ISSN: 2710-0588

Scraper Point Attitude Optimization in the Scraping Process of Aviation Composite Curved Surface

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Abstract

Aiming at the interference problem between the tool and the surface during the contact between the blade position and the composite material during the off-line programming scraping process of aviation composite parts, the contact effect of the blade during the scraping process of the composite surface is discussed, and a rotation projection attitude optimization strategy is proposed. Firstly, by constructing the mathematical model of the contact between the scraper and the surface, the geometric properties of the scraper and its contact on the surface are analyzed. Then, the non-uniform rational B-spline (NURBS) surface is used to reconstruct the surface, and the position information of the local area of the contact point is obtained to obtain the normal direction and curvature. In order to evaluate the contact effect of the scraper, an objective function is defined to minimize the contact error between the scraper linear trajectory and its projection on the surface, thereby quantifying the contact accuracy. By comparing the position and attitude of the scraper before and after optimization, the effectiveness of the proposed optimization method is verified. The optimized scraper posture significantly improves the contact accuracy with the composite surface, better adapts to the geometric characteristics of the complex surface, and ensures the efficiency and consistency of the scraping process. The research results provide a new perspective and method for the future development of automatic scraping process, and also provide an effective solution and technical means for other industries in the application scenario of curved scraping.

Keywords

Composite surface, rotation projection, geometric features, curvature.

1. Introduction

In the modern manufacturing industry, composite materials have become indispensable materials in high-end applications such as aerospace, automobile manufacturing, and wind energy equipment due to their excellent mechanical properties and lightweight characteristics. Although robot gluing has been maturely applied in the automotive field, it has not been widely used in the field of aviation manufacturing due to the diverse structural forms of aviation components, difficulty in trajectory control, and the particularity of colloids [1].

Curved surface scraping is an important surface treatment process in the processing of composite materials. Its main functions include repairing material damage, enhancing structural strength and providing sealing protection. The quality of scraping adhesive directly affects the bonding strength and structural integrity of the composite, which is very important to ensure the reliability and safety of the final product [2]. In the process of surface scraping, the introduction of robot and automation technology provides the possibility to improve the processing efficiency and accuracy.

In recent years, the research on the optimization of robot spraying and grinding process has become active. In contrast, there are significant differences between the application of robots in scraping process and other surface treatment processes such as spraying and grinding. Although spraying and polishing have been widely used in many industries and have achieved mature automation results, there are many differences between their process flow, technical requirements and quality standards and scraping glue. [3] The spraying process mainly focuses on the uniform distribution of the coating on the surface of the workpiece to ensure the thickness and adhesion of the coating. The grinding process focuses on removing excess substances on the surface of the material and improving the smoothness and flatness of the surface. These processes usually handle relatively smooth and regular surfaces, and have relatively low requirements for posture adjustment of process equipment.

However, the scraping process needs to deal with various surfaces with complex shapes and variable curvatures. In the process of scraping, the scraper should not only keep uniform contact with the surface, but also dynamically adjust the posture between different parts of the workpiece surface to adapt to the challenges brought by the change of the geometric characteristics of the surface. Compared with the spraying and grinding process, scraping glue has stricter requirements on the control of tool attitude. Any slight attitude deviation may lead to uneven scraping glue, glue residue and even workpiece damage. Therefore, how to effectively optimize the position and posture of the scraper to meet the needs of complex surfaces is one of the core problems in the automation of the scraping process.

Tool posture, that is, the position and direction of the tool relative to the workpiece, is one of the important factors determining the quality of scraping. In the process of scraping glue on complex surfaces, the position and attitude of the tool not only affects the efficiency of the processing, but also directly affects the accuracy and surface smoothness of the processing. The traditional pose setting usually depends on the calculation of off-line programming software. By off-line programming of the surface, the scraping path is generated. However, this method is often difficult to achieve the best scraping effect when dealing with complex three-dimensional surfaces. The main reason is that the variable curvature and irregular shape on the complex surface make the tool need to continuously adjust the posture at different positions to adapt to the local geometric characteristics of the surface. This demand increases the complexity of machining path planning and attitude adjustment, and also puts forward higher requirements for existing programming and control technologies.

In this paper, the algorithm of scraper attitude optimization is discussed. Based on the algorithm of fixed angle step rotation, the normal vector of the scraper around the contact point rotates at a certain angle. The rotated straight lines are projected on the surface along the normal direction. Through algorithm optimization, the error between the straight line and the projection curve is the smallest. At this time, the spatial position of the straight line is the best attitude of the scraper. The research in this paper will provide new ideas for solving the problem of attitude optimization in the process of scraping complex surfaces and verify the feasibility of the method.

