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Path Planning for Spray Painting Robot of Horns Surfaces in Ship Manufacturing

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Abstract. Generating paint gun path for complex free-form surfaces in shipbuilding industry to ensure uniform paint deposition is highly challenging due to their complex geometry, especially for horns surfaces. In this paper, a tool trajectory optimization method was proposed based on dip angle spray in order to solve the problems of poor coating uniformity and material waste for spraying horns surface with curved patches. A dip angle spray model was developed based on the Beta distribution model on the planar surface by principle of differential geometry. The spray path optimization models for dip angle spraying on cylindrical surfaces of three cases were proposed and compared first to define the best case which yields the best painting quality. Then we used the best strategy on a horns surface in a shipyard to evaluate the effectiveness and robustness of designed algorithm. This algorithm can also be extended to other applications.

1. Introduction

Spray painting robots are commonly adopted in many industries such as automobiles, furniture and shipbuilding industry to improve productivity as well as painting quality. However, the traditional "artificial teaching" style of spraying robots have largely limited their usage since it involves tedious teaching process which can be time-consuming and energy-inefficient, thereby making the off-line programming a hot topic among researchers [1].

The shape of workpiece and the tool parameters can strongly influence the quality of painting [2]. Some early researches studied the painting quality of plane of near-plane surfaces [3, 4, 5]. Later, Balkan [6] used experimental paint thickness distribution resulting from a single painting stroke applied on a flat surface to predict the painting thickness and found that Beta model was more accurate than traditional parabolic model. Zaki [7] developed an economic automatic system for spray painting of a general three dimensional surface. In order to improve the painting quality on free-form surfaces, Chen [8] proposed to split a free-form surface into several patches and conducted an experiment to verify the proposed method. However, the method was only applicable to simple free-form surfaces. Sheng [9] proposed a tool-path planning approach which optimizes the tool motion performance and the thickness uniformity of geometry-complicated parts consisting of multiple freeform surfaces. Chen [10, 11] pointed out that a complex free-form surface is consisted of several patches and then proposed trajectory integration algorithm which helped better the material quantity deviation. However, like other former researchers, he split a free-form surface into several near-plane patches which might cause low painting quality and painting efficiency problem especially when there are too many patches

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due to the complex geometric character of a free-form surface. To solve the above-mentioned problem, Gong [12] developed an algorithm to divide complex free-form surfaces into several regular surfaces and established static models for regular surfaces. In order to improve the accuracy of the spray gun model, Zhang [13] developed a natural quadric mathematical model of arc spray gun trajectory considering gun spraying flow.Some scholars also proposed trajectory planning schemes with Bézier curves, which can also ensure painting quality for free-form surfaces [14,15]. However, the modelinng of Bézier curves is very time-consuming and its mathematical expression can be too complicated to generate satisfactory trajectories [16]. Fu [17] proposed a genetic algorithm-based surface segmentation method in which complex surface are divided into several small curvature surfaces and it simplified the subsequent trajectory planning operations. Zhou [18] discussed the automatically generated trajectories on regular surfaces using cutting-projection processing, visual simulation results demonstrate the effectiveness and practicality of the proposed algorithm. In order to solve the problems of poor coating quality and paint waste for spraying inner/outer horns surface, a tool trajectory optimization method was proposed based on dip angle spray. The simulation results illustrated the feasibility and availability of these optimization model and algorithms [19, 20]. However, they only assumed that the horns surface were composed of two near-plane patches. If one of the patches was actually a curvature surface, then their methods might not work out well. In order to solve the problems of coating growth rate modeling for varied dip-angle spraying technology, Zeng [21] developed a prediction mode of coating growth rate. Experiments have shown that the prediction model has good fitting precision.

In this paper, we proposed an algorithm to solve the problem of poor coating for spraying horns surfaces with curvature patches. Curvature patches can be fitted into cylindrical surfaces to simplify the problem without losing too much accuracy compared with being fitted into planes. The dip angle spray model for cylinders were constructed by principle of differential geometry. Based on the dip angle spray model, we then established a trajectory generation model and optimized the parameters to get the best painting quality. Simulation results showed that the proposed method yields satisfactory results.

