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A New Point Cloud Slicing based Path Planning Algorithm for Robotic Spray Painting*

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***Abstract*—In order to make traditional point cloud slicing algorithm suitable for robotic spray path planning of complex surface, four improvements are put forward in this paper. Firstly, adaptively choose the dominant eigenvector direction of oriented bounding box of spray target as the normal vector direction of the slicing plane. Secondly, propose intersection-projection joint segmentation method to obtain points for constructing spraying path. Thirdly, use polynomial fitting and uniform interpolation method to construct smooth spray path. Finally, propose an iteration formula of interval between adjacent slicing planes to obtain equal distance spray path for variable curvature surfaces. Numerical examples show that the proposed algorithm can generate robotic spraying path directly from point cloud model, and suitable for complex, irregular shape spray target.**

I. Introduction

When using robot for spraying paint, the automatic spray gun mounted at the end of the spray robot need to move at constant spray distance and spray speed along the surface of work piece to paint the surface evenly. Therefore, the quality and efficiency of spray depend mainly on the reasonability of the spray path. In recent years, along with the increasingly extensive application of painting robot, the path planning technology of robotic spray painting has developed from early manually teaching to off-line programming based on 3D model[1], and the planning algorithms were researched widely and developed rapidly. Chen et al. used the intersecting line of a set of planes and the surface to generate spray path after converting the surface to triangular patch [2,3]. Atkar et al. put forward a method in which a seed curve was generated on the surface and a set of offset curves from the seed curve were selected as the spray path [4]. However, automatic path planning of robotic spray painting has not accomplished yet, because people still have to pre-process the digital model of spraying target, before they can use those above-mentioned algorithms.

Recently a kind of algorithm called point cloud slicing is worth paying attention to. It was firstly used in reverse engineering field, and its biggest advantage is that the path can be generated directly from point cloud without any pre-processing work. Besides, this algorithm has good practicability because point cloud model can describe any complex shape, and can be obtained easily from CAD model or measurement equipment.

However, point cloud slicing algorithm also has some places needed to be improved, in order to use it for automatic spray path planning, e.g. computational efficiency is a big problem because point cloud model has big data size, and point cloud model lacks information of boundary and connection. Therefore, a new path planning method of complex surface robotic coating is proposed in this paper, by improving and optimizing traditional point cloud slicing algorithm. The new algorithm is also verified and analyzed by typical example.

II. Requirement Analysis

Robotic spray painting process shows in fig. 1. Firstly, liquid paint is ejected from the nozzle and atomized into fine particles by compressed air, then the particles impact and adhere to the surface of spray target, forming continuous film. With moving of the spray gun, a uniform continuous paint film generates on the surface [5].

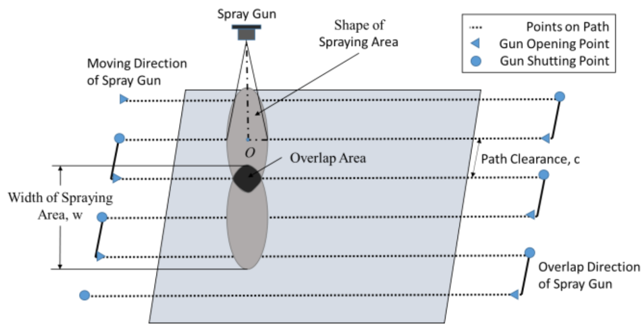

Figure 1. Schematic diagram of spraying process

To guarantee uniformity and completeness of paint film, robot spray path is a set of "parallel" curve on the surface. The shape of the curve is profile of the surface, and the clearance between paths should be as even as possible.

To be convenient for practical application, spray path is expressed usually in discretization way. Define a set of points on path L_i, as a spray path:

$$L_i = \left(l_{i,1}, \quad l_{i,2}, \quad \dots \quad , l_{i,n}\right) \tag{1}$$

Where l_{ij} are points on path L_i, which represents location and vector of path point:

$$l_{ij} = \left(x, \quad y, \quad z, \quad \alpha, \quad \beta, \quad \gamma\right) \tag{2}$$

Where (x, y, z) is the coordinate of the path point, (x, y, z) is the direction vector of the axis of the spray gun, the direction is

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from TCP (Target Center Point, TCP) to nozzle of the spray gun.