2. Mathematical Modelling

2.1. Geometric model and attitude description of scraper

The blade of the scraper is a flat edge, which is the working part of the scraper. The geometric shape is a straight line. The main body is a flaky structure. In the process of robot scraping glue, when the blade of the scraper contacts with the free-form surface, the contact area is geometrically represented as a line. This line is a part of the surface, which can form different curvatures and lengths on different surface shapes, depending on the geometry of the surface and the attitude of the scraper. Suppose that the scraper is a straight line segment with a fixed length L, the endpoints are A and B, the midpoint is $P = (x_m, y_m, z_m)$, and the initial position at both ends of the line segment is represented by a vector. Assuming that the direction vector of the line segment is V, the two ends of the line segment can be expressed as:

$$\boldsymbol{A} = P - \frac{1}{2}\boldsymbol{v}, \boldsymbol{B} = P + \frac{1}{2}\boldsymbol{v} \tag{1}$$

Where $V = (v_x, v_y, v_z)$ is the direction vector of the line segment.

In three-dimensional space, the attitude of the scraper can be described by its position and direction in space. A local coordinate system$O_s - X_s Y_s Z_s$ is used to define the specific position and attitude of the scraper. The coordinate system changes with the movement and rotation of the scraper. The global coordinate system $O - XYZ$ is introduced to describe the position and direction in the entire workspace [4]. The position of the scraper is described by its centroid$O_s = (x_s, y_s, z_s)$. Indicates the position of the scraper in its local coordinate system. The position of the centroid point in the global coordinate system is described by a displacement vector Ts, which represents the position of the origin of the scraper in the global coordinate system. The direction of the blade is described by its three key vectors in the local coordinate system, see Figure 1.

The main normal direction (n_p): represents the normal direction of the scraper working face (the plane where the blade is located).

$$\boldsymbol{n_p} = \begin{bmatrix} n_{px} \\ n_{py} \\ n_{pz} \end{bmatrix} \tag{2}$$

Normal (n_s): a vector perpendicular to the motion direction of the scraper and the normal direction of the plane.

$$\boldsymbol{n}_s = \begin{bmatrix} n_{sx} \\ n_{sy} \\ n_{sz} \end{bmatrix} \tag{3}$$

Tangential normal direction (t): represents the moving direction of the scraper on the surface of the workpiece.

$$t = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} \tag{4}$$

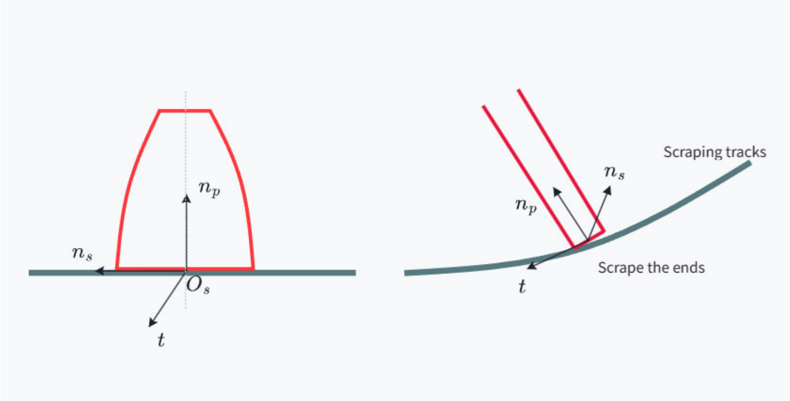

Figure 1. Scraping trajectory posture

2.2. Establishment of free surface model of composite materials

When studying the free-form surface scraping of composite materials, the first step is to construct a free-form surface model and analyze its characteristics. Because the change of free-form surface in space is complex and difficult to predict, the combination of basis function and control vertex is generally used to describe the surface. The NURBS method can accurately describe free-form surfaces and conic curves, and shows great flexibility in the surface construction process. By adjusting the control points and weight factors, the surface shape can be effectively modified. NURBS surface still maintains its geometric characteristics after translation and other transformations. It has geometric invariance and is suitable for designing complex curves and surfaces. Therefore, it has become the most commonly used surface modeling technology [5]. It is a standard practice to use non-uniform rational B-splines to characterize free-form surfaces, which has been widely used in many fields such as computer graphics and computer-aided meters [6].

