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Investigation on the Trajectory Planning of Spray Gun of Spray Robot and Its Spraying Effect

Hong Min and Shuai Li*[1]

College of Mechanical and Electrical Engineering, Zaozhuang University, Zaozhuang, China;
**lishuai66@163.com*

Abstract

The industrial robot plays a very important role in stabilizing and improving the quality of products, production efficiency, working conditions and the rapid upgrading of products. It is often composed of a mechanical body, control device, driving system and detection and sensing device, and can be used in three-dimensional space to complete integration of automatic production and processing equipment. Spraying robot is one of the most important advanced coating production and processing equipment. It has the advantages of considerable flexibility and wide working scope, high spraying quality and material utilization efficiency. Due to the increasing competition for the market share, it should minimize the cost continually to accomplish the producing process. For the spraying process, how to optimize the trajectory of the spray gun and the spray parameters are the key factors to reduce the material consumption and improve the efficiency. In this paper, the spray gun trajectory and spraying effect are studied, and the experimental results show that the spray trajectory and spray effect are available. The results can also be used in other fields to get better performance.

Keywords: *trajectory planning, spray gun, spray robot, spraying effect*

1. Introduction

The industrial robot [1-2] is composed of a mechanical body, control device, driving system and detection and sensing device. It is a humanoid operation, automatic control, repeatable programming, and can be used in three-dimensional space to complete a variety of mechanical and electrical integration of automatic production and processing equipment. It plays a very important role in stabilizing and improving the quality of products, the production efficiency, the working conditions and the rapid upgrading of products. Robot technology [3-5] is the combination of computer control theory, multi discipline mechanism, information and sensor technology, artificial intelligence, bionics. It is extremely active and can be widely used in various fields.

Spraying robot [6-10] is one of the most important advanced coating production [11] and processing equipment. Its advantages can be shown in following several aspects: (1) the large flexibility and wide working scope; (2) improving the spraying quality, spraying efficiency and material utilization; (3) easy operation and maintenance, and off-line programming; (4) the high utilization rate. Due to the programming ability, the spraying robot is applied to all kinds of situations, such as the automotive coating industry [12-13] and aerospace coating industry [14-15]. In the automotive coating industry, the automobile front cover, bumper, luggage, engine parts and other components can be sprayed. In the aerospace coating industry, the special equipment surface coating can be realized according to the different requirements of the material. Due to the wide

[1] Corresponding Author

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application range and work in the case of dangerous and environment, spraying robot has been widely used.

In the process of spraying operation, the mechanical arm of the spraying robot is around the surface of the workpiece to complete the spiral motion. With selection of the appropriate trajectory [16-20] and parameters in the spray process, production efficiency can be significantly improved. The spraying effect of spraying robot is related to the surface shape of the workpiece, the parameters of the spray gun, and way of the trajectory planning and other parameters. For products, such as the surface of the rocket, automobile, furniture and other products, the spraying effect on its surface will directly affect the quality of the product. Product surface finish depends on the surface of the coating uniformity to a certain extent. If the surface coating uniformity is not high, bumps of the solvent will appear, which can cause production with the unsmooth surface or product damage due to the surface heat stress concentration caused by the ununiformed heat effect. Meanwhile, coating with bigger thickness is prone to rupture in the use of the process, which can result in the waste of spraying material. With the rapid development of CAD/CAM technology [21-23] and the improvement of product quality requirements, optimization of the spray gun trajectory is with increasing interest. In order to meet the new requirements of spraying operation and the production target with high efficiency and the low cost, research on the new model and the optimization method of the spray gun is a hot spot.

Aiming at the path design and optimization problem [24] of spray gun of spray robot for the plane, the minimum variance between the coating thickness of the arbitrary points on the surface and the ideal coating thickness on the whole surface is proposed as the objective function. Meanwhile, the influence of the spray gun trajectory, velocity curve, gun mode and spray opening angle on the spraying effect should be discussed. Based on this work, the effectiveness of the numerical method to solve the optimization trajectory is studied after adding the constraint conditions. For the thermal spraying robot [25-26] for rotating object, the coating accumulation model and optimization of the trajectory of the robot have been studied, and a simple mathematical model is used to simulate the accumulation of coating in different spraying distance and direction, and an iterative method is put forward to optimize the trajectory of the spraying robot.