Thus the distance between two adjacent paths L_i and L_{i+1} can be expressed as the mean value of the distances between all corresponding points on the two paths, denote as μ:

$$\mu = \frac{1}{n}\sum_{j=1}^{n} d\left(l_{i,j}, l_{i+1,j}\right) \tag{3}$$

Where $d(l_{i,j},l_{i+1,j})$ is the distance between corresponding path points $l_{i,j}$ and $l_{i+1,j}$ on two adjacent paths L_i and L_{i+1}.

Therefore, the optimization objective of robotic spraying path planning can be described as minimize the distance difference between corresponding points of two adjacent paths, i.e. the root-mean-square error is smallest, shown as equation（4）.

$$Min \quad \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(d\left(l_{i,j}, l_{i+1,j}\right) - c\right)^2} \tag{4}$$

Where c is the desired path clearance between two adjacent paths. It is usually set as 0.3 to 0.5 times of the width of spraying area.

III. Point Cloud Slicing Algorithm

The essence of point cloud slicing is to get the profile of the point cloud by intersection computation of certain plane and the point cloud, as shown in Fig. 2. It is used firstly in reverse engineering field for fast model rebuilding, and also be applied to generate tool path of CNC machine recent years[6,7].

The procedure of calculating point cloud slicing is: for certain slicing plane, define a slicing thickness δ firstly, get all the points located at two sides of slicing plane within $\delta/2$; then find all the nearest point pairs of slicing plane, connect each point pairs to form line segments; calculate the intersection of slicing plane and line segments, the intersection points are seen as the segmentation of the point cloud.

To avoid losing shape information, the basic assumption of applying point cloud slicing method is that the surface of slicing target is smooth, and its curvature variation is little and continuous.

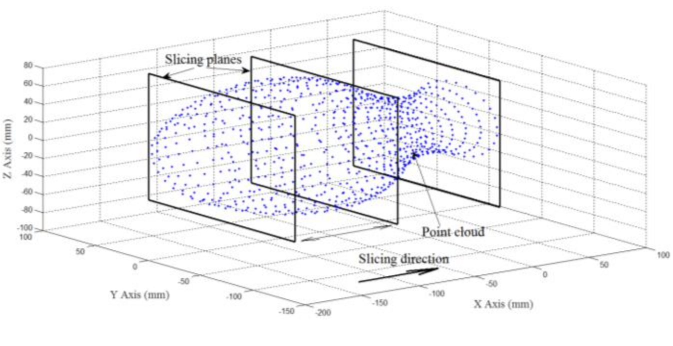

Figure 2. Schematic diagram of point slicing

For any point cloud, point slicing can be calculated one by one after the location and direction of the first slicing plane and the amount of all slicing planes are defined.

The segmentation obtained through point cloud slicing can reflect the profile of arbitrary geometry shape, and suitable for applications like reverse engineering. However, the profile cannot be used directly as robotic motion path without smoothing and interpolation. Besides, necessary extension and reconstruction are also needed when the path is for spray painting robot, considering the uniformity and completeness requests of film thickness. Consequently, improvement and optimization of traditional point cloud slicing method are discussed in next section.

IV. Improvement And Optimization

A. Adaptive determination of slicing plane direction

The direction of slicing plane in traditional point cloud slicing is selected as the X, Y or Z axis of the model, or a direction selected manually. In this paper, we propose an adaptive method to determine the direction: PCA method (Principle Component Analysis, PCA) is used to construct OBB (Oriented Bounding Box, OBB) of the point cloud model firstly, then the direction of the dominant eigenvector of the minimum bounding box is selected as the direction of the normal vector of the slicing plane. The advantage of this method is that it can guarantee the slicing plane is perpendicular to the direction of longest axis of the point cloud. In fact, we found that spraying path obtained in this way is often shorter and more reasonable.

Besides, the other advantage of using OBB is that we can construct a new coordinate system using three eigenvectors of the OBB, then rotate the coordinate system of the point cloud to align with the new coordinate system, so that the following segmentation steps is much easier, as slicing plane is perpendicular to the X axis of point cloud model.