2. Dip Angle Spray Modelling On Cylindrical Surfaces

Paint distribution model is needed in order to generate paint gun path. In view of the accuracy and flexibility, we consider a Beta distribution model. The paint flux q is given by equation (1) as follows:

$$q(r) = q_{\max}(1-\frac{4r^2}{w^2})^{\beta-1}, r \in \left[0, \frac{w}{2}\right]. \tag{1}$$

figure 1 shows paint accumulation of dip angle spray on a cylindrical surface. P_1 is a reference plane and P_2 is a parallel plane which passes the point B; α is the angle of gun axis and the line of the point B to gun center; h_s is the actual tool height; h is the desired tool height. β is the angle of gun axis and the normal vector of C, which is the dip angle of the spray gun. Suppose the material sprayed on a small area C_1 is projected to the area C_2. The film thickness of C_2 can be modeled as:

$$q_2 = q_1(S_1 / S_2) = q_1(\frac{h}{hs})^2. \tag{2}$$

figure 2(a) shows a circle C_3, which is a perpendicular to the material emission direction. The material on C_3 is projected to the free-from surface with deviation angle δ, as shown in figure 2(b). The material thickness on C_3 and C_4 can be expressed as:

$$q_3 = q_2 / \cos(\alpha);\quad q_4 = q_3 \cos(\delta). \tag{3}$$

Based on Equation (2), (3), the material thickness on the cylindrical surface can be obtained as:

$$q(r) = q_{\max}(1-\frac{r_s^2}{R^2})^{\beta-1}(\frac{h}{h_s})^2 \cos(\delta) / \cos(\alpha). \tag{4}$$

Where:

$$h_S = h + x\sin\beta \pm (\rho - \sqrt{\rho^2 - x^2}); \cos\beta = h + x\sin\beta \pm (\rho - z)\cos\beta; \quad \delta = \alpha \pm \gamma - \beta$$

$$r_s = \frac{h\sqrt{(x\cos\beta)^2 + y^2 \pm (z\sin\beta)^2}}{h_S} \tag{5}$$

$$\alpha = \arccos\left(\frac{h_S}{\sqrt{(x + h\sin\beta)^2 + y^2 + (\sqrt{\rho^2 - x^2} - (\rho + h\cos\beta))^2}}\right)$$

When the surface is a plane, ρ is infinite, and the dip angle spray model for planes can be obtained in Equation (4).

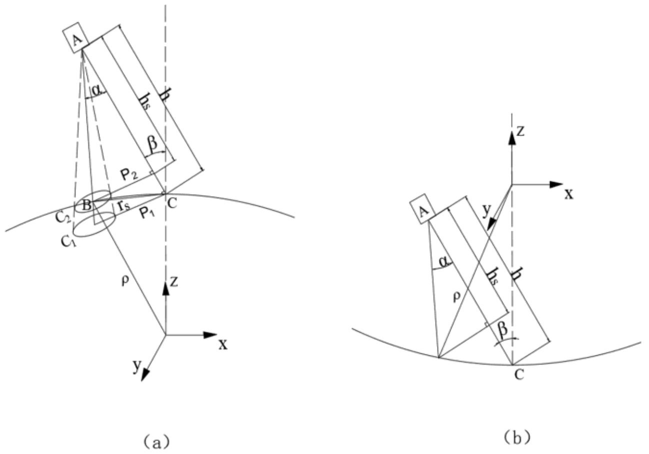

Figure 1. Profile of dip angle spray process on cylindrical surfaces.

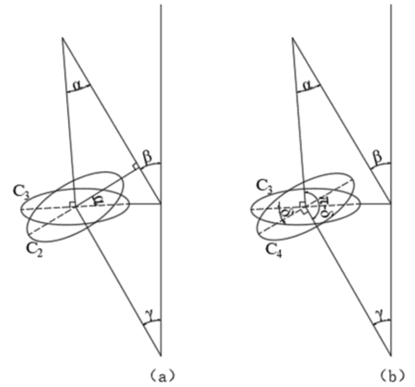

Figure 2. Material projection.

3. Optimal Trajectory Planning for Cylindrical Surfaces

The trajectory of the dip coating on cylindrical surfaces can be divided into three situations: reverse-dispersion, reverse-concentration and direction-parallel, which is shown in figure 3.

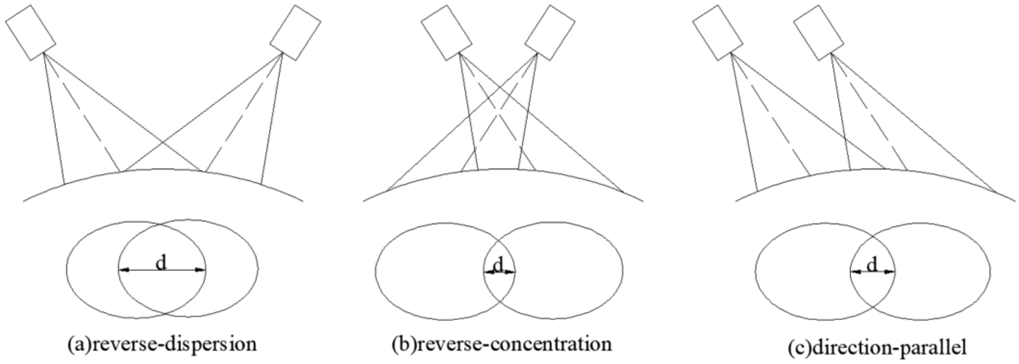

Figure 3. Three schemes of dip angle spray on cylindrical surfaces.