Suppose that the composite material surface is a NURBS surface with degree p in u direction and degree q in v direction, then the rational vector function expression of the surface is:

$$S(u,v)=\frac{\sum_{i=0}^{m}\sum_{j=0}^{n}\omega_{ij}\,P_{ij}N_{i,p}(u)N_{j,q}(v)}{\sum_{i=0}^{m}\sum_{j=0}^{n}\omega_{ij}\,N_{i,p}(u)N_{j,q}(v)}0\le u,v\le 1 \tag{5}$$

In this formula, u and v are surface parameter variables ; p_{ij} is the control point on the surface, and ij represents the number of meshes ; w_{ij} is a weight factor associated with control points, p, q denotes the number of weight factors, $N_{i,p}(u)$, $N_{j,q}(\mathrm{v})$ are defined as the non-rational B-spline basis functions on the node vectors u, v, respectively [7]. In the process of free-form surface scraping, the free-form surface represented by NURBS provides great flexibility and accuracy. By precisely adjusting the NURBS control points and their weights, free-form surfaces with complex geometric shapes can be generated, thereby improving the accuracy and smoothness of the scraping tool path. In addition, the geometric description based on NURBS also provides a good mathematical basis for the calculation of the normal vector and tangent plane of the control contact point, which is helpful to optimize the motion trajectory and attitude control in the scraping process.

2.3. Contact point normal and curvature calculation

In the process of free-form surface scraping, the contact point between the scraping tool and the free-form surface has complex geometric characteristics. In order to describe the curvature and normal direction of the contact point during the scraping process, it is necessary to analyze the local geometric properties of the surface. It is of great significance to study the curvature and normal direction of the contact point between the scraping tool and the free-form surface to improve the accuracy of the scraping process. The normal vector of the contact point is one of the key parameters to characterize the local direction of the surface, which is perpendicular to the tangent plane of the point. The general free-form surface of the parametric form is $S(u,v)$, and any point $P(u,v)$ on the surface can be expressed as.

$$P(\mathrm{u,v})=\big(x(\mathrm{u,v}),\mathrm{y(u,v)},\mathrm{z(u,v)}\big) \tag{6}$$

Among them, u, v are free-form surface parameters, and the three components x, y, z are two element differentiable functions of the parameters u, v.

At the contact point $P(u,v)$ on the surface, the normal vector at the contact point can be obtained by calculating the first type of parameter derivative of the surface. The tangent vector is the derivative along the direction of the parameters u and v on the surface. According to the surface expression, the first-order partial derivative at this point can be expressed as:

$$S_u = \frac{\partial P(u,v)}{\partial u}, S_v = \frac{\partial P(u,v)}{\partial v} \tag{7}$$

Here, S_u and $S_v$are the tangential vectors along the direction of u and v at the point $P(u,v)$, respectively. The normal vector $N(u,v)$is the cross product of these two tangent vectors:

$$N(u,v) = \frac{S_u \times S_v}{|S_u \times S_v|} \tag{8}$$

In the actual scraping process, when the scraping tool contacts with the free-form surface, the scraping surface of the tool should maintain a certain relationship with the normal direction of the contact point to ensure the uniform distribution of the glue. On the basis of the normal direction of the contact point, the relative attitude of the scraping tool can be adjusted to make it move along the direction of smaller curvature, so as to reduce the uneven scraping caused by excessive curvature change. At the same time, the curvature of the contact point will directly affect the direction and distribution of the force applied to the tool, thus affecting the scraping accuracy. The curvature at the contact point is characterized by the second derivative of the surface.

The second-order partial derivative of this point can be expressed as:

$$S_{uu} = \frac{\partial^2 P(u,v)}{\partial u^2} \tag{9}$$

$$S_{uv} = \frac{\partial^2 P(u,v)}{\partial u\, \partial v} \tag{10}$$

$$S_{vv} = \frac{\partial^2 P(u,v)}{\partial v^2} \tag{11}$$

These second-order derivatives and first-order derivatives together constitute the basic form of the surface, which is used to calculate geometric quantities such as principal curvature and Gaussian curvature. Through the principal curvature $k1$ and $k2$, the curvature characteristics of the contact point can be described [8]. The principal curvature and normal vector of the surface contact point $P(u,v)$ are shown in the figure 2. After the normal vector is obtained, the tangent plane of the contact between the scraper and the surface is determined. The feed direction and running direction of the scraper can be judged by the direction of the maximum and minimum principal curvature, and the specific posture position of the scraper is determined by optimization calculation.