B. Intersection-projection joint segmentation

As mentioned before, intersection method is selected in traditional point cloud slicing algorithm to obtain the profile of point cloud. However, the intersection points obtained is not sufficient for construct spray path, as the spray path has to longer than the spray target.

For example, if intersection method is used to calculate slicing for the point cloud model shown in Fig.3 with irregular edge, only the solid line part of the spray path in the figure can be calculated out.

Therefore, the dark area in the figure cannot be covered adequately if we spray along this path. Actually, the dotted line shown in the figure should be selected as spray path, in order to cover all the area uniformly.

In addition, spray path at the edge of the surface should extend outward an appropriate length to guarantee the thickness of coating film is uniform at the edge of the spray target. Unfortunately, it also cannot be obtained through intersection method.

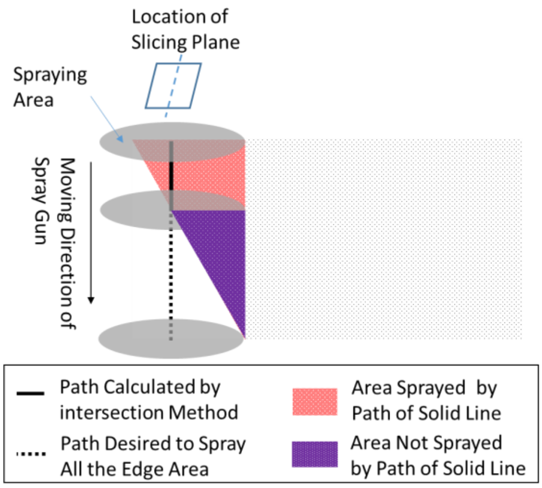

Figure 3. Defect of path obtained by traditional point cloud slicing

To avoid the defect mentioned above, two improvements of traditional point cloud slicing are put forward:

1） define slicing thickness as the width of spray area, so that all the points within the spray area could be considered while slicing;

2） put forward a new intersection-projection joint segmentation algorithm, its procedure is:

Step 1: get all the points within the slicing thickness range of the current slicing plane Γ , named as P_Γ ;

Step 2: obtain the intersection points set P_Γ^{inter} by intersection method, then get the maximum and minimum Y coordinate, Y_{max} and Y_{min} , of all the points in P_Γ^{inter} ;

Step 3: put the points in P_Γ whose Y coordinate are less than Y_{min} into point set P_Γ^- , whose Y coordinate are greater than Y_{max} into point set P_Γ^+ ;

Step 4: calculate the length in Y direction of P_Γ^{inter} , P_Γ^- and P_Γ^+ , named as $L\left(P_\Gamma^{inter}\right)$, $L\left(P_\Gamma^-\right)$ and $L\left(P_\Gamma^+\right)$;

Step 5: calculate the amount of projection points in P_Γ^- and P_Γ^+ by equation (5).

$$\begin{cases} N\left(P_\Gamma^-\right) = L\left(P_\Gamma^-\right) / L\left(P_\Gamma^{inter}\right) \times N\left(P_\Gamma^{inter}\right) \\ N\left(P_\Gamma^+\right) = L\left(P_\Gamma^+\right) / L\left(P_\Gamma^{inter}\right) \times N\left(P_\Gamma^{inter}\right) \end{cases} \quad (5)$$

Where $N\left(P_\Gamma^{inter}\right)$ is the amount of points in P_Γ^{inter} .

Step 6: divide the points in P_Γ^- and P_Γ^+ equidistant into $N\left(P_\Gamma^-\right)$ and $N\left(P_\Gamma^+\right)$ sub sets along Y axis respectively, $N\left(P_\Gamma^-\right)$ and $N\left(P_\Gamma^+\right)$ are the number of sub sets;

Step 7: for each sub set of P_Γ^- and P_Γ^+ , select the point which is nearest to the slicing plane Γ , and project it to Γ .

The meaning of step 5 and 6 is to make sure the points selected to be projected are uniformly distributed along y axis, otherwise the subsequent fitting of spray path will be affected.

Using this algorithm, integrated spray path which can cover all the edge areas of spraying target can be obtained, for point cloud with any edge shape. For example, an integrated spray path of irregular surface is shown in Fig. 4, the blue path points are obtained by intersection method, and the red points are obtained by projection method.

