A hybrid tool-path with no pause generation algorithm for 3D printing

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Abstract. With the development of the manufacturing industry, 3D printing has gradually become a focus of attention due to its unique advantages such as fast speed and low threshold. As an important part of the printing process, scanning path planning directly affects the quality of the molded part. Based on the existing path research, this paper proposes a new filling algorithm, which uses the idea of Fermat spiral to achieve continuous filling, and the contour offset, partition and some unfilled areas are optimized respectively. Finally, the new algorithm is tested on common graphics to prove its superiority.

1. Introduction

Since the new century, with the development of our society, the traditional mode of life and production is gradually being changed by new science and technology. In light of its advantages of fast speed, high precision and low cost, a wide variety of applications of 3D printing have been seen in a large number of industries such as biomedicine, precision manufacturing, aerospace, medical devices [1]. The process of 3D printing is to accumulate layer by layer from line to surface and from 2D to 3D. The most basic operation is a lot of cross-sectional scanning. Different scanning methods have a great influence on molding accuracy, mechanical properties and molding efficiency [2]. In addition, at this stage the printing materials and equipments are relatively expensive. Optimal tool-path planning can not only greatly extend the life of the printing equipments, but also save materials. Therefore, scholars have done a lot of research on the tool-path planning of 3D printing and a series of algorithms have been proposed.

On the basis of the research on the existing scanning path planning, this paper proposes a new path planning algorithm. While maintaining the accuracy, the proposed path planning algorithm is able to generate a continuous tool path to fill a series of geometric figures without pausing. Then, the simulation is carried out on several common images. In the second section, algorithm improvements made by predecessors on scanning path planning are reviewed, and we point out the advantages and disadvantages of several common path planning algorithms. We give a detailed introduction to the proposed new algorithm in the third section. In the fourth section, we verify the implementation of the new algorithm and compare it with the previous classic scanning algorithm. Finally, we summarize the article, put forward the shortcomings and point out the future work direction.

2. Related work

Since the appearance of 3D printing technology, the research on its path planning method has not
stopped. In order to meet the different requirements of molded parts, multiple path planning algorithms are proposed. At present, the common print path types are divided into four types.

Parallel line path is the most common path type, which is composed of a series of parallel line segments in a certain direction and connected by small turns. As a special case of parallel path, Onuh proposed a star-like path in order to reduce the warpage of the molded part during the printing process, which consists of scanning lines radiating outward from the center of the target [3]. Huang divided the parallel scanning lines into groups, and then processes the scanning line groups with a certain interval in a sequence, so as to ease the temperature field gradient and realize the small deformation of parts [4]. Ding and Rajan calculated the optimal filling direction according to the graphic features. With the reduction of routes, the filling problem caused by the corner and the acceleration or deceleration have been significantly improved [5,6]. Although the parallel path path algorithm is simple and easy to implement, it cannot guarantee the accurate printing of the boundary that is not parallel to the set direction, and the path often breaks. So it is necessary to switch the nozzle frequently, especially when dealing with the regions to be filled with complex boundary or internal cavity structure. The contour offset path is a set of parallel lines of equidistant contour obtained by multiple offset on the contour, which can effectively solve the problem of boundary accuracy [7]. Ren introduced the spiral path to solve the problem of jumping between the contour paths of each layer, reduced the idle stroke, and used the linear combination of mapping and reparameterization to establish the optimal spiral path. Zhao used a low-curvature Fermat spiral to achieve filling, applying the inner and outer double helix structure and the close distance between the starting points to realize the connection between sub-regions [8]. Xiong added the concept of centroid to the algorithm, and reduced the self-intersection of the ring by variable spacing operations [9]. Zhao proposed a new self-intersection point detection algorithm which effectively avoided the subsequent judgment of the intersection of each contour ring and reduced the algorithm complexity [10]. In the face of complex boundary conditions, the calculation of contour offset path is very particularly large, and the direction changes frequently during the scanning process, which is accompanied by problems such as ring intersection and island. Fractal path scanning is actually an iterative process in mathematics. According to the requirements of accuracy and the characteristics of graphics, the region to be filled is divided into different sizes of grids, and the appropriate fractal model is selected. By using Hilbert curve, the uniform distribution of temperature field can be realized and the intensity characteristic can be maximized [11]. By judging the order and number of intersections of the original fractal curve and the contour, Yang realized the clipping of the fractal curve, which provided a feasible method for scanning and filling of complex polygons. However, the clipped curve is no longer continuous, and a large number of idle stroke will occur. Wah used the combination of NP and genetic algorithm to solve the connection problem between sub regions, and obtains the shortest connection stroke [12]. In order to improve the problem that the single route of fractal curve is short and the direction needs to be changed frequently, Li used the mapping relationship between Hilbert curve and Bezier to generate chamfer or arc to replace the original right angle transition [13]. Due to the limitations of single type printing path, it can not meet the requirements of accuracy and efficiency in industry. More and more people choose to combine multiple paths, which will be the main development trend of path planning in 3D printing.

To sum up, the following four key factors should be considered in the tool-path planning of 3D printing:

1) The algorithm is simple: a too complex algorithm will cause a lot of time to be spent on the preliminary calculation, reducing production efficiency.