We employ figure 3(a) and 3(b) to calculate the painting thickness on a point *s*, figure 3(c) can also be calculated similarly. The painting thickness of a given point *s* can be expressed as follow:

$$T_s(x) = \begin{cases} T_1(x) & 0 < x < d - a(\pm\beta) \\ T_1(x) + T_2(x) & d - a(\pm\beta) < x < a(\pm\beta). \\ T_2(x) & a(\pm\beta) < x < d \end{cases} \tag{6}$$

Where a is the length of the long axes of dip angle spray model of the cylindrical surface; x is the position coordinate; T_1 and T_2 are dynamic single stroke coating deposition thickness which is calculated from static coating growth rate model:

$$T_1(x)=2\int_0^{t_1} f(r_1,x,y,\pm\beta)dt,\ \ 0<x<a(\pm\beta);\ \ T_2(x)=2\int_0^{t_2} f(r_2,x,y,\mp\beta)dt,\ \ d-a(\pm\beta)<x<d. \quad (7)$$

Where

$$\begin{aligned}
&t_1=b\sqrt{1-(\frac{x\mp\Delta a}{a})^2}/v; t_2=b\sqrt{1-(\frac{x-d\pm\Delta a}{a})^2}/v\\
&r_1=\frac{h sin\alpha\sqrt{x^2+y^2}}{h\pm x\sin\beta}; r_2=\frac{h sin\alpha\sqrt{(x-d\pm\Delta a)^2+y^2}}{h\mp(x-d)\sin\beta}\\
&a(\pm\beta)=\frac{K_1(\pm\beta)\sin\varphi}{\cos K_2(\pm\beta)}; \varphi=\arctan(\frac{R}{h}); y=vt_{1,2}; \Delta a=|a-a(\pm\beta)|\\
&K_1(\pm\beta)=(K_3-\sqrt{\rho^2-h^2\tan^2(\varphi\pm\varphi_1)-2\rho h\cos\beta\tan^2(\varphi\pm\varphi_1)})\cos(\varphi\pm\varphi_1)\\
&K_2(\pm\beta)=\arcsin(\frac{K_3\sin(\varphi\pm\varphi_1)}{\rho})-\arcsin(\frac{h\sin(\varphi)}{\rho}+\sin(\varphi\pm\beta))\\
&K_3=\sqrt{\rho^2+h^2+2\rho h\cos\beta}; \varphi_1=\arcsin(\frac{\rho\sin\beta}{K_3}); a=\frac{a(+\beta)+a(-\beta)}{2}; b=\frac{aR}{\sqrt{a^2-\Delta a^2}}.
\end{aligned} \quad (8)$$

Note that: t_1 and t_2 are the spraying time on the point *s* by the two adjacent strokes respectively; r_1 and r_2 are the distance from point s to the projection center of the spray gun of two adjacent strokes; Δa is the vertical distance of the elliptical center to the spray trajectory; *b* is the length of the short axes of dip angle spray model of the cylindrical patch.

In order to find the optimal velocity *v*, the overlap distance *d* and the dip angle of the spray gun *β*, the mean square error of the thickness deviation from the average thickness T_d must be minimized. Here the coating uniformity is taken as the objective for trajectory optimization:

$$\min E=(T_d-T_{\max})^2+(T_d-T_{\min})^2. \quad (9)$$

The optimal parameters *d*, *v*, *α* can be obtained by the genetic algorithm.

4. Simulation Results

4.1. Problem Setup.

According to the actual situation of the shipyard, we set the desired film thickness T_d=100μm, and the maximum error of the film thickness to be Ts=20μm. The overlap distance range 100mm<*d*<500mm, spray gun velocity range 200mm/s<*v*<1000mm/s. The spray gun height 200mm<*h*<600mm.

The workpieces, shown in figure 4 and 5, are used to test the algorithm, which is a cylindrical surface with a radius of 1000mm and a horns surface in a shipyard consisted of two different patches. The first patch is a plane while the second patch is a cylindrical surface with a radius of 1500mm, the angle of the two patches is 120°. We assume that the dip angle of the spray gun for the plane to be β_1, then the dip angle for the cylindrical surface is 60°–β_1.

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Figure 4. A cylindrical surface.

