Smooth path generation method of laser cladding bit repair robot based on 3D automatic measurement of wear surface point cloud

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Abstract. In the work of repairing worn drill bits by laser cladding robots, the worn surface often presents irregular curved surfaces, which brings difficulties to cladding. Aiming at the generation of cladding path on irregular curved surfaces of worn drill bits, this paper proposes a method of searching interpolation points by equal defocusing. Firstly, perform point cloud slice processing on the 3D model of the worn drill bit. Then the point cloud model is fitted by the cubic B-spline curve. Finally, the proposed method is used to screen out the actual operating processing points of the robotic arm. By comparing the coincidence degree between the actual cladding path and the curved surface, the feasibility of using the method of searching interpolation points by equal defocusing on the fitted path to obtain a smooth path is verified.

1. Introduction
As an important mining tool in the resource acquisition industry, oil well drill bits are prone to wear and tear during long-term use, and replacement of new drill bits will have a greater impact on economic benefits. Laser cladding repair technology has become an important research direction in the repair of worn drill bits with its advanced energy saving and environmental protection concept. Since laser cladding work is harmful to human eyes, it is an inevitable trend to use robotic arms to carry laser automatic cladding. The abrasion of oil well drill bit often presents irregular curved surface shape, so the curved surface processing path of the robot arm is the key issue of the quality of cladding.

Figure 1. Drill bit to be repaired. a worn drill bit. b 3D model
In order to make the robotic arm better complete the processing of irregular shapes during processing, many researchers have studied the smooth path of the robotic arm processing. Xie et al.\cite{1} used the B-spline curve smoothing algorithm to remove sharp corners on the 3D printing path, and the results showed that the printing rate was accelerated, but the production of too many processing points was not conducive to the operation of the robotic arm. Zheng et al.\cite{2} established a new path topology relationship by extracting the size information and topology information of the CAD model of complex parts, and using the binary tree algorithm model, but the feasibility in actual processing has yet to be verified. In intelligent welding using a robotic arm, Zhang et al.\cite{3} scanned out the three-dimensional information of the weld seam and extracted the weld seam features through gray-scale images, and used the B-spline curve to fit the data points to obtain a smooth welding path.

This paper studies the generation of smooth machining path on the surface of the worn drill bit in figure 1(a). Because the wear surface of drill bits is often random and irregular, the complete and ordered point cloud is often not obtained when the 3D vision equipment scans its shape. The point cloud in figure 2(b) has three large holes, which makes difficulties in generating the processing path.

2. Point cloud model processing and fitting method

2.1. 3D point cloud acquisition and slicing

In this paper, the 3D point cloud of the surface is obtained by using a blu-ray scanning camera, and uses the geomagic studio software to denoise the original point cloud to remove the extra plane.

In the actual cladding path, each cladding channel has a different width according to the configuration of the process parameters, so the horizontal number of the path can be determined according to the width of the processing surface. And the point cloud slicing technology is used to slice the curved surface point cloud to divide the vertical path and finally generate the path point cloud such as shown in figure 2. It is found that the distance between the path points at the point cloud missing is large, which is not conducive to cladding the actual surface. Therefore, it is necessary to use the B-spline curve to smoothly fit the entire point cloud model.

![Figure 2. Point cloud slice](image)

2.2. B-spline curve fitting

In industrial manufacturing, the general G2 continuity curve can meet the requirements of accuracy and shape continuity. When using the point cloud obtained by scanning to fit a path, the fitted path must pass through the point cloud data to have practical meaning. Generally, the curve generated by the B-spline method by setting the control points cannot determine the route well, so the method of using the cubic B-spline interpolation curve (G2 continuous) is selected to fit the path.