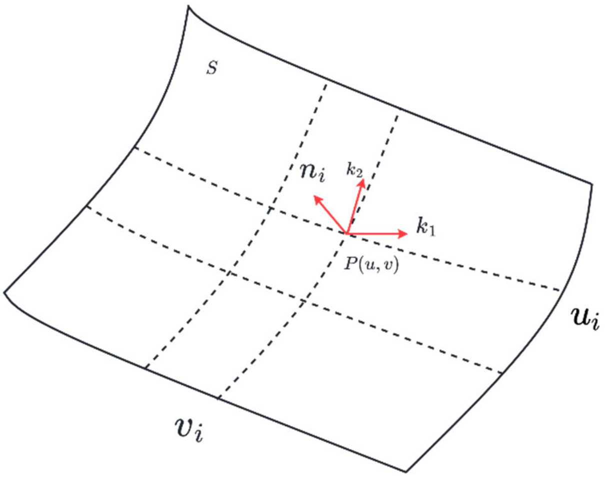

Figure 2. NURBS surface principal curvature and normal vector diagram

3. Research on Optimization Error of Scraper Attitude

3.1. Data acquisition

As a powerful CAD / CAM software, UG (Unigraphics) provides a variety of methods to obtain surface data. These methods can be divided into operation interface method and programming interface method. Specifically, it includes extracting surface features, extracting regional surfaces, procedurally obtaining surface point data, using NXOpen API, surface analysis tools, and interface operations. It is a basic operation to extract surface features by importing the known part model into UG software, which aims to obtain the existing surface from the solid or sheet model. Open the model file in the working environment of UG, by selecting the [insert] →[mesh surface]→[through the curve grid] command. After completing the curve selection, UG will generate a new surface model, as shown in Figure 3.

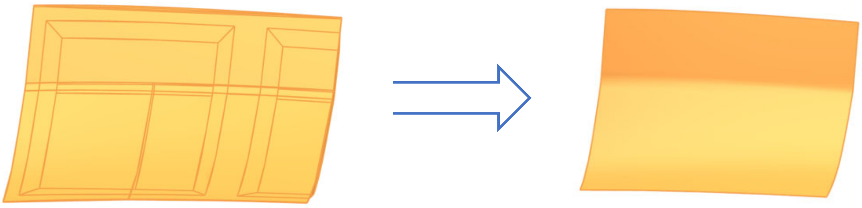

Figure 3. Scraping glue surface model

In the study of surface data acquisition, the secondary development of UG / NX provides a powerful tool. By calling the functions in UG / NX API, UF _ MODL _ ask _ face _ props and UF _ MODL _ ask _ face _ parm are mainly used to query the properties of the surface. These attributes not only include the type and boundary information of the surface, but also cover many geometric features such as curvature, tangent and normal vector. Used to locate a specific point on a surface. The function can return the coordinates of the point and reflect its specific position in the three-dimensional space. In addition, the function also outputs tangent vectors in the u and v directions, which are important features for describing the local shape of the surface. Finally, the geometric information related to the parameters is returned. As shown in the figure4.

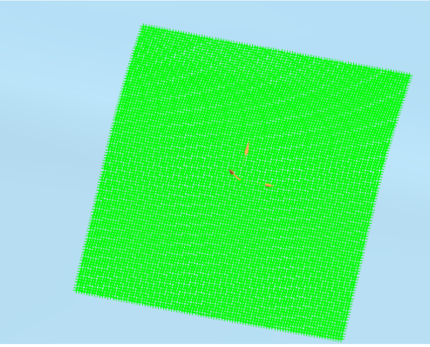

Figure 4. Local data information acquisition

3.2. Rotation and projection of scraper

The line segment rotates at a certain angle based on the contact point of the surface, where the rotation axis is the normal direction of the contact point, and its normal direction n is obtained by calculating the partial derivative of the surface at this point. In three-dimensional space, around a unit vector $\vec{u} = (u_x, u_y, u_z)$,the rotation matrix $R(\vec{u}, \theta)$of the rotation angle θ can be calculated by Rodriguez rotation formula, or can be directly constructed by the following steps:

$$R(\vec{u},\theta)=\begin{bmatrix} \cos(\theta)+u_x^2\cdot(1-\cos(\theta)) & u_x\cdot u_y\cdot(1-\cos(\theta))-u_x\cdot\sin(\theta) & u_x\cdot u_z\cdot(1-\cos(\theta))+u_y\cdot\sin(\theta) \\ u_y\cdot u_x\cdot(1-\cos(\theta))+u_x\cdot\sin(\theta) & \cos(\theta)+u_y^2\cdot(1-\cos(\theta)) & u_y\cdot u_z\cdot(1-\cos(\theta))-u_x\cdot\sin(\theta) \\ u_x\cdot u_x\cdot(1-\cos(\theta))-u_y\cdot\sin(\theta) & u_x\cdot u_y\cdot(1-\cos(\theta))+u_x\cdot\sin(\theta) & \cos(\theta)+u_z^2\cdot(1-\cos(\theta)) \end{bmatrix} \tag{12}$$

The rotation vector $\vec{v}$ is multiplied by the rotation matrix $R(\vec{u}, \theta)$:

$$\vec{v}' = R(\vec{u}, \theta) \cdot \vec{v} \tag{13}$$

where $\vec{v}'$ is the rotated vector.

The linear segment equation after rotation can be expressed as:

$$\gamma(t) = P + tv', t \in \left[-\frac{1}{2}, \frac{1}{2}\right] \tag{14}$$

In order to find the projection point of the line segment on the surface, the equation needs to be solved:

$$s(u, v) - \gamma(t) = 0 \tag{15}$$

In order to find the projection curve of the straight line segment on the surface, the intersection point of the straight line and the surface is solved.

Substitute the linear equation into the surface equation:

$$S(u, v) = P + tv \tag{16}$$

For the equations of u, v and t, expand the surface equation S (u, v):

$$\begin{aligned} S_x(u,v) &= x_p + tv_x \\ S_y(u,v) &= y_p + tv_y \\ S_z(u,v) &= z_p + tv_z \end{aligned} \tag{17}$$

The values of t and corresponding (u, v) are obtained by solving the equations.

The projection curve of the straight line segment is expressed as a parameter equation:

$$Q(t) = S\big(u(t), v(t)\big) \tag{18}$$

where $u(t)$ and $v(t)$are functions of the line segment parameter t.

3.3. Error calculating

In order to minimize the difference between the straight line segment and the projection curve, an objective function for evaluating the contact effect is defined to minimize the error between the projection curve of the scraper on the surface and the straight line of the scraper. The objective function is established to quantify the contact effect, and the error of the line and curve of the objective function is minimized. It is necessary to define an error function $E(\theta)$, where θ denotes the rotation parameter of the line segment. The error function will be used as the objective function of the optimization problem to find the best rotation angle, so that the difference between the rotated line segment and the projection curve is minimized. For each point $P(t,\theta)$ on the rotating line and the corresponding projection point $Q(t,\theta)$, define the distance:

$$d(t) = \| P(t,\theta) - Q(t,\theta) \| \tag{19}$$

The error function E (θ) is the sum of squares of the distances of all points on the line segment:

$$E(\theta) = \int_{-\frac{L}{2}}^{\frac{L}{2}} \|\mathbf{P}(t,\theta) - \mathbf{Q}(t,\theta)\|^2 dt \tag{20}$$

In this paper, the objective function is defined by establishing the mathematical model of the contact between the scraper and the free surface.

The iterative process of the algorithm is as follows:

1.Initialization parameters: select an initial parameter value θ_0 as the initial position of the projection curve parameters.

2.Calculate the projection point: Under the given parameter θ, the current parameter θ is used to calculate the projection point $Q(t,\theta)$ of each point $P(t,\theta)$ on the straight line on the surface.

3.Calculate residuals: For each point P, calculate the difference between it and the projection point Q, that is, the residual e_i.

4.Construct residual sum of squares: Calculate the sum of squares of all residuals $E(\theta) = \Sigma_{\mathrm{i}=1}^{n} e_i^2$.

5.Calculation of gradient: Calculate the gradient $\nabla E(\theta)$ of the error function $E(\theta)$with respect to parameter θ.

6.Update parameters: Use gradient information to update the value of the parameter θ to reduce the error function $E(\theta)$.

7. Check the convergence: Repeat the iterative process until the change of the error function is less than the allowable range of the error, and the iteration ends. The optimization flow chart is shown in Fig.5.