For the trajectory planning of spray painting robot on the curved surface, off-line CCD camera method is used to obtain the CAD data of the workpiece. Based on this, the design method of the 3D trajectory of the spray gun spray robot is discussed, and the related principles of the 3D space path design of the spraying robot spray gun are proposed. The key factors of distance between two spray paths are pointed out. In addition, the dynamic performance of the spraying robot is also used as a breakthrough point for the optimization of the spray gun trajectory to reduce the paint waste and motor load. In the premise of quality ensuring of the coating, various parameters of the spraying process are optimized.

On the problem of the path design with the surface of the workpiece, the surface CAD model based framework of automatic spray gun trajectory generation system is proposed, which can be widely applied to other similar fields. The practicability of the system has been improved. Meanwhile, under the framework of the automatic generation system of gun trajectory, the multi-objective optimization problem of spraying effect is also studied, and a trajectory optimization method is presented to optimize the spraying time and coating uniformity, and the combination optimization problem of spray gun trajectory on complex surface is firstly proposed.

The spraying problem of complex curved surface can be optimized by the method of surface patch. By establishing the optimization objective function with constraints, CAD model of the surface is processed with triangulation. Combined with the coating thickness allowance error and the topology relationships between the triangles, the surface is sliced and defined that at least one boundary of the latter pieces containing the boundary information. This can help the planning of the average normal vector of the latter pieces as the jet direction so as to complete the complex surface of the work piece. In addition, the mathematical model of air spray gun on the free surface is established after the coating accumulation rate model is established.

For the path planning method of spraying robot on complex free surface, the objective function is established to optimize the path model and spray gun direction, which lays a theoretical foundation for the research of spray robot trajectory optimization on complex free surface. Continuous path can be obtained by the optimization method for path interval based on the space frequency domain method. This method can meet the quality requirements of the surface coating thickness. In view of the characteristics of the vehicle's complex vehicle door surface, the mathematical model of the spray gun is established based on the injection mechanism. The accurate mathematical model of the gun has been proposed and the influence of the geometric parameters of the complex free surface on the spray trajectory optimization is analyzed. According to the curvature change of surface, the surface can be meshed into a series of simple surfaces. On these surfaces, the properties of geodesic in the differential geometry is used to select the proper curve. Here, the Gauss-Bonnet theorem will give the theoretical support. After the determination of the proper curve, the offset curve can be obtained according to the distance from the curve and the proper curve. For the optimization of the offset distance between the offset curve and the proper curve, based on difference between the mean curvature and the Gauss curvature, the simple surfaces can be classified into planar, spherical and extrusion plane to discuss the optimal scheme. These curves generated by the method is the trajectory of the spray gun on the simple surface, and finally, the optimal objective function is established and solved.

Besides, the optimization problem of spray gun trajectory at the junction of patches is also very important. According to the establishment of the optimization objective function, spray rate and track spacing on the spray gun trajectory is solved. The simulation experiments show that the position relationship between spray gun trajectory and patches has great influence on the coating uniformity.

Due to the complexity of the surface of the workpiece, the trajectory design and optimization of the spray gun is still in continuous research, and certain results had been achieved. However, there is still room for improvement. In this paper, trajectory design of the spray gun and the effect of spraying process are studied, which can provide reference for the optimization of the spraying process. The reminder of the paper is organized as following: (1) the trajectory design is introduced in Section 2; (2) the mesh method for complex surface is introduced in Section 3; (3) the verification is described in Section 4; and (4) the conclusion is shown in Section 5.