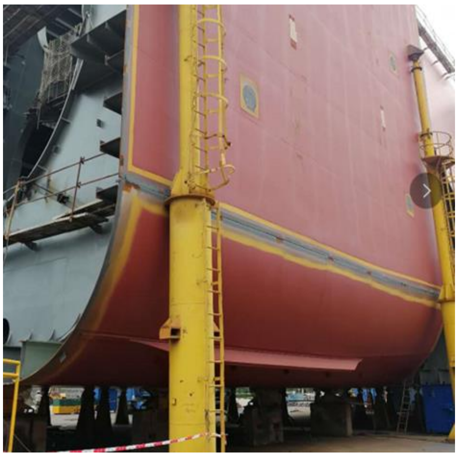
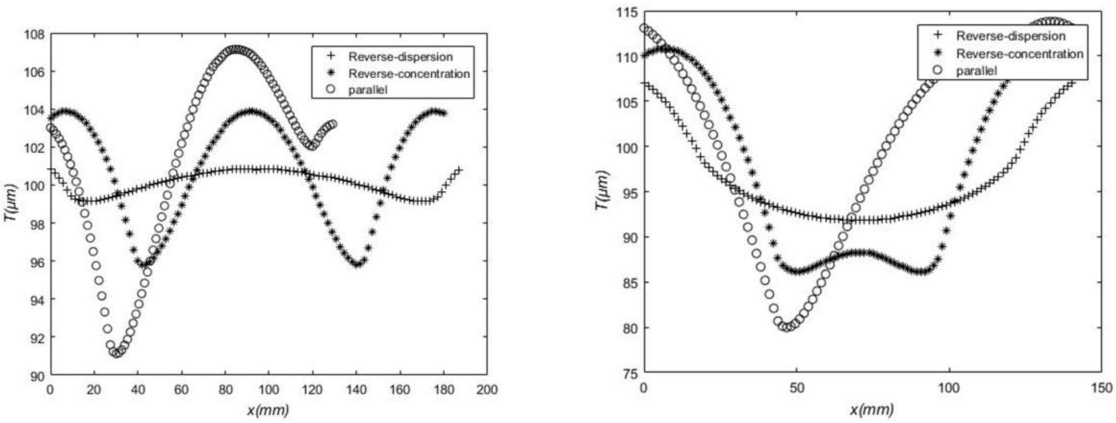


Figure 5. A horns surface.

4.2. Analysis of Results.

4.2.1. Dip angle spray on the cylindrical surface. We set the dip angle of the spray gun to be 10°, 20° and then use the function(9) to optimize parameters in three different conditions shown in figure 3, the distributions of painting thickness are shown in figure 6.



(a)10° (b)20°

Figure 6. The painting thickness distribution of different dip angles.

From the simulation results shown in figure 6(a), (b) we can conclude that the painting quality of reverse-dispersion on the cylindrical surface is the best.

4.2.2. Dip angle spray on the horns surface. The painting strategy on the horns surface is shown in the figure 7, we use reverse-dispersion to ensure the best painting quality on the horns surface.

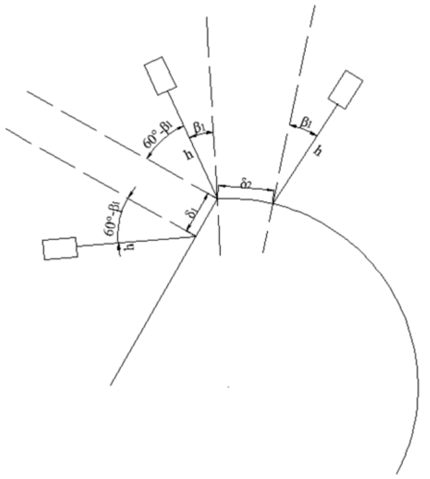


Figure 7. The painting strategy.

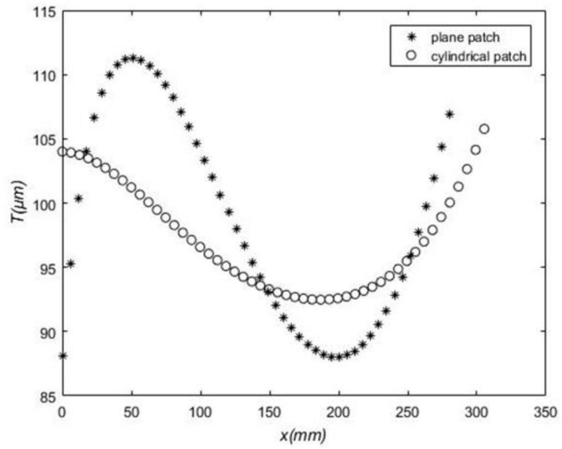


Figure 8. The painting thickness distribution.

The painting quality can be seen in figure 8, we can conclude that the painting strategy in this paper yields satisfactory results.

5. Conclusion

In this paper, a dip angle spray trajectory generation approach for horns surfaces is developed. By examining three different dip angle spray strategies on cylindrical surfaces, we conclude that reverse-dispersion yields better painting uniformity compared to reverse-concentration and parallel painting. Then we employ reverse-dispersion strategy on horns surface and it can be seen from the simulations that our approach is effective and yields satisfactory results.

6. Acknowledgments

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