The equation of cubic B-spline interpolation curve is:

\[
Q(u) = \sum_{i=0}^{n} N_{i,3}(u) d_i , \quad i = 0,1,2,3, \ldots , n
\]

(1)

Where \(d_i\) represent the control points. And \(N_{i,3}(u)\) are the basis function determined by the node vector and the node, whose standard algorithm Deboor-Cox recurrence formula is as follows:

\[
\begin{align*}
N_{i,0}(u) &= \begin{cases} 
1, & u_i \leq u < u_{i+1} \\
0, & \text{other} 
\end{cases} \\
N_{i,k}(u) &= \frac{u-u_i}{u_{i+k}-u_i} N_{i,k-1}(u) + \frac{u_{i+k+1}-u}{u_{i+k+1}-u_{i+1}} N_{i+1,k-1}(u)
\end{align*}
\]

(2)
2.2.1. Calculation of node vector

In the parameter design, because the data points obtained by the point cloud are not uniformly distributed, the chord length method can allocate different proportions according to the chord length between the non-equidistant data points, which is a more suitable method.

Suppose there are \( m+1 \) data points \( q_i (i=0,1,2,3,\ldots,m) \), then \( m+3 \) control points are needed. In order to make the first and last control points pass the first and last data points, the first \( k+1 \) parameters should be set to 0, and the last \( k+1 \) parameters should be set to 1. The nodal vector parameters of the cubic B-spline combined with the chord length method can be expressed as:

\[
\begin{align*}
    &u_0 = u_1 = u_2 = u_3 = 0 \\
    &u_{j+3} = \frac{\sum_{i=0}^{m} q_i}{m}, \quad j = 1,2,3,\ldots,m-1 \\
    &u_{m+3} = u_{m+4} = u_{m+5} = u_{m+6} = 1
\end{align*}
\]

(3)

B-spline curve interpolation is the process of inverting control points when the basis function and data points are known. For an open loop curve, the process of obtaining its control points is as follows:

\[
\begin{bmatrix}
    a_1 & b_1 & c_1 & \cdots & a_m & b_m & c_m \\
    a_2 & b_2 & c_2 & & \cdots & a_{m+1} & b_{m+1} & c_{m+1} \\
    \vdots & & & \ddots & & & \vdots & \vdots \\
    a_{i-1} & b_{i-1} & c_{i-1} & & & & & \\
    a_i & b_i & c_i & & & & & \\
    a_{i+1} & b_{i+1} & c_{i+1} & & & & & \\
    \vdots & & & \ddots & & & \vdots & \vdots \\
    a_{m-1} & b_{m-1} & c_{m-1} & & & & & \\
    a_m & b_m & c_m & & & & & \\
\end{bmatrix}
\begin{bmatrix}
    d_1 \\
    \vdots \\
    d_{m+1} \\
\end{bmatrix}
= 
\begin{bmatrix}
    e_1 \\
    \vdots \\
    e_{m+1} \\
\end{bmatrix}
\]

(4)

Where \( \Delta_i = u_{i+1} - u_i \), \( \dot{q}_0 \) and \( \dot{q}_m \) are the tangent vectors of the first and last data points.

2.2.2. Boundary conditions

The \( m+1 \) equations are not enough to calculate the \( m+3 \) control vertices. It is necessary to add two boundary condition equations of the first and end points to find all the control points. There are two main methods for adding boundary conditions: setting free points and tangent vector points. There are many ways to find the points of the tangent vector. The method of finding the tangent vector in this paper is as follows:

\[
\begin{align*}
    a_1 &= 1, \quad b_1 = c_1 = 0, \quad e_1 = q_0 + \frac{\Delta_0}{2}, \dot{q}_0 \\
    a_m &= b_m = c_m = 1, \quad e_m = q_m - \frac{\Delta_{m-1}}{3}, \dot{q}_m \\
    a_{m+1} &= b_{m+1} = 0, \quad c_{m+1} = 1, \quad e_{m+1} = q_m - \frac{\Delta_{m+2}}{3}, \dot{q}_m
\end{align*}
\]

(5)

Figure 3 shows the comparison between the fitting result and the actual data points line segment under the boundary conditions of the free points and the tangent vector points.