2. Trajectory Design

According to the principle of the path planning of the nozzle and the characteristic of the rotating curved surface of the workpiece, the spiral spraying tool path is adopted, as shown in Figure. 1. The spiral nozzle has good continuity, which can keep the direction of the head of the nozzle and avoid too much other wasted motion. It is helpful to ensure the quality of surface spraying. The spray head path can be fed at a given speed along the curved surface of the workpiece through driving the spraying tool and the workpiece with low speed. The row spacing of Δl is determined by the feed rate v_f of the spray head. The relation between them can be described as:

$$\Delta l = \frac{2\pi v_f}{v_w} \tag{1}$$

Where, the feed speed v_f is composed of the radial speed v_t, workpiece lifting speed v_z, which means:

$$v_f = v_x + v_z \tag{2}$$

It can be seen that the quality of spraying can be improved according to decrease the row spacing with improving the workpiece speed v_w when processing efficiency keeps constant.

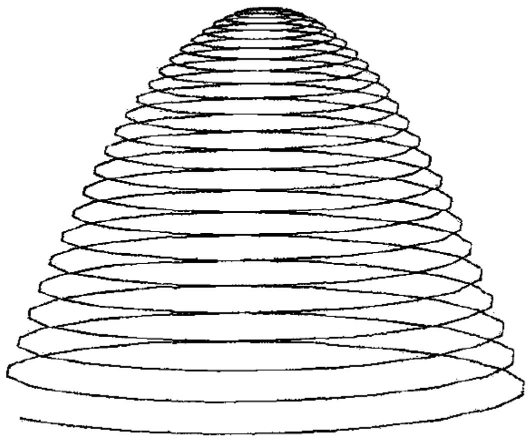

Figure 1. The Spiral Spraying Tool Path

Figure 2 shows the trajectory of spraying nozzle when spraying the complex surface. The dotted line represents the complex surface, and the solid line shows the path of the nozzle. When spraying the complex surface, the surface can be directly rotated to realize the spiral nozzle trajectory. When the spraying nozzle crosses the vacant area (area without spraying process), the motion of the complex surface will change from rotating the whole circle to reciprocate with a certain angle, and vacant area will not be sprayed. For other parts of the body, complex curved surface still needs rotating spiral spraying tool path.

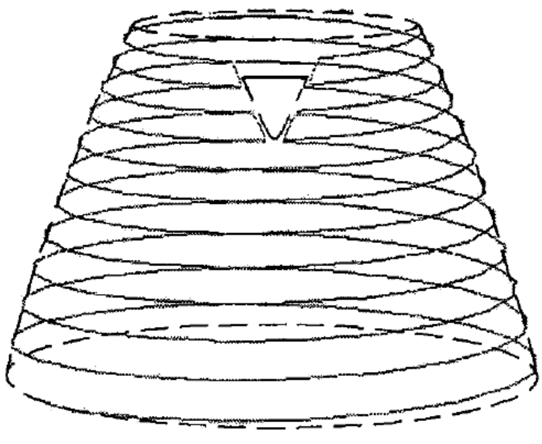

Figure 2. Complex Surface and Certain Area without Spraying Process

Position data of the spray gun are composed of radial direction (X axis) displacement Δx_i, workpiece ascending and descending (Z axis) displacement Δz_i, oscillation angle of the workpiece in the X-Z plane, and interpolation period T_i. A section of path of the spray gun is shown in Figure 3. In the spraying process, the spray gun will move along the generatrix with certain speed, and the workpiece moves around Z axis with rotating speed. Then, it will form the spiral tool path.