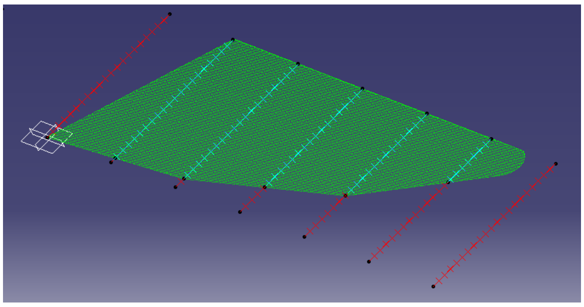
Figure 4. Example of intersection-projection joint segmentation

C. Path construction

The points generated by slicing algorithm in the slicing plane are along the profile of the spraying object, but they cannot be used directly as path points for spraying. In order to obtain smooth and even path points, least square method is used to fit the slicing points to polynomial curve firstly, and then uniform path points can be generated by uniform interpolation.

In order to minimize the computational complexity, the maximum degree k of polynomial curve is defined by equation （7）.

$$\min(k) = \sum_{i=2}^{n-1} f(z_i) + 2 \quad (7)$$

Where n is the amount of points for fitting, $f(z_i)$ can be calculated by equation (8).

$$f(z_i) = \begin{cases} 1 & if \ (z_i - z_{i-1}) \times (z_{i+1} - z_i) \le 0 \\ 0 & else \end{cases} \quad (8)$$

Where z_i is the Z coordinate of the ith path point.

The principle of equation (8) is that the maximum degree of polynomial curve is equal to the amount of inflection points. Inflection point is easy to judge by its neighbor points, for example, path points 4, 6 and 9 in Fig. 5 are inflection points.

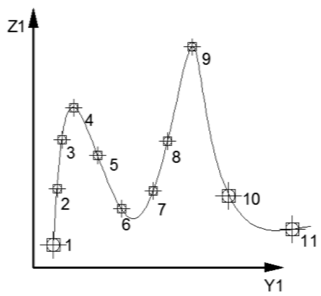

Figure 5. Schematic diagram of inflection point

To obtain sufficient fitting accuracy by minimum degree of polynomial curve, let k begins to increase from 1. Calculate fitting error after each fitting, if fitting error meets the requirement, the next fitting will be cancelled and the current k is taken as the optimum fitting degree of polynomial curve.

After obtaining the fitted curve, generates path points for spraying by uniform interpolating at certain step size, between the minimum y axis value and the maximum y axis value of the slicing points.

As for the normal vector of path point, find m nearest points of path point i in original point cloud, construct m directed triangular patches, then the weighted average of their normal vectors is the normal vector of ith path point.

D. Optimization of interval between slicing plane

Traditional point cloud slicing algorithm does not go deep into the problem of interval between slicing plane, the value of interval is constant. But we found that the spray path obtained by constant interval slicing will appear relatively obvious distance error, especially when the curvature of the spraying target of the spraying object varies significantly, as shown in Fig.6. The distance error will do harm to the thickness uniformity of the coating film.

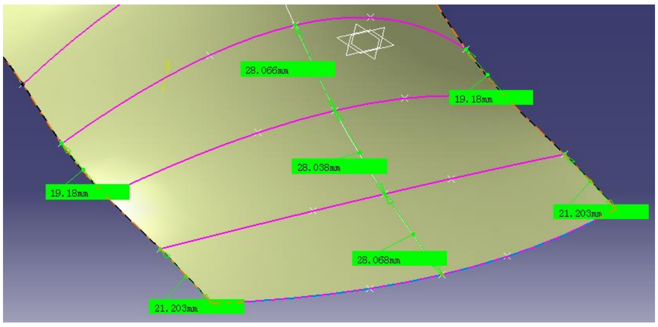

Figure 6. Problem of equal interval slicing

Consequently, an iterative formula for the interval between slicing planes based on the principle of triangle similarity is put forward in this paper, which can adjust adaptively the interval between slicing according to the shape of the spray object, as shown in equation (9).

$$d_{t+1} = d_t + \lambda \cdot \frac{c - \mu_t}{\mu_t} d_t \qquad (9)$$

Where μ_t is the mean of actual distance between the current path and the next path after tth iteration, and can be calculated by equation (3).

