Research on Curved Layer Slicing and Spatial Path Generation Method in Five-axis Material Extrusion Process

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Abstract. The traditional additive manufacturing technology uses a plane-cutting method, and the printing path of each layer is limited to a single plane. When printing thin-walled parts, there are problems such as high surface displacement, poor mechanical properties, and the need to add support structure. The paper proposes a five-axis additive manufacturing technology using curved surface slice method. Specifically, it includes a triangular mesh vertex offset surface slicing algorithm based on half-edge data structure and a path planning algorithm based on triangular mesh adjacent topology and geodesic distance field; a series-parallel hybrid five-axis material extrusion printing device has been developed, which fully combines the advantages of the small cumulative error of the parallel mechanism and the large working space of the series mechanism. The proposed surface cutting and path planning method is used to print thin-walled spherical parts and skull substitutes. The surface roughness of the printed parts is significantly improved. The results show the correctness and feasibility of the algorithm.

1. Introduction
Additive manufacturing technology uses the method of adding materials layer by layer to manufacture physical parts [1]. After nearly 40 years of development, it has demonstrated significant value and broad application prospects in strategic emerging industries such as aerospace, rail transit, new energy, new materials, and medical instruments[2]. The traditional plane cutting technology needs to cut the model into thin layers along the Z axis to complete the layer-by-layer accumulation [3]. Therefore, the outer contour of the printed part will produce a "step effect", resulting in the decrease in printing accuracy and the increase in the surface roughness of the part [4]. In addition, support needs to be added when printing the cantilever structure, which prolongs the printing time and wastes printing materials[5]. When the support is removed, it is easy to cause damage to the surface of the part and reduce the surface quality of the printed part.

In order to overcome the above shortcomings, scholars have successively proposed adaptive slices, multi-directional slices, and variable thickness slices [6]. These layering methods are all based on dividing the part model into several plane layers, and do not fundamentally solve the inherent defects of traditional plane layering additive manufacturing technology. Based on this, Chakraborty et al. [7] proposed a curved surface layer material extrusion method. Firstly, the model is divided into several curved surface layers, and then a multi-axis printing device is used to make the nozzle motion trajectory
to fill each layer of curved surfaces, and then accumulate layer by layer from bottom to top [8], and finally complete the model printing.

We adopt a five-axis printing method for surface slices, and propose a triangle mesh vertex offset surface slice algorithm based on half-edge data structure. The algorithm has low complexity and does not lose the geometric topological relationship of the offset surface during the layer cutting process, thereby reducing the shape distortion. We propose a path planning algorithm based on the triangular mesh adjacent topological relationship and geodesic distance field, which can plan printing paths with different filling styles in free-form surfaces; based on the above algorithm, a series-parallel hybrid five-axis material extrusion device was built, and the correctness and feasibility of the aforementioned algorithm were verified by printing a representative model.

2. A method of surface cutting layer based on triangular mesh offset

Aiming at the shortcomings of the existing surface layering[9], this section will introduce a method of triangular mesh vertex offset surface layering based on half-edge data structure. The brief steps are as follows:

1) Read the triangular mesh model of the part, and establish the topological relationship between points, lines and surfaces based on the half-edge data structure.

2) Segmentation of the upper and lower surfaces of the model and optimization of the triangular mesh.

3) The above surface is used as the basic surface, and each vertex is offset in the opposite direction of its normal vector to obtain the offset surface.

4) Take the offset surface as the basic surface, and intersect the original model to get the next offset surface. Repeat this step until the end of the slice.

Firstly, the half-edge structure is used to store the position information of the vertices of the triangular mesh and the topology information between geometric elements. Then, take the equal thickness and thin-walled parts as an example to perform curved surface cutting and path planning. The upper surface of the model is used as the basic offset surface of the curved surface tangent layer, and the upper surface of the model is segmented based on the normal vector direction of the triangular surface and its adjacent topological relationship. The normal vector of each vertex is equal to the mean value of the normal vector of the triangular face containing the vertex, and the calculation formula is (1). The area composed of triangles whose normal vector and the positive Z-axis angle is less than 90° constitutes the upper surface, as shown in Figure 1(a).

\[ N_v = \frac{1}{n} \sum_{i=1}^{n} N_{fi} \]  (1)

Where: \( N_v \) —— normal vector of mesh vertex \( v \); \( n \) —— the number of triangle meshes surrounding the vertex \( v \); \( N_{fi} \) —— the normal vector of the \( i \) triangular mesh.