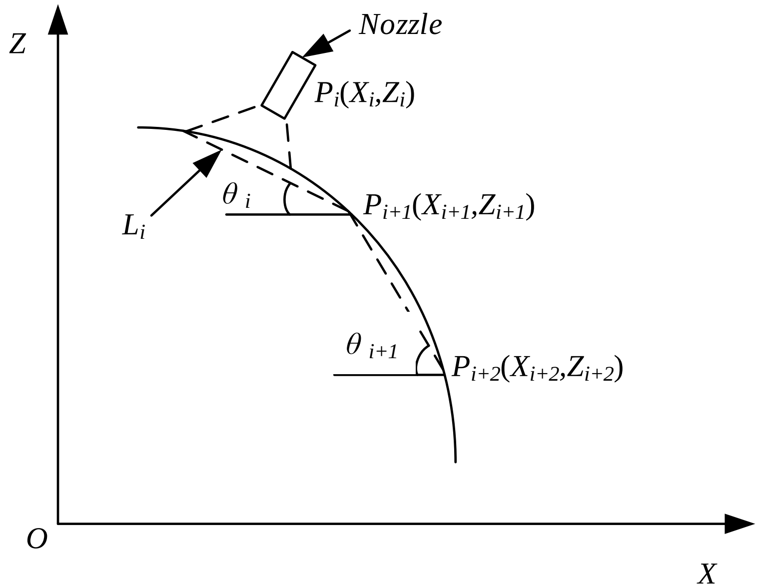

Figure 3. Position of the Nozzle

In the period T_i, if the nozzle moves the length of L_i, the corresponding area can be expressed as the following:

$$S_i = \frac{\pi}{\cos\theta_i}(x_{i+1}^2 - x^2) = \pi L_i(x_{i+1} + x_i) \tag{3}$$

Then the spray rate will be:

$$k_v = \frac{S_i}{T_i} \tag{4}$$

The position of the nozzle will be:

$$\begin{pmatrix} \Delta x_i \\ \Delta z_i \\ \Delta\theta_i \\ T_i \end{pmatrix} = \begin{pmatrix} x_{i+1} - x_i \\ z_{i+1} - z_i \\ \theta_{i+1} - \theta_i \\ \pi L_i(x_{i+1} + x_i)/k_v \end{pmatrix} \tag{5}$$

The feed rate at each direction can be calculated by:

$$\begin{pmatrix} v_{x_i} \\ v_{z_i} \\ \omega_{\theta_i} \end{pmatrix} = \begin{pmatrix} \dfrac{\Delta x_i}{T_i} \\ \dfrac{\Delta z_i}{T_i} \\ \dfrac{\Delta \theta_i}{T_i} \end{pmatrix} \quad (6)$$

The coating thickness increases with the decreasing of the spacing between two neighbouring spray gun paths. Therefore, the coating thickness can be adjusted by the spacing between neighbouring pathes of the spray gun. The spacing is related to the workpiece rotating speed. If set the spacing as ΔL_i, the relationship between ω_i and L_i can be described as:

$$\omega_i = \frac{2\pi L_i}{\Delta L_i T_i} \quad (7)$$

According to the description, The spray rate can be used to control the speed of each axis. Here, in order to prevent inhomogeneous coating thickness caused by the nozzle shape changing, rotating nozzle, which utilizing the reverse thrust of the paint sprayed, is used to improve the uniformity of the paint.

3. The Slicing Method for Complex Surface

In the actual production process, most of the product shape are complex free-form surface. A schematic view of a free curve surface is shown in Figure. 4. It is difficult to directly write mathematical expressions for the surface. Therefore, research on robot trajectory optimization method has great significance on the complex free surface spraying. But due to the complexity of the character of the free surface geometry and spraying effect affected by many factors, gun trajectory directly optimized on the free surface has a certain degree of difficulty. Especially when the free surface appeared with large curvature, number of patches generated in the region will be more than other regions according to the existing spray theory. Meanwhile, patch size and shape will be small and narrow, which goes against the next step of trajectory optimization.