We found that this equation can usually calculate out the optimum interval between slicing planes which meets the limit of error quickly by 3 to 5 iterations. However, oscillation phenomenon appears sometimes during iteration and the algorithm cannot converge, if the limit of error is too small. Therefore a step size correction factor λ is introduced into equation (9), which is to make sure the algorithm to be convergent by reducing step size when oscillation phenomenon appears。

The procedure of calculating the next slicing plane Γ_{t+1} with current slicing plane Γ_t is described as following:

Step 1: initialize the limit error ε of iteration and the ideal distance c between adjacent paths, let $d_0 = c$, $t = 0$, $\lambda = 1$;

Step 2: calculate the location of slicing plane of tth iteration by d_t , obtain point cloud slicing and spray path, calculate the actual distance μ_t between adjacent paths;

Step 3：if $t > 1$ and $\mu_t > \mu_{t-1}$, reduce λ and go to step 2;

Step 4：if $|\mu_t - c| \le \varepsilon$, stop iterating, d_t is the optimized interval between slicing, the next slicing plane Γ_{t+1} can be located by d_t ; else, go to step 5;

Step 5：calculate d_{t+1} by equation (9), let $t = t + 1$, go to step2.

E. procedure design

In summary, the flow chart of proposed path planning algorithm for robotic spraying based on point cloud slicing is shown in Fig. 7.

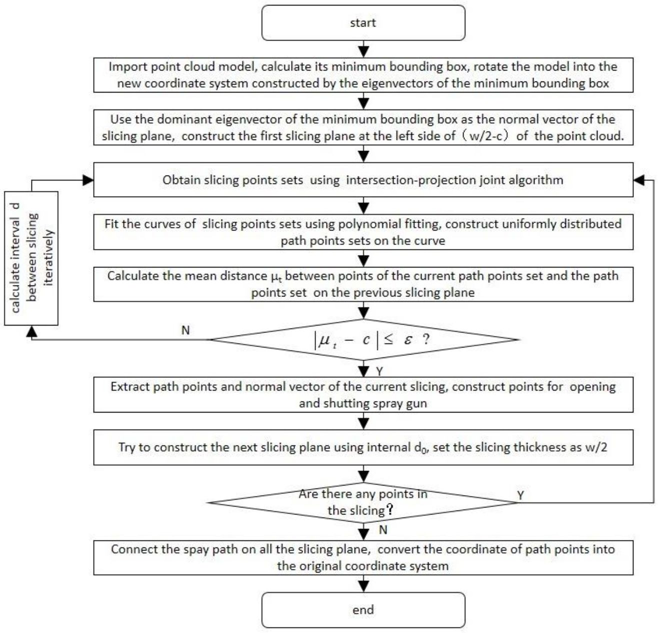

Figure 7. Flow chart of proposd path planning algorithm

V. Experiment

Numerical experiments have demonstrated the validity of our algorithm. One of the representative examples is selected and presented in this paper, shown in Fig. 8. This target is typical because it has dramatically varying curvature and irregular edge.

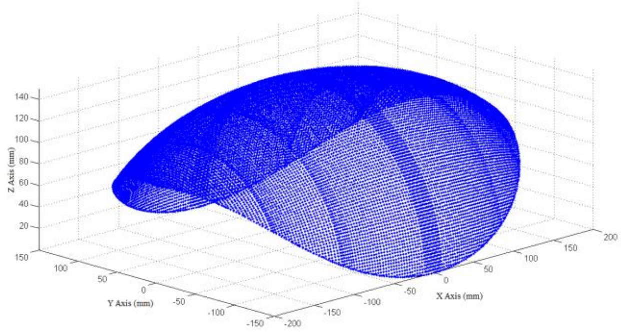

Figure 8. Typical spraying target example for test

The spray path obtained by traditional point cloud slicing algorithm is shown in Fig. 9. As the path is calculated only by intersection method, all the points are within the range of the point cloud model. If spray gun moves along this path, the edge area of the target cannot be covered uniformly. On the other hand, the spray path obtained by the algorithm in this paper is shown in Fig. 10. Using intersection-projection joint slicing algorithm, complete spray path is constructed at the edge of the model, which can make sure all the area of the spraying target can be covered uniformly.

