TRAJECTORY CONTROL AND PARAMETER OPTIMIZATION OF PLASMA ROBOT GUN

by

Xiaohua CHEN[a*], Zhanshan WANG[a], and Kailei LIU[b]

[a] Department of Mechanical and Electrical Engineering,
Suzhou Vocational Institute of Industrial Technology, Suzhou, China
[b] School of Mechanical Engineering, Jiangsu Institute University of Technology, Changzhou, Chian

Original scientific paper
https://doi.org/10.2298/TSCI190602069C

A plasma robot model with redundant freedom is proposed for the shortage of flexibility in the complex working environment of plasma robot. The existence of redundant degrees of freedom leads to the complex motion characteristics of the plasma robot joints. The trajectory of the end of the spray gun is difficult to describe. Therefore, a trajectory optimization algorithm based on fitness function is proposed. In the plasma robot joint space, a parabolic linear fitting is adopted. The error between the actual trajectory and the desired trajectory is taken as fitness function. Genetic algorithm is applied to find the optimal solution for the parameters in trajectory planning. The orthogonal experimental model of the parameters of the plasma spray gun is set up. The optimum working parameters of the spray gun are obtained through the analysis and study of the power, atmospheric pressure and the distance of the gun. Finally, the rationality of the proposed method is proved by simulation and test.

Key words: *plasma robot; trajectory; fitness function; genetic algorithm*

Introduction

The plasma surface modification technology uses the plasma spray gun as the carrier, which does not require other low pressure vacuum equipment and high maintenance cost, and can simultaneously separate the production area and the application area. It is one of the hotspots in the current research field of plasma technology [1-3]. The surface of the plasma surface modification technology has a complex shape and a wide variety of types, and not all of the base surfaces need to be treated, such as large cavity walls, oral teeth, *etc.* [4]. Therefore, higher requirements are placed on the plasma spray gun in terms of flexibility and stability [5]. Although the traditional plasma surface modification robot can meet these requirements to a certain extent, it can handle some planes and simple curved surfaces, but it is difficult to meet the surface modification treatment requirements for complex shape and uneven material surface [6-9]. In view of the above problems, the flexibility and stability of the plasma robot can be increased by increasing the redundancy of the plasma robot, but the increase of the redundancy degree also increases the difficulty of controlling the motion trajectory of the plasma robot gun, so the plasma redundancy is the optimization of the robot's end motion trajectory and gun parameters has become a hot issue in plasma technology research [10-12].

* Corresponding author, e-mail: cxh05123@163.com

During the working of the plasma robot, the desired trajectory on the working base of the lance is known. Therefore, the trajectory optimization of the plasma robot is mainly the trajectory control of the joint space of the redundant robot, so that the trajectory of the end of the lance and the desired trajectory of the working base are Match. Due to the redundant nature of the plasma robot, there are numerous optimization inverse solutions in the joint space, which makes the movement characteristics of the plasma robot in the joint space very complicated, which makes the end of the gun movement path difficult to describe [13-16]. In this paper, some reference points are selected based on the desired trajectory, and the inverse kinematics is solved to obtain the inverse solution of joint space optimization. Secondly, the parabolic line fitting is performed in the joint space of the plasma robot. The points on the fitted curve are selected. The kinematics of the plasma robot is used to obtain the end motion trajectory, which is compared with the expected trajectory to define the error of the desired trajectory and the actual trajectory. The degree function is used to realize the trajectory optimization processing of the plasma robot by using the genetic algorithm. At the same time, the parameters of the spray gun are optimized on the basis of the optimized trajectory. The optimal parameter combination of the surface modification treatment of the spray gun is obtained by orthogonalization test and water drop angle test [17-21].

In this paper, based on the optimization requirements of the plasma trajectory and the parameters of the spray gun in the process of plasma redundant robots [22], the fitness function optimization algorithm and the orthogonalization test scheme are proposed, and the optimized trajectory of the end gun is optimized and optimized. The optimized combination of the parameters of the trajectory of the trajectory finally verified the rationality of the method used in this paper through simulation and experiment.

Plasma redundant robot model and test equipment

Figure 1 shows the working model of a plasma redundant robot. The spray gun has seven degrees of freedom (DOF) and the rotating shell has one DOF. It consists of a six-DOF manipulator, a single-DOF slide, and a rotating housing. The guide rail, the six-DOF manipulator and the plasma spray gun form a plasma redundant robot model, and the working base is on the single-DOF rotating shell. When the working radii of the working base is determined, the rotational freedom will be in a constrained state. Therefore, the trajectory of the plasma spray gun is mainly determined by a redundant robot with seven DOF.