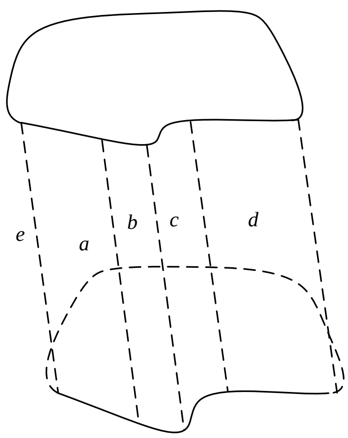

Figure 4. Schematic View of Free Surface Slices

In this paper, an apropriate method is developed for the free surface slicing. For a large free surface, it contains both small curvature part and larger curvature part. In order to make the spraying effect on the two parts of the surface keep equally well, it is necessary to divide the surface into two parts separately. From the pre-set coating thickness error and airbrush spray radius, large free surface is firstly planning into small curvature and large curvature group, and then different slicing algorithm for different group is given. The detailed algorithm is described as the following:

(1) Large free surface is divided into triangular parts by topology algorithm, and set the coating thickness error range, spraying radius and the slice regularity coefficient.

(2) According to the principle of geometric topology, connect the triangles to form a larger slice. If the geometry parameters of larger slice generated is with larger curvature, the next step will be executed. Otherwise, step 4 will be executed. The curvature can be set with a certain value.

(3) Extract the curved surface with larger curvature, the triangulation of the surface will be restored to the original state. The restored surface will be discreted by the isoparametric method, and the discreted surfaces will be fitted by special methods, such as least square method.

(4) Extract the curved surface with smaller curvature, the processed surface can be seen as a plane or a natural curve surface.

It can be seen from the above algorithm, before the spray trajectory optimization, a large free surface is sliced into a combination of a number of approximately plane and several approximate natural curve surfaces. The slicing of the complex surface is completed.

4. Verification

For an ideal spray gun trajectory model, it should have good adaptability to all kinds of curved surface with spraying uniformity. In order to verify the validity of spiral spray gun trajectory, the simulation experiment has been developed. In the simulation, spray parameters are set as following: (1) the amount of paint is set as 225 ml/s; (2) spray cone angle theta is set as 0 ˚; (3) coating utilization coefficient is set as 0.83; (4) mean spraying time of points is set as 0.4s.

The simulation results are shown from Figure.5 to Figure. 8.

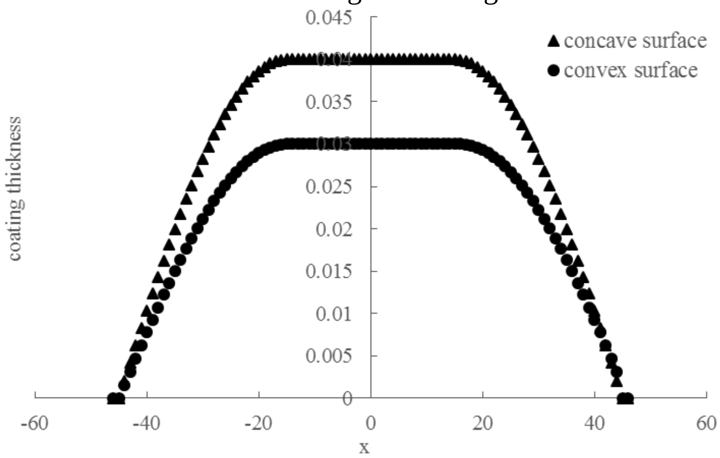

Figure 5. Initial Coating Thickness on Concave Circular Arc Surface without Time Modification