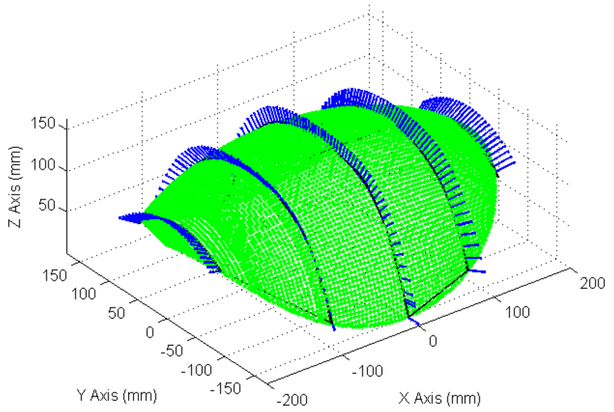

Figure 9. Path obtained by traditional point cloud slicing algorithm

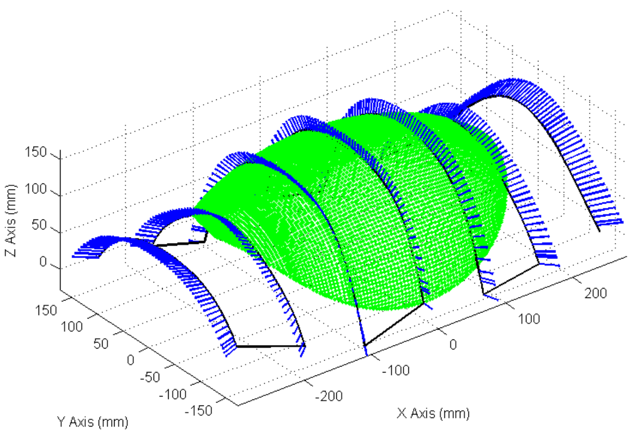

Fig. 10 Path obtained by improved algorithmin

Besides, to demonstrate the validity of the optimization of interval between slicing plane, distance errors of path obtained through equal distance slicing and obtained through proposed algorithm are shown and compared in Fig. 11. Blue points "o" are distances between corresponding path points on adjacent spray path calculated by traditional point cloud slicing algorithm, red points "+" are distances between corresponding path points on adjacent spray path calculated by the algorithm in this paper. It is obvious that distances error of path obtained by the algorithm in this paper is smaller, therefore more helpful to obtain uniform coating film. Besides,

To further compare the rationality of the two spray path, β distribution model is used to simulate the film thickness of spraying target. Both the modeling and simulation method and detail can be found in literature [8].

The coating thickness distribution of spray path calculated by equal distance slicing is shown in Fig. 12. The maximum thickness is 32.3 μm, the minimum thickness is 4.4 μm, the root mean square error is 6.53. The coating thickness is obviously thinner at the edge area, which means the spraying target was not covered uniformly.