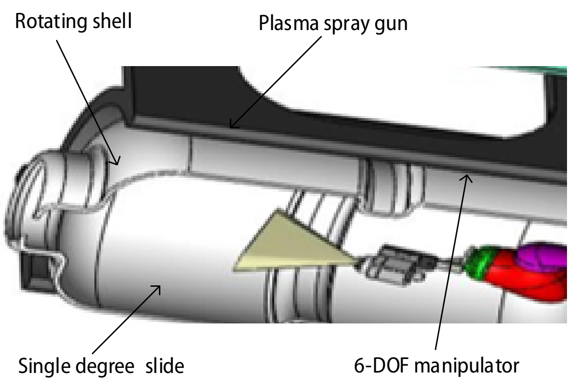

Figure 1. Model of plasma redundant robot

Trajectory optimization control

Establish a plasma redundant robot co-ordinate system as shown in fig. 2.

The kinematics positive solution of the plasma redundant robot is calculated in the co-ordinate system shown in fig. 2, and the end pose equation after fitting can be obtained:

$$\mathrm{T}_m = \begin{bmatrix} n_{xm} & o_{xm} & a_{xm} & p_{xm} \\ n_{ym} & o_{ym} & a_{ym} & p_{ym} \\ n_{zm} & o_{zm} & a_{zm} & p_{zm} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

At the same time, there is a desired pose on the desired trajectory at the end of the gun:

$$\mathrm{T}_q = \begin{bmatrix} n_{xq} & o_{xq} & a_{xq} & p_{xq} \\ n_{yq} & o_{yq} & a_{yq} & p_{yq} \\ n_{zq} & o_{zq} & a_{zq} & p_{zq} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

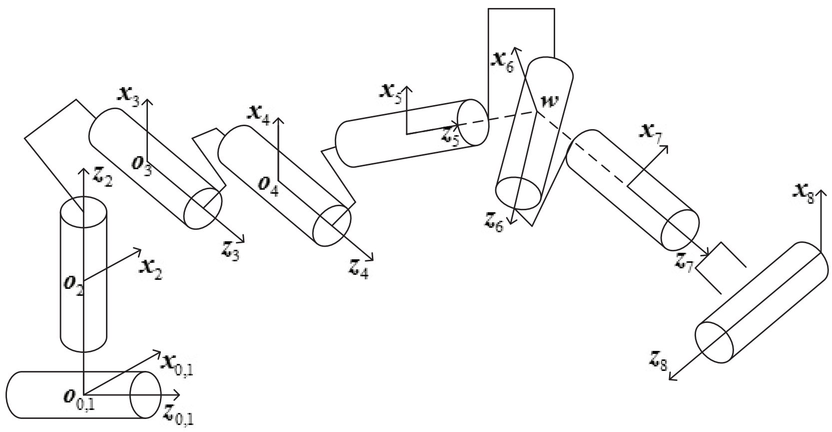

Figure 2. Plasma redundant robot co-ordinate system

The difference between the desired pose and the fitted pose is defined as the evaluation function. The smaller the difference between the two, the higher the fitness, which means that the fitting of the joint space of the plasma robot is more reasonable. In this paper, the position vector and attitude vector in the pose matrix are used as the target, and the fitness function constructed by the linear stretch evaluation function is used to study the error between the desired pose and the fitted pose.

$$F = \frac{(c-1)fit_{\text{avg}}}{fit_{\max} - fit_{\text{avg}}} fit(\ddot{\theta}) + \frac{fit_{\max} - c fit_{\text{avg}}}{fit_{\max} - fit_{\text{avg}}} fit_{\text{avg}} \tag{3}$$

where F is a fitness function constructed by a linear tensile evaluation function, $fit(\ddot{\theta})$ – an evaluation function that reflects the pose deviation, as shown in eq. (4). The $fit_{\max}$ represents the maximum value of $fit(\ddot{\theta})$, fit_{avg} represents the average value of $fit(\ddot{\theta})$, c indicates the optimal number of individual copies, the value is determined according to the size of the group, in this article $c = 2$. According to the characteristics of the linear stretching algorithm, the evaluation function $fit(\ddot{\theta})$ must be non-negative, otherwise the correlation transformation needs to be performed, and the evaluation function $fit(\ddot{\theta})$ defined in this paper can guarantee non-negativeness, so the fitness function defined in this paper is suitable.

$$fit(\ddot{\theta}) = \sum_{i=1}^{2} \sqrt{\left\|(p_q - p_m)\right\|^2 + \left\|(n_q - n_m)\right\|^2 + \left\|(o_q - o_m)\right\|^2 + \left\|(a_q - a_m)\right\|^2} \tag{4}$$

Since the requirements of the trajectory control of the plasma robot are to achieve basic control functions for motion such as speed and acceleration. In order to achieve continuous control of joint variables such as displacement, velocity and acceleration, the detection sensor is continuously measured with relevant parameters in the robot control system, and real-time feedback constitutes a closed-loop servo control system.