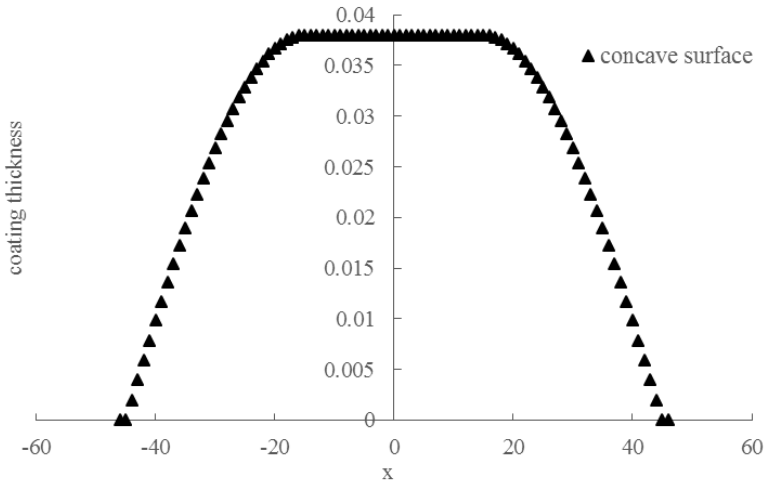

Figure 6. Coating Thickness on Concave Circular Arc Surface with Time Modification

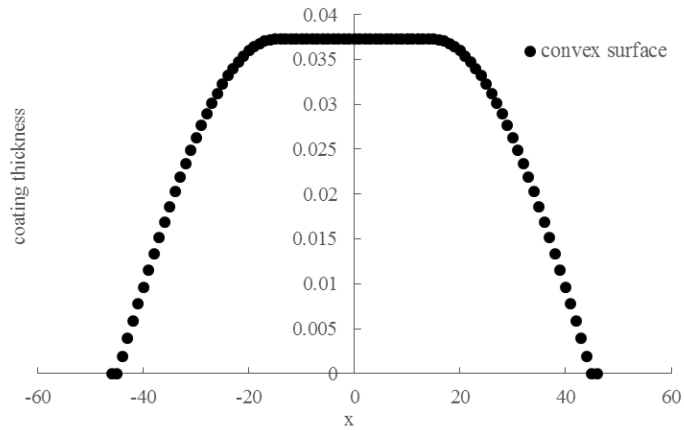

Figure 7. Coating Thickness on Convex Circular Arc Surface with Time Modification

If the spraying time is equal for the two workpiece surfaces, two different coating thicknesses will appear, as shown in Figure. 5. In the figure, the upper line is the thickness distribution curve of a concave circular arc surface, while the lower line is the thickness distribution curve of a convex circular arc surface. When the spraying time is modified, coating thickness of the two kinds of circular arc surfaces will be almost the same just under simple conditions without modification of the nozzle path. The comparative study indicated that the spray gun path model can better describe the actual injection pattern, and it also has a certain degree of adaptability to the curved surfaces. This experiment also can verify the feasibility of the modeling method.

In order to verify the surface slicing method, a curved surface has been used as the study object, as shown in Figure. 4. With the spray method, the distribution of coating thickness along the X axis is shown in Figure. 8. It can be seen that the thickness is almost the same. Even at the surface part with larger curvature, the thickness still keeps with little difference.

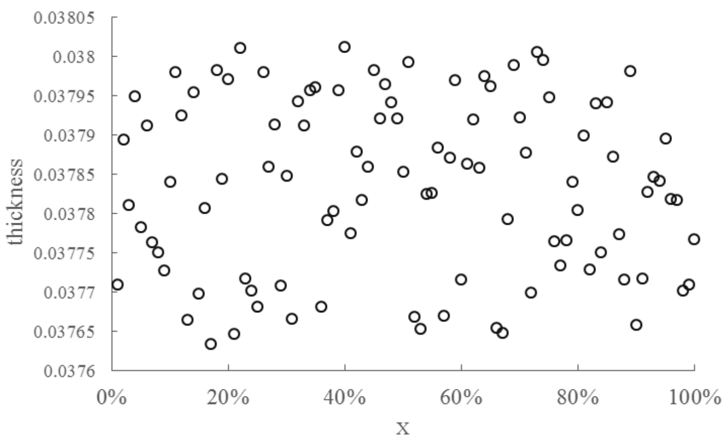

Figure 8. Coating Thickness on Convex Circular Arc Surface with Time Modification

5. Conclusion

As one of the most important kinds of the industrial robot, spraying robot is an advanced coating equipment. It has the advantages of considerable flexibility and wide working scope, high spraying quality and material utilization efficiency. In the process of spraying process, the mechanical arm of the spraying robot is around the surface of the workpiece. With selection of the appropriate trajectory and parameters in the spray process, production efficiency can be significantly improved. Therefore, how to plan the trajectory has great meaning to the energy and material saving and the efficiency improving.