![Figure 3. The boundary conditions. a free points. b tangent vector points.](image)

By calculating the mean square error of fitting curve and actual line segment, the fitting accuracy of two boundary condition methods is compared. The mean square error (MSE) calculation formula is:
Where \( y_i \) are the real data, \( \hat{y}_i \) are the data after fitting, \( n \) is the number of samples, and \( \omega_i \) are the proportion of distribution. As shown in table 1, the accuracy of the fitting curve in figure 3(a) is significantly lower than that in figure 3(b). The condition of the tangent vector points make the fitting curve closer to the tangent direction of the original line segment, and the degree of agreement is higher.

### Table 1 Mean square error under two boundary conditions

| Boundary conditions | Free point | Tangent point |
|---------------------|------------|--------------|
| Mean square error   | 0.6560     | 0.2375       |

3. Generation of actual processing path

3.1. Searching interpolation points by equal defocusing

In the actual cladding of the curved surface, the robotic arm cannot completely follow the fitted curve path to scan and cladding, and its actual movement is a polygon formed by the processing points to approximate the fitted path. In order to simplify the processing point complexity and meet the process error, this paper is based on the interpolation point search method of the maximum defocus to generate the path processing points.\(^{(4)}\)

As shown in figure 4, set a defocus amount threshold, starting from point \( d_i \), connect \( d_{i+2}, d_{i+3}, d_{i+4} \) in turn, and determine the points in the middle range. Whether the distance to the line exceeds the threshold. If it exceeds at point \( d_j \), then \( d_{j-1} \) is the interpolation point obtained from the search. Finally, a series of processing point set \( [q_1,q_2,q_3,...,q_n] \) can be obtained, which is the actual cladding processing path point of the robot arm.

![Figure 4. Interpolation principle of simplified processing point](image)

All the actual processing points are calculated in turn by using the equal defocus path search interpolation algorithm on the fitted path, and they are connected by straight line segments. The processing path shown in figure 5(b) is obtained. Figure 5(a) is the processing path obtained by directly using the point cloud data to perform the equal defocus interpolation algorithm. After comparison, it is found that the processing path in figure 5(a) has a relatively large deviation at the point cloud cavity, and the entire processing path in figure 5(b) is more regular and fits the actual curved surface.

![Figure 5. Path comparison before and after B-spline processing](image)

Table 2 shows the path data in the two cases. The greater the defocus setting, the fewer path points
and the greater the deviation. It can be seen that when the defocus of b path is set larger than a path and the processing path points are almost the same, b path can better fit the curved surface fitting path, indicating that the proposed method has more advantages.

| Defocus | Path a | Path b |
|---------|--------|--------|
|         | 0.1    | 0.5    |
| Number of data | 107    | 110    |

3.2. Example simulation of drill bit

The experimental object is a PDC drill bit. Select one of the worn areas on the surface to generate the cladding path. It can be seen from Figure 6 that the actual cladding path is connected by a limited number of processing points, and its profile has a high degree of agreement with the curved surface.

4. Conclusions

This article is aiming at the generation of the robot cladding path on the wear surface of the drill bit, by denoising and slicing the incomplete point cloud model. The cubic B-spline interpolation curve was used to fit the discrete point cloud, the results show that the fitting path has a high similarity with the original surface shape. By setting a reasonable defocus threshold, the processing interpolation points were selected on the point cloud path and the fitting path respectively, and the comparison found that the interpolation points on the fitting path were closer to the actual surface. Finally, the cladding path was generated for the wear part of the drill bit. It shows that the proposed cladding path generation
method effectively reduces the actual operation complexity of the robot arm, improves the processing efficiency and guarantees its process accuracy, and provides an effective reference for the actual work of repairing the drill bit.

Figure 7. Collection of actual drill bit data

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