(a) Surface segmentation results on the model     (b) Comparison of surface offset results

Figure 1. Surface slice processing based on triangular mesh offset

The offset of the triangular mesh surface is completed by the method based on vertex offset. For non-boundary vertices, offset along the opposite direction of its normal vector, the calculation formula is (2). For boundary vertices, offset along the negative direction of the Z axis, the calculation formula is (3).

\[ V_{offset} = V_{origin} - N_v \cdot T \]  (2)
Where: \( V_{\text{offset}} \) —— coordinates of non-boundary vertices after offset; \( V_{\text{origin}} \) —— coordinate before offset of non-boundary vertex; \( N_v \) —— the unit normal vector of the vertex; \( T \) —— the layer thickness of the curved surface; \( V'_{\text{offset}} \) —— the coordinates of the boundary vertex offset; \( V'_{\text{origin}} \) —— the coordinates before the edge vertex offset; \( e \) —— the unit vector in the vertical downward direction; \( \theta \) —— the angle between the vertex normal vector and the positive direction of the \( Z \) axis.

The single offset result of the base surface is shown in Figure 1 (b), the gray surface is the base surface, and the yellow surface is the offset surface.

3. Printing path planning on the triangular mesh surface

In order to solve the problem of nozzle printing path planning on arbitrary triangular mesh surfaces, this section proposes a path planning algorithm based on triangular mesh adjacent topology and geodesic distance field. The steps are as follows:

1) Construct a half-edge data structure, select the zero point of the geodetic distance on the triangular mesh, calculate the positions of the remaining vertices to the zero point, and establish a geodesic distance field;

2) Extract the contours in the ranging field, the difference between adjacent contours is equal to the diameter of the nozzle, and the contour is the trajectory of the knife contact;

3) Calculate the knife axis vector of each knife contact, and calculate the corresponding wire extrusion amount by combining the slice thickness and the nozzle size.

We use the ICH algorithm (Improving Chen and Han’s Algorithm) to calculate the geodesic distance between two points on the triangular grid [10].

\[
d = \sigma + \min(\sigma |w| + |rv|)
\]  

Where: \( d \) —— geodetic distance between two points; \( \sigma \) —— the geodetic distance from point \( v \) to point \( s \); \( r \) —— a point in window \( w \); \( w \) —— a window located on one side of the triangular grid \( f \); \( t \) —— a point on the triangular grid \( f \); \( v \) —— the pseudo source point corresponding to window \( w \).

After completing the establishment of the geodesic distance field, combined with the topological relationship between geometric elements on the surface of the triangular mesh, isolines can be extracted from the distance field in an orderly manner. The geodetic distance value of each isoline point is calculated according to formula (5).

\[
d_i = \begin{cases} 
    r, i = 1 \\
    (2i+1)r, i > 1
\end{cases}
\]  

Where: \( d_i \) —— the geodetic distance of the point on the \( i \) contour line; \( r \) —— the nozzle radius of the printer; \( i \) —— the serial number of the contour.

Relying on the above algorithm, different end-to-end printing paths are shown in Figure 2.
4. Application of curved surface cutting method in five-axis material extrusion forming

Taking the spherical shell model as an example, the roughness of the upper surface of the spherical shell sample prepared by three-axis printing and five-axis printing was measured respectively. The thickness of the one-sided cutting layer and the curved surface cutting layer are set to be 0.1mm. The curved surface cutting layer and nozzle path of the five-axis printing are generated according to the algorithm proposed in this paper. In the five-axis printing process, the first surface of the model adopts pseudo-tangential printing mode, and the upper surface adopts normal printing mode, and the printing can be completed by adding up layer by layer.

The sample of the three-axis printing spherical shell is shown in Figure 3(a), and the upper surface roughness Ra is measured to be 21.7μm. The cross-sectional profile of the upper surface is shown in Figure 3(b). It can be seen from the figure that Plane slicing method will produce obvious "step effect", resulting in the deterioration of the surface quality of the part and increasing the shape error of the printed part. The five-axis printed spherical shell sample with curved surface cut layer is shown in Figure 3(c), and the measured upper surface roughness Ra is 4.3μm, and the cross-sectional profile of the upper surface is shown in Figure 3(d). The contour line is a smooth arc, and there is no obvious "step effect". Therefore, the surface roughness of the five-axis printing spherical shell sample with curved-cutting layer is much lower than that of the flat-cutting three-axis printing sample with the same layer thickness. This shows that five-axis printing can not only reduce or even remove the support structure, but also significantly improve the surface quality of the parts and reduce the surface roughness of the parts.
5. Conclusion
This paper proposes a triangle mesh vertex offset surface slicing algorithm based on half-edge data structure and a path planning algorithm based on triangle mesh adjacent topological relationship and geodesic distance field. Corresponding model processing software was developed, and a series-parallel hybrid five-axis material extrusion printing device was built to verify the correctness of the algorithm. The effect of the five-axis printing process on the surface quality of parts was studied. By printing a typical spherical shell model, the correctness and feasibility of the algorithm in this paper are verified.

Subsequent research content includes expanding the application range of five-axis printing, variable-layer-thickness surface cutting algorithms for models of unequal thickness and thin-walled parts, more comprehensive research on variable-layer thickness five-axis printing processes, and the anti-interference algorithm in five-axis printing process.

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