In this paper, the spray gun trajectory and spraying effect are studied. The concave and convex surfaces are adopted as the study objects. In the simulation, when the spraying time is equal for the two workpiece surfaces, two different coating thicknesses will appear. The thickness on the concave surface will be bigger and that on the convex surface will be thinner. When the spraying time is modified, coating thickness of the two kinds of circular arc surfaces will be almost the same just under simple conditions without modification of the nozzle path. The comparative study indicated that the spray gun path model can better describe the actual injection pattern, and it also has a certain degree of adaptability to the curved surfaces. The experimental results show that the spray trajectory and spray effect is available. Meanwhile, the slicing method for complex surface also gives a better performance. The method can also be used in other fields to get better performance.

References

[1] P. Liu and Q.-M. Li, "Modeling inverse solution of mechanism configuration for delta industrial robot", Design, Manufacturing and Mechatronics, **(2015),** pp. 385-391.

[2] M. Palpacelli, "Static performance improvement of an industrial robot by means of a cable-driven redundantly actuated system", Robotics and Computer-Integrated Manufacturing, **(2016)**, pp.1-8.

[3] M. R .Pedersen, L. Nalpantidis, R. S. Andersen, C. Schou, S. Bogh, V. Kruger and O. Madsen, "Robot skills for manufacturing: From concept to industrial deployment", Robotics and Computer-Integrated Manufacturing, **(2016)**, pp.282-291.

[4] S. Wanfeng, C. Xiangang, M. Hongwei, Z. Hailong and W. Pengkang, "Kinect-Based Vision System of Mine Rescue Robot for Low Illuminous Environment", Journal of Sensors, 8252015 (9 pp.)-8252015 (9 pp.), **(2016).**

[5] L. Shi, X. Tian and C. Zhang, "Automatic programming for industrial robot to weld intersecting pipes", International Journal of Advanced Manufacturing Technology, no. 9-12, **(2015)**, pp. 2099-2107.

[6] Z. Cai, H. Liang, S. Quan, S. Deng, C. Zeng and F. Zhang, "Computer-Aided Robot Trajectory Auto-generation Strategy in Thermal Spraying", Journal of Thermal Spray Technology, no. 7, **(2015),** pp. 1235-1245.