This control method requires the plasma redundant robot end gun to complete the task within a certain control accuracy requirement according to the predetermined trajectory, speed and acceleration. This requires that the fitness function needs to converge rapidly as the number of iterations increases. The simulation diagram is shown in fig. 3. As the number of iterations increases, the fitness function will be more accurate.

The joint velocity and acceleration of the medium ion robot are coupled to the fitness function. As the number of iterations increases, the fitness function begins to converge rapidly, which proves that the joint velocity and acceleration meet the trajectory control requirements of the plasma robot.

At the same time, in order to verify the correctness of the obtained simulation trajectory, this paper takes the S-shaped inlet of a certain type of aircraft as an example to simulate the approximation degree of the fitted trajectory and the desired trajectory. The simulation trajectory of the end is formed by surface fitting. As shown in fig. 4, the simulation results prove the simulated trajectory and the desired trajectory. Highly consistent, so it proves the correctness of the method used in this paper.

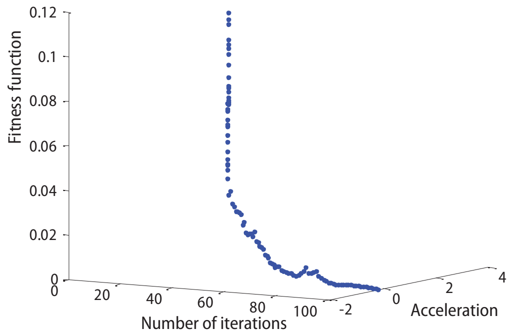

Figure 3. Iterative graph of fitness function

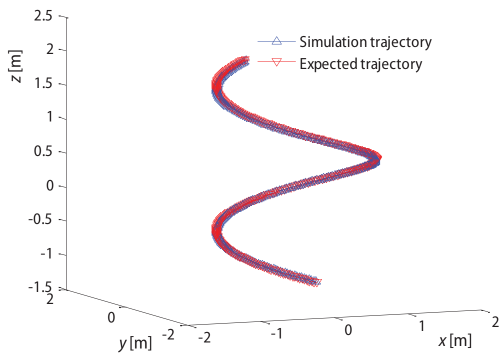

Figure 4. Simulation verification of aircraft S inlet

For plasma redundant robots, the stability of joint space motion and the accuracy of end effector motion have a large impact on surface modification quality and efficiency. In this paper, the trajectory planning is carried out in the joint space of the plasma robot to ensure the stability of the joint operation of the plasma robot. At the same time, the genetic algorithm is used to optimize the parameters in the trajectory planning, so that the joint space is positively resolved to the end Cartesian co-ordinate system, the characteristic time of the plasma robot. The difference between the trajectory on the point and the desired trajectory on the base is small. It can be seen from the simulation results that the end movement of the plasma redundant robot is very consistent with the requirements of the desired trajectory.

Optimization of spray gun parameters

In this paper, under the premise that the trajectory control accuracy of the plasma redundant robot meets the requirements, the power supply, gas pressure and spray gun distance of the plasma spray gun are optimized. The indicator for measuring the quality of surface modification is the water drop angle test. The smaller the angle measured, the better the quality of the plasma surface modification. Based on the test of the inlet surface, the water drop angle tester is used to detect the water droplet angle between the liquid and the solid. The wettability between the liquid and the solid can be detected by this method. The better the wettability, the smaller the water drop angle and the infiltration. The worse the sex, the larger the water droplet angle.

Taking the surface of the air intake of the aircraft as an example, the orthogonal test method is designed to study the influence of the main process parameters on the water drop angle test. Table 1 shows the variation range of the spray gun parameters.

The orthogonal test was designed according to the range of variation of each parameter as shown in tab. 2. The water drop angles measured in the test are shown in tab. 3.

It can be seen that when the pressure is 0.3 MPa, the distance is 12 mm, and the power supply power is between 1700 W and 1900 W, the water drop angle takes a small value. In order to obtain a set of effective parameter values, the orthogonalization test analysis is further performed on the power supply power, as shown in tabs. 4 and 5, respectively. The smaller the droplet angle test value, the better the selected parameter value. The minimum value of the droplet angle test is the optimal parameter selected.