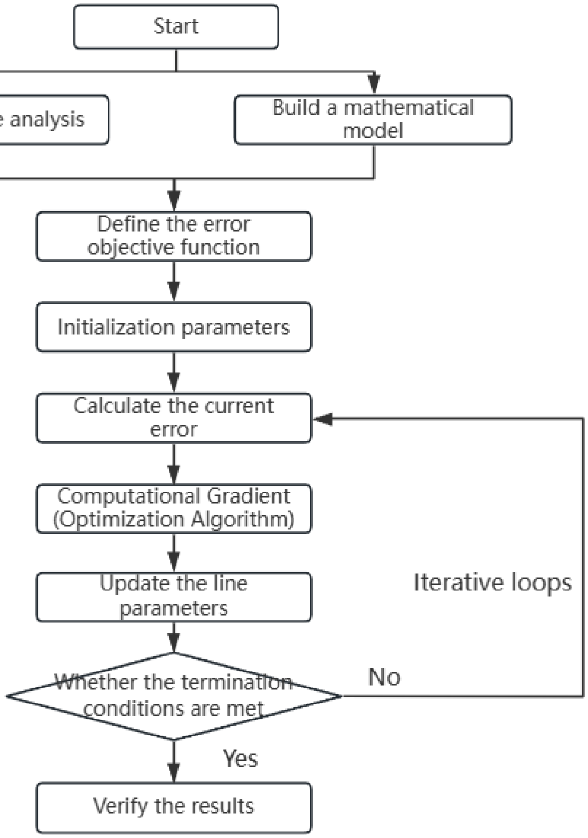

Figure 5. Scraper attitude optimization flow chart

By continuously adjusting the parameter θ, the residual between the projection point of the point on the line on the target surface and the original point is minimized. The core of the whole process is the calculation of the gradient and the update of the parameters. The purpose is to find the parameter value that minimizes the error function $E(\theta)$, so as to achieve the best fitting of the curve. Output the spatial attitude position of the scraper when the error between the scraper and the surface is the smallest.

4. Experimental Simulation and Error Comparison

In order to verify the correctness and effectiveness of the algorithm, MATLAB simulation calculation is used for an aviation composite component. It is proved that the point posture generated by the robot in the scraping process is compared with the optimized one. A point on the surface is selected as the contact point between the scraper and the surface. The data of the area around the contact point is extracted by UG secondary development. The initial position and direction of the scraper are defined. The length is 100 mm, and the midpoint of the scraper is located at the contact point. The tangent plane of the normal vector N and the point is obtained. As shown in Fig.6.

Let the straight line rotate in the tangent plane for error calculation. The range and step size of the rotation angle are set to rotate one circle around the normal direction, and the step size is 1 degree. By rotating the direction of the scraper, the error between the straight line and the projection curve along the normal direction on the surface at each angle is calculated. By comparing the error values at different rotation angles, the optimal angle corresponding to the minimum error can be determined, and the effect of the angle in practical application can be evaluated. As shown in Figure 7, it is possible to obtain the degree of rotation of the straight line on the tangent plane relative to the initial position.