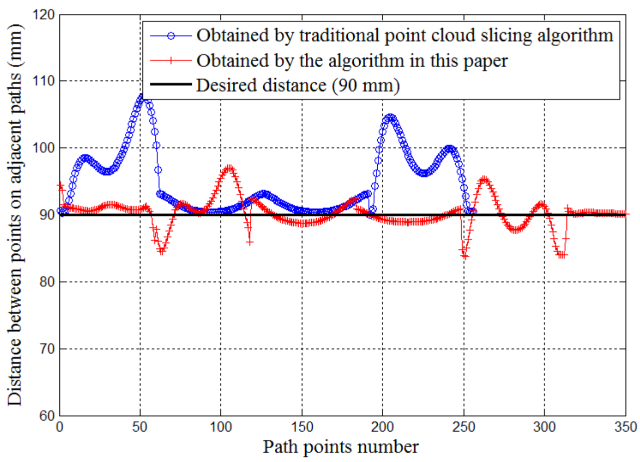

Fig. 11 Distance error comparison of two algorithms

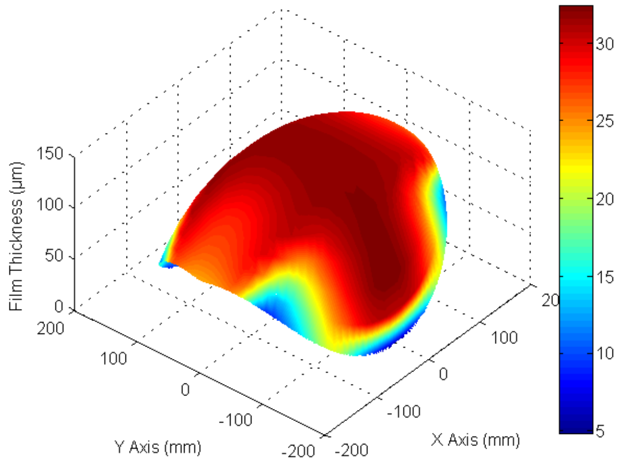

Fig. 12 Film thickness distribution of spray path obtained by traditional point cloud slicing algorithm

The coating thickness distribution of spray path calculated by the algorithm in this paper is shown in Fig. 13. The edge area of the surface is covered uniformly, the maximum thickness is 38.9 μm, the minimum thickness is 17.6 μm, the root mean square error is 3.08. We can see that the coating thickness uniformity and completeness is much better.

Comparison indicates that the spray path obtained by our algorithm is more complete and rational. We interpret this result to the proposed intersection-projection joint segmentation method and optimization of interval between slicing planes. Besides, the non-constant interval between slicing planes is also helpful to avoid losing spraying target shape information.

It should be noted that the purpose of discussing the uniformity here is to verify the reasonability of the spray path. In actual use, the uniformity of the coating thickness can be further improved by optimizing the spray velocity.

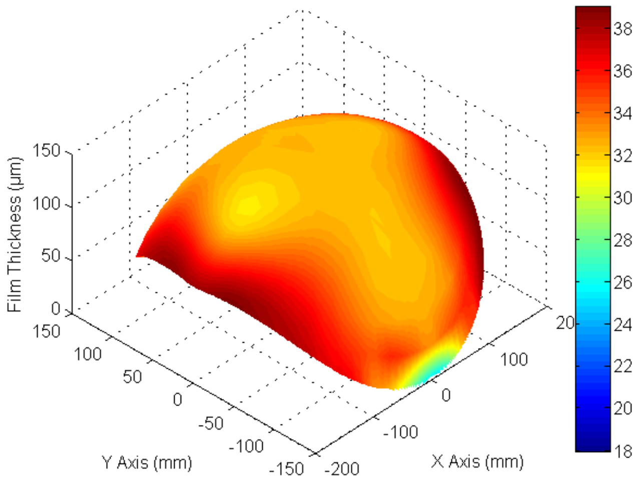

Fig. 13 Film thickness distribution of spray path obtained by improved algorithm

VI. CONCLUSION

The advantage of robotic spray path planning based on point cloud slicing is that it can operate directly on point cloud without any extra manual preprocess. Combining with external measurement equipment, automatic planning can be realized, so that production preparation time can be reduced significantly. However, unlike model reconstruction, there are some special requirements have to be taken into account to make point cloud slicing algorithm suitable for robotic spray path planning.

Based on analyzing and summarizing former research results, four significant improvement of traditional point cloud slicing algorithm are discussed in this paper, i.e. adaptive determination of slicing plane direction , new intersection-projection joint segmentation method, construct path through polynomial fitting and uniform interpolation, and adaptively adjust the interval between adjacent slicing plane. Finally, a complete point cloud slicing based robotic spray path planning algorithm is proposed, which is suitable for any complex spray target.

The advantages of spray path obtained by proposed algorithm, such as uniformity and completeness, are discussed in this paper to validate our research. However, we would like to pointed out that the uniformity of coating thickness can be further improved by optimizing spray velocity, which is not discussed in this paper, as it is not the key content of this paper.

In future study, there are still some issues needed to be discussed: determination of points for opening and shutting spray gun on multiple connected surface, spray path partition of large surface which cannot be painted by single robot in constant station, optimization of the length of spray path, and so on.

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