Droplet angle test is carried out by special instruments. The principle is that the smaller the value of water drop angle, the more optimized the selected parameters are. At this time, the minimum value of the water drop angle

Table 1. Range of parameter variation of spray gun

Gun parameters	Variable	Range
Power supply [W]	x_1	1000-2000
Gas pressure [MPa]	x_2	0.2-0.4
Gun distance [mm]	x_3	8-16

Table 2. Orthogonal design test

Numbering	Power supply [W]	Gas pressure [MPa]	Gun distance [mm]
1	900	0.2	12
2	900	0.3	8
3	900	0.4	16
4	1150	0.3	8
5	1150	0.4	16
6	1150	0.2	12
7	1400	0.4	16
8	1400	0.2	12
9	1400	0.3	8
10	1650	0.2	16
11	1650	0.3	12
12	1650	0.4	8
13	2000	0.3	12
14	2000	0.4	8
15	2000	0.2	16

Table 3. Water drop angle test value

Numbering	Water drop angle	Numbering	Water drop angle	Numbering	Water drop angle
1	48.2	6	49.0	11	10.5
2	46.7	7	42.0	12	18.4
3	43.6	8	42.9	13	19.8
4	44.8	9	37.0	14	25.4
5	46.9	10	29.8	15	29.5

Table 4. Power supply power optimization test

Numbering	Power supply [W]	Gas pressure [MPa]	Gun distance [mm]
16	1700	0.3	12
17	1725	0.3	12
18	1750	0.3	12
19	1775	0.3	12
20	1800	0.3	12
21	1825	0.3	12
22	1850	0.3	12
23	1875	0.3	12
24	1900	0.3	12

Table 5. Numerical test of water drop angle optimization

Numbering	Water drop angle
16	20.5
17	16.8
18	13.7
19	9.5
20	8.0
21	9.5
22	10.0
23	15.5
24	20.4

measured is 8.0°. At this time, a set of optimized plasma spray gun combination parameters are obtained. The power supply power is 1825 W, the atmospheric pressure is 0.3 MPa, and the spray gun distance is 12 mm. The water droplet angle optimization test chart is shown in fig. 5.

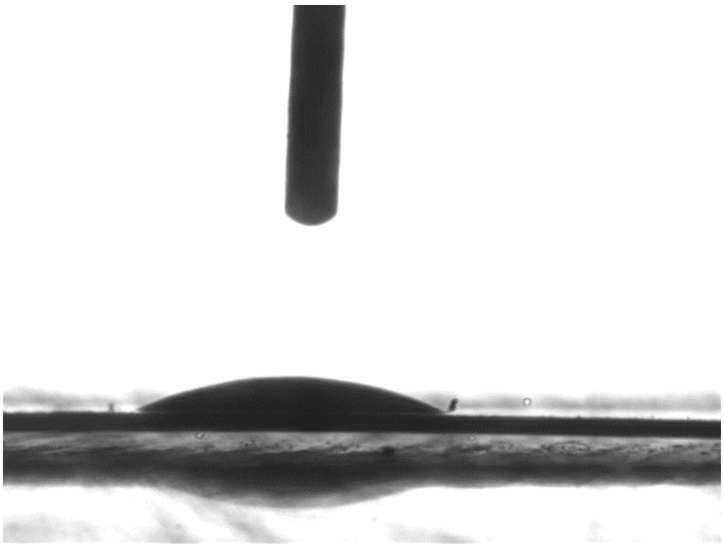

Figure 5. Diagram of water drop angle optimization test

Conclusion

Firstly, a plasma robot model with redundant DOF is established, which increases the flexibility of the plasma surface modification task. Secondly, the surface modification trajectory of the plasma robot is optimized, which makes the surface modification work have higher processing precision. Finally, it is orthogonal. The optimized test parameters of the plasma spray gun were obtained by the test, and the correctness of the conclusions obtained in this paper was verified by the water drop angle test.

Competing interests

The authors declare that they have no competing interests regarding the publication of this paper.

Acknowledgment

This work is supported by National Natural Science Foundation of China Fund Funding (51805228); Natural Science Research Projects of Jiangsu Higher Education Institutions (19KJD460006).