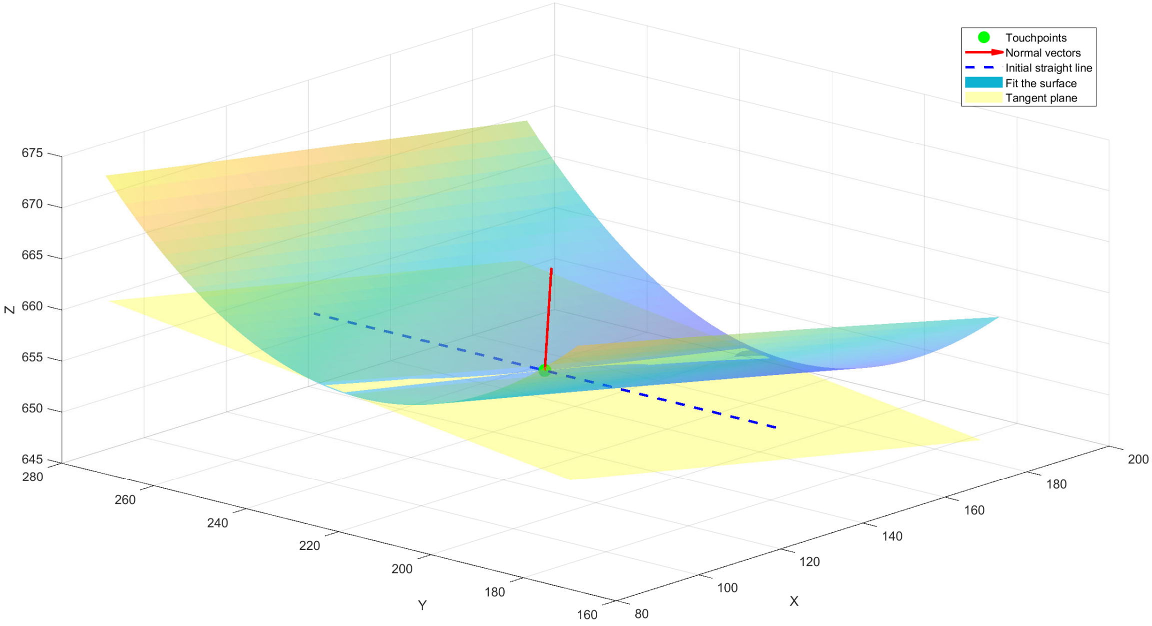

Figure 6. Local area surface of contact point

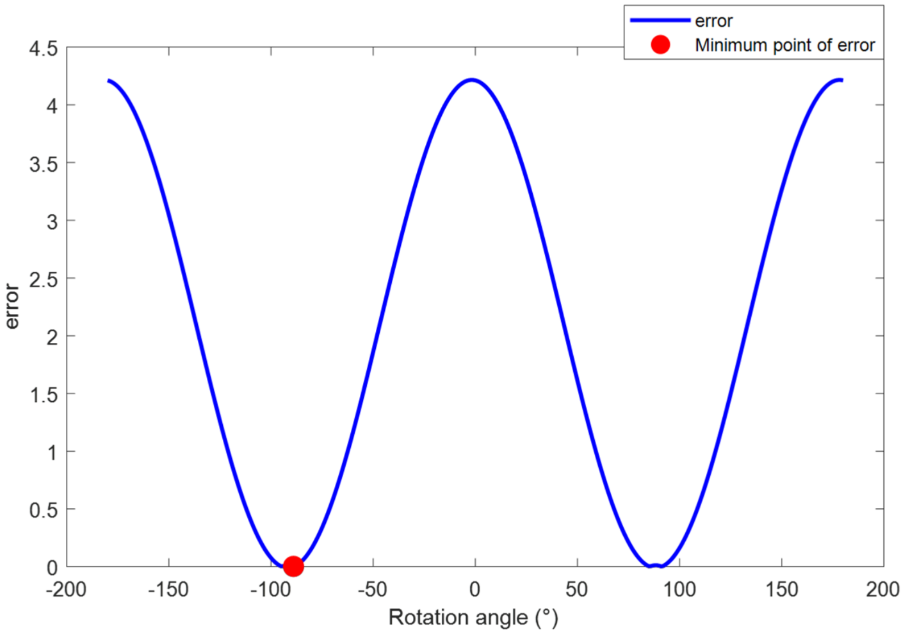

Figure 7. Rotation error analysis diagram

In the experiment, in order to deeply analyze the performance of the scraper under different postures, the error when it rotates around the XYZ axis is systematically analyzed. Specifically, by rotating the direction of the scraper along the normal vector and gradually adjusting it in the angle range of-180° to 180°, the error value at each angle is calculated. These error values reflect the deviation between the actual position of the scraper and the theoretical surface obtained by local surface fitting. The size of the error represents the accuracy of the scraper fitting with the surface under a specific attitude.

The error analysis is discussed for the rotation of the scraper around the X axis, Y axis and Z axis, as shown in Fig.8. When rotating around the X axis, the error analysis diagram shows that the error value shows a certain fluctuation trend with the change of the rotation angle, and the error reaches the local minimum value at some angles, which indicates that the attitude of the scraper at these angles is more matched with the fitting surface. Similarly, the error analysis of the rotation around the Y axis reveals the influence of the attitude adjustment of the scraper in another plane on its error. Similar to the X-axis error change, there is also a specific angle around the Y-axis to minimize the error value. Finally, the error diagram when rotating around the Z-axis further shows the relationship between the attitude change and the error of the scraper in the third dimension. Although the fluctuation range is different from the first two, the overall trend is consistent, indicating that the attitude of the scraper at some angles can be more consistent with the theoretical surface.

