} \\ z_{1C1} \end{bmatrix},$$

where $[M_y]^{-1}$ – inverse transformation matrix for the tilt of the positioner table axis,

$$[M_y]^{-1} = \frac{[M_y]^T}{\det[M_y]}.$$

The angle of rotation of the positioner around the Z axis:

$$C_1 = C - \frac{r_{C1} - r_{C0}}{\pi} \cdot 180.$$

The angle J_1 can be found from the equation:

$$J_1 = \arctan\left(\frac{y_{1C1}}{x_{1C1}}\right),$$

where x_{1C1}, y_{1C1} – tool position coordinates.

The projections of the robot's arms on the X and Z axes give a system of equations:

$$\begin{cases} L_{35} \cos(J_3 - J_2) + L_{56} \cos(J_5 - J_3 + J_2) + \\ + L_{12} \cos \alpha + L_{23} \sin(J_2) - \frac{x_{1C1}}{\cos(J_1)} = 0; \\ L_{35} \sin(J_3 - J_2) - L_{56} \sin(J_5 - J_3 + J_2) + \\ + L_{12} \sin \alpha + L_{23} \cos(J_2) - z_{1C1} = 0. \end{cases}$$

Since the tool must have a vertical orientation to ensure the uniformity of the powder spray, the condition is introduced into the system of equations:

$$J_2 - J_3 - J_5 = 0.$$

To determine the angles J_2 и J_3 , methods for solving systems of nonlinear equations are used. In particular, the `fsolve` function was used in the application software package for solving technical problems of MATLAB R2012b. The angles J_4 и J_6 are assumed to be 0.

Thus, we get the coordinates of the recalculated points and the vector of the values of the rotation angles of the robot and positioner links:

$$J = [J_1, J_2, J_3, J_4, J_5, J_6, J_7, J_8].$$

Simulation Results

To confirm the correctness of the created mathematical model, a simulation of processing was performed in the academic version of the Fanuc ROBOGUIDE program. Next, a NC-program was generated with the positioner fixed.

In the MATLAB R2012b program, an executable module was created that reads the input text file, recalculates the coordinates, and outputs the output text file. Input and output file record structure:

X_0 – row 6 of the coordinates of the start point;

X_1 – row 6 of the coordinates of the end point;

O_t – coordinates of the tool's coordinate system relative to the world coordinate system;

O_p – coordinates of the positioner's coordinate system relative to the world coordinate system;

Next, the new NC-program is loaded back into Fanuc ROBOGUIDE, where the processing process is re-simulated in order to verify the correctness of the coordinate recalculation.

Testing of Deposition Modes

A research of the modes is based on the analysis of statistical data, which consider the macro-and microstructure of samples obtained via DMD. The DMD modes during the experiment are shown in Table 1.

Table 1. Modes of metal deposition of powder material

Mode parameter	Sample no.							
	1	2	3	4	5	6	7	8
	Value							
Laser radiation power P, W	1000	1200	1400	1600	1000	1200	1400	1600
Side step of deposition S, mm	1,6				1,4			
Powder consumption, g/s	31							
Deposition speed V, mm/min	1200							
Vertical deposition pitch t, mm	0,4							

The maximum size of single defects found in the sample material is shown in Table 2.

Table 2. Microhardness, type and maximum size of defects in samples

Sample no.	Maximum size of defect				Average microhardness value, HV _{0,1/5}
	Area of looseness, mm ²	Average pore diameter, mm	Maximum pore diameter, mm	Maximum junction length, mm	
1	0,0042	0,0475	0,055	0,13	317,5
2	0	0,03425	0,047	0,4	313
3	0,000174	0,0275	0,045	0,1	301
4	0,0064	0,02375	0,05	0,16	301,5
5	0	0,03125	0,035	0,08	293,5
6	0,0485	0,02225	0,04	0,086	305,5
7	0	0,019	0,03	0,17	282,5
8	0	0,03	0,03	0	272,5

Discussion

On this complex, the part can be processed in two ways: by simply moving the robot, which coordinates the position of the additive head, or by involving a positioner, which allows larger part of movements to be used, which allows the robot to reduce the number of movements and, thereby, reduce positioning errors.

Since the NC-programs for growing complex parts have a much larger volume compared to the NC-programs for palletizing, the robot controller is often unable to implement such programs. Therefore, further development in the field of optimization will go to reduce the volume of the NC-program by using loops and subprograms.

Conclusion

This article presents the results of the development of a mathematical model that considers the collaborative work of a six-axis robot manipulator and a two-axis positioner. In addition, the model takes into account the accuracy set by the user, which makes it possible to rationalize the recalculation of coordinates and adjust the degree of involvement of the positioner in the execution of the NC-program.

In the Fanuc ROBOGUIDE a robotic technological complex was modeled, on which the simulation of working out NC-programs took place. As a result of the recalculation of the coordinates, a significant proportion of the movements began to work out the positioner, while the

manipulator made movements of the tool, correcting deviations of the specified trajectory from the trajectory of movement along the arc of the positioner.

Analysis of technological modes of the DMD according to the generalized quality factor shows that the most preferable deposition modes are 5 and 8 modes.

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