[7] D. Hegels, T. Wiederkehr and H. Mueller, "Simulation based iterative post-optimization of paths of robot guided thermal spraying", Robotics and Computer-Integrated Manufacturing, **(2015),** pp.1-15.
[8] M. Al- Mamury, N. Manivannan, H. Al-Raweshidy and W. Balachandran, "Mobile robot based electrostatic spray system for controlling pests on cotton plants in Iraq, Matthews", J. editor, Electrostatics, **(2015)**
[9] Y. Chen, X. Ji and W. Tang, "Pipeline spraying robot: structure and pose adjustment", Journal of Beijing University of Aeronautics and Astronautics, no. 2, **(2015)**, pp. 209-15.
[10] S.-C. Huang, P. Li and W-X Zhao, "Research on Control System of Multi-rotor UAV for Pesticide Spraying", Automation & Instrumentation, no.5, **(2015)** pp. 9-12.
[11] S.-Y. Chen, T. Mochizuki, Y. Abe, M. Toba, Y. Yoshimura, P. Somwongsa and S. Lao-ubol, "Carbonaceous Ti-incorporated SBA-15 with enhanced activity and durability for high-quality biodiesel production: Synthesis and utilization of the P123 template as carbon source. Applied Catalysis B-Environmental", **(2016)**, pp. 800-809.
[12] D. M. Ceballos, C. Reeb-Whitaker, M. Sasakura, R. Dills and M. G. Yost, "Protection Efficacy of Gloves Against Components of the Solvent in a Sprayed Isocyanate Coating Utilizing a Reciprocating Permeation Panel. Annals of Occupational Hygiene", no. 3, **(2015)**, pp. 358-372.
[13] F. Xie, X.-J. Liu, C. Wu and P. Zhang, "A novel spray painting robotic device for the coating process in automotive industry", Proceedings of the Institution of Mechanical Engineers Part C-Journal of Mechanical Engineering Science, no.11, **(2015)**, pp. 2081-2093.
[14] Z. Yazdani, F. Karimzadeh, M. H. Abbasi and A. Amini, "Improvement of Tribological Behavior of Ti-6Al-4V Alloy Using Nanostructured NbSi2 and NbSi2-Al2O3 Plasma Spray Coatings", Transactions of the Indian Institute of Metals, no. 5, **(2015)**, pp. 927-934.
[15] G. Yoganandan, K. P. Premkumar and J. N. Balaraju, "Evaluation of corrosion resistance and self-healing behavior of zirconium-cerium conversion coating developed on AA2024 alloy", Surface & Coatings Technology, **(2015)**, pp. 249-258.
[16] M. Bagherian and A. Alos, "3D UAV trajectory planning using evolutionary algorithms: A comparison study", Aeronautical Journal, no. 1220, **(2015)**, pp. 1271-1285.
[17] J. Park, S. Karumanchi and K. Iagnemma, "Homotopy-Based Divide-and-Conquer Strategy for Optimal Trajectory Planning via Mixed-Integer Programming", Ieee Transactions on Robotics, no. 5, **(2015),** pp. 1101-1115.
[18] D. Pascarella, S. Venticinque, R. Aversa, M. Mattei and L. Blasi, "Parallel and distributed computing for UAVs trajectory planning", Journal of Ambient Intelligence and Humanized Computing, no. 6, **(2015)**, pp. 773-782.
[19] Y. Zhu, X. Huang and S. Li, "A novel six degrees-of-freedom parallel manipulator for aircraft fuselage assemble and its trajectory planning", Journal of the Chinese Institute of Engineers, vol. 7, **(2015)**, pp. 928-937.
[20] Y Yang, B Jiang and S Hu, "Fast Trajectory Planning for VGT Manipulator via Convex Optimization", International Journal of Advanced Robotic Systems, **(2015).**
[21] M. Karl, "In vitro studies on CAD/CAM restorations fabricated with Procera technology: An overview", Quintessence International, no. 7, **(2015)**, pp. 561-574.
[22] J.-H. Lee, "AN ACCELERATED TECHNIQUE FOR A CERAMIC-PRESSED-TO-METAL RESTORATION WITH CAD/CAM TECHNOLOGY", Journal of Prosthetic Dentistry, no. 5, **(2014)**, pp. 1021-1023.
[23] M. Wolf, P. Schumacher, F. Jaeger, J. Wego, U. Fritz, H. Korbmacher-Steiner, A. Jaeger and M. Schauseil, "Novel lingual retainer created using CAD/CAM technology. Evaluation of its positioning accuracy", Journal of Orofacial Orthopedics-Fortschritte Der Kieferorthopadie, no. 2, **(2015)**, pp.164-174.
[24] W. Zhanzhong, L. Chaoying, C. Linzhang and F. Xiaoke, "Method of spray gun path generation based on Z-map theory. Applied Mechanics and Materials", **(2012),** pp. 558-62.
[25] Z. Cai, H. Liang, S. Quan, S. Deng, C. Zeng and F. Zhang, "Computer-Aided Robot Trajectory Auto-generation Strategy in Thermal Spraying", Journal of Thermal Spray Technology, no.7, **(2015)**, pp. 1235-1245.
[26] D. Hegels, T. Wiederkehr and H. Mueller, "Simulation based iterative post-optimization of paths of robot guided thermal spraying. Robotics and Computer-Integrated Manufacturing", **(2015)**,pp.1-15.