References

[1] Madoliat, R., *et al.,* Acoustic Model Order Reduction for the Lowest Condition Number in Inverse Method, *AIP Advances, 7* (2017), 6, pp. 139-152
[2] Goncalves, V. M., *et al.,* Parsimonious Kinematic Control of Highly Redundant Robots, *IEEE Robotics and Automation Letters, 1* (2016), 1, pp. 65-72
[3] Zheng, F. Y., *et al.,* The Mathematical Model and Mechanical Properties of Variable Center Distance Gears Based on Screw Theory (in Chinese), *Mechanism and Machine Theory 101* (2016), July, pp. 116-139
[4] Dai, J. S., Historical Relation between Mechanisms and Screw Theory and the Development of Finite Displacement Screws (in Chinese), *Journal of Mechanical Engineering, 51* (2015), 13, pp. 13-26
[5] Yang, A., *et al.,* Situational Awareness System in the Smart Campus, *IEEE Access, 6* (2018), Oct., pp. 63976-63986
[6] Chen, W. C., *et al.,* Design of Redundant Robot Painting System for Long Non-regular Duct, *Industrial Robot, 43* (2016), 1, pp. 58-64
[7] Sommer, H., *et al.,* Automatic Differentiation on Differentiable Manifolds as a Tool for Robotics, *Springer Tracts in Advanced Robotics, 114* (2016), Apr., pp. 505-520
[8] Omranpour, H., Shiry, G. S., Manifold Based Map Representation for Mobile Robot Using Euclidean Data Difference Dimension Reduction, *Engineering Applications of Artificial Intelligence, 45* (2015), Oct., pp. 234-245
[9] Wu, J., *et al.,* Differential Diagnosis Model of Hypocellular Myelodysplastic Syndrome and Aplastic Anemia Based on the Medical Big Data Platform, *Complexity, 2018* (2018), ID 4824350
[10] Jin, W., *et al.,* Bounded Perturbation Resilience of Projected Scaled Gradient Method, *Computational Optimization and Applications, 63* (2016), 2, pp. 365-392
[11] Zhao, J. W., *et al.,* Self-Motion Manifolds of a 7-DOF Redundant Manipulator (in Chinese), *Journal of Mechanical Engineering, 43* (2007), 9, pp. 132-137
[12] Lara, M., Complex Variables Approach to the Short-axis-Mode Rotation of a Rigid Body, *Applied Mathematics & Nonlinear Sciences, 3* (2018), 2, pp. 537-552
[13] Teli, M. D., *et al.,* Application of Atmospheric Pressure Plasma Technology on Textile, *Journal of the Textile Association, 75* (2015), 6, pp. 422-428
[14] Bartis, E. A. J., *et al.,* On the Interaction of Cold Atmospheric Pressure Plasma with Surfaces of Bio-molecules and Model Polymers, *Plasma Chemistry and Plasma Processing, 36* (2016), 1, pp. 121-149
[15] Abu-Dakka, F. J., *et al.,* A Direct Approach to Solving Trajectory Planning Problems Using Genetic Algorithms with Dynamics Considerations in Complex Environments, *Robotica, 33* (2015), 3, pp. 669-683
[16] Yin, S. Y., *et al.,* An Adaboost Based Face Detection System Using Parallel Configurable Architecture with Optimized Computation, *IEEE Systems Journal, 11* (2017), 1, pp. 260-271
[17] Peng, W. X., *et al.,* Hydrogen and Syngas Production by Catalytic Biomass Gasification, *Energy Conversion and Management, 135* (2017), Mar., pp. 270-273
[18] Vajravelu, K., *et al.,* Effects of Second-Order Slip and Drag Reduction in Boundary Layer Flows, *Applied Mathematics & Nonlinear Sciences, 3* (2018), 1, pp. 291-302
[19] Nassim, A., Abderrahmane, A., Boosting Scores Fusion Approach Using Front-end Diversity and Adaboost Algorithm, for Speaker Verification, *Computers and Electrical Engineering, 9* (2017), 2, pp. 1-15
[20] Bekishev, A. T., Korobochkin, Y. B., Numerical Method of Estimating the Maximal Likelihood of a Smooth Parametric Manifold, *Automation and Remote Control, 77* (2016), 7, pp. 1180-1194
[21] Kokurin, Mikhali, Y., Stable Gradient Projection Method for Nonlinear Conditionally Well-Posed Inverse Problems, *Journal of Inverse and Ill-Posed Problems, 24* (2015), 3, pp. 323-332
[22] Zhao, B., Target Monitoring on Face Detection Based on Improved Adaboost Algorithm, *Lecture Notes in Electrical Engineering, 309* (2014), Jan., pp. 373-377

Paper submitted: June 2, 2019
Paper revised: September 9, 2019
Paper accepted: September 12, 2019