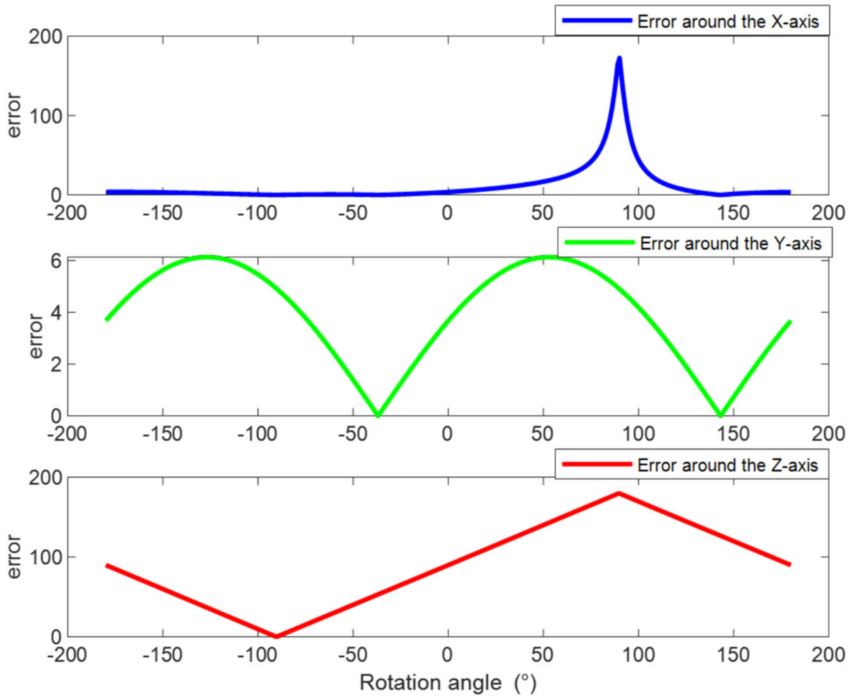

Figure 8. Error analysis diagram around XYZ

Through the error analysis diagram, the best rotation attitude of the scraper in the three-dimensional space can be clearly found, that is, the angle with the smallest error. Considering the error change trend around the XYZ axis, it can be determined that the scraper achieves the highest degree of agreement with the fitted surface at these optimal angles. These analysis results provide an important reference for the subsequent attitude optimization, which is helpful to further improve the accuracy and performance stability of the scraper in complex surface operations.

Comparing the posture of the robot 's off-line programming with the optimized posture, the posture obtained by the two methods is compared with reference. The scraper posture of the off-line programming interferes with the surface during contact, and the contact point of the optimized scraper is accurately positioned. The scraper plane not only fits better with the surface, but also adjusts its relative position by rotation, thereby improving the contact state and improving the scraping accuracy.

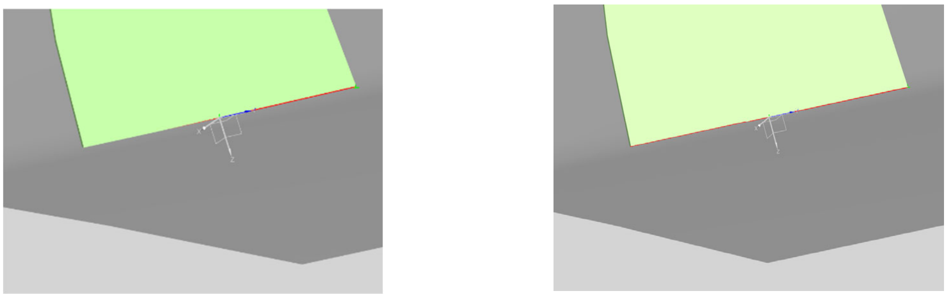

Figure 9. Comparison of surface scraping posture before and after optimization

5. Conclusion

This paper aims at the problems existing in the contact process of scraper on the surface of aviation composite parts during the processing of composite materials. In this paper, the pose optimization of the scraper in the scraping process of complex surfaces is studied, and a method based on the rotation algorithm is proposed to minimize the error between the scraper line and the surface projection. Through the establishment of mathematical model, the geometric characteristics and attitude description of the scraper are analyzed in depth, and the free surface model is constructed by NURBS method, which provides strong support for the motion trajectory and attitude control in the scraping process. The experimental results show that the optimized scraper attitude significantly improves the contact accuracy with the composite surface. The error analysis at different rotation angles reveals the optimal matching between the scraper and the theoretical surface under a specific attitude, which effectively reduces the uneven scraping caused by the attitude deviation. Compared with the traditional off-line programming method, the optimized scraper posture can better adapt to the geometric characteristics of complex surfaces and ensure the efficiency and consistency of the scraping process.

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