2) Guarantee geometric accuracy: Overlaps and vacancies in filling will affect the strength and performance of the molded part. Therefore, the accuracy problem needs to be paid attention to, especially in the boundary part.

3) Decrease path elements: path element is the single scanning line in the tool-path. The change of
path direction will lead to the appearance of nozzle acceleration and deceleration, which will not only speed up the machine wear, but also reduce the printing efficiency.

4) Reduce the idle stroke: The number of idle strokes represents the number of opening and closing of the print head. From the perspective of prolonging the service life of the equipment, the occurrence times of empty stroke should be reduced; from the perspective of printing efficiency, the distance of idle strokes should be shortened.

At present, various path planning algorithms can meet the above single or multiple conditions, but there are still some blind spots which can not be taken into account, and there is still room for improvement. Therefore, this paper proposes a new tool-path planning algorithm which integrates the advantages of existing methods to meet the growing needs of industry.

3. The design of new optimal tool-path algorithm
This section describes the proposed new path planning algorithm in detail. For a given region, the algorithm first uses Fermat spiral to fill the boundary contour. On the basis of ensuring the boundary accuracy, it is convenient to connect with the subsequent sub-region path. Then the region is divided according to the extreme value, and the improved parallel path is used to fill each sub-region. Finally, partition adjustment and connection are carried out. The following steps are all verified on a region containing three inner holes of circle, rectangle and triangle.

3.1 Find contour by polygonal straight skeleton
The traditional contour path algorithm uses offset intercept to construct equidistant line of edge to realize the path. It will appear the phenomenon of self intersection, intersection and island, and the subsequent Boolean operation processing is more troublesome, increasing the workload. In this paper, the straight skeleton is used to extract the offset polygon, which improves the calculation speed.

The straight skeleton is a variant of the central axis introduced by aichholzer. It simulates the parallel movement of the boundary, and each vertex propagates along the angular bisector wavefront. The whole skeleton is generated by tracking and recording the trajectory and changes of the vertex. In the shrinking process, the collision between the edge and the vertex is mainly divided into two types of events: edge events (multiple vertices are combined into one or even disappear), and split events (concave vertices divide the edge into two). The main process is as follows:

1. Establish priority sequence \( Q \). In the polygon vertex list \( S = \{p_1, p_2, \ldots\} \), for the vertex \( p_i \), if it is convex, calculate the intersection of its corresponding angle bisector and the adjacent angle bisector, and select the closest to \( Q \). If it is a concave point, extend both sides in reverse. If two extension lines intersect on the same side, the intersection point of the corner bisector of the triangle formed by the intersecting edges is calculated. Select all the points that meet the requirements and put the nearest one into \( Q \). (As shown in figure 1).

2. Calculate straight skeleton. For each point \( v_i \) in the priority sequence \( S \), if \( v_i \) is the intersection point generated by the edge event, we record \( (v_i, p_i) \) and \( (v_i, p_{i+1}) \) as skeleton edges (where \( p_i \) and \( p_{i+1} \) is generating vertex), and update the list \( S \) with \( v_i \) replace \( p_i, p_{i+1} \). If \( v_i \) is the intersection point generated by the split event, \( (v_i, p_l) \) is regarded as skeleton edges (where \( p_l \) is the corresponding concave point). And the original list change into two by splitting \( p_l \) to \( v_i, v_j \).
As for the transformation from contour offset path to Fermat spiral path and how Fermat spiral connects among sub-regions, it has been explained in detail in [7], and we will not repeat here.

3.2 Polygon partition

It is difficult to handle arbitrary regions and achieve continuous filling. The so-called partition is to decompose a complex region into a series of basic graphics that can be filled by a sub-path. There are many ways to decompose complex region. At present, the most common one in 3D printing is convex decomposition of polygons. The algorithm is complicated, the calculation amount is large, However, not all the concave points have an impact on the continuity of the path. Therefore, it will lead to the increase of the number of sub regions and reduce the production efficiency.

This paper adopts the method of judging the extreme points in the filling direction to determine the dividing line, so as to partition. The algorithm flow is shown in the figure below, which can be summarized as the following three steps: Step 1: Find out extremum point set $B$ of polygon in the Y direction. As shown in the figure below, the final set of extreme points $B = \{b_1, b_2, b_3, b_5, b_6, b_9, b_{10}, b_{12}\}$. Step 2: Judge whether the point position in the left and right direction of the extreme point is inside the filled region. The left position of point $b_{10}$ is outside the area, so no dividing line is generated. Similarly, point $b_{12}$ does not produce a dividing line. Step 3: Add the segmentation line at the remaining extreme points to realize the partition. As shown in the following figure, the region is divided into 14 regions.

3.3 Improved continuous path

For internal tool-path planning, we choose a closed parallel line path proposed by Dwivedi [13], also known as "go and back strategy" [14]. Similar to the Fermat spiral path mentioned above, it also has two characteristics: the starting and end point are adjacent, so the generated path is continuous and closed; the starting point can be selected at any position in the path, which is convenient for subsequent sub-paths the connection between.

It can be seen from the figure that there are still underfilled regions. This is because this closed parallel line path requires that the filled lines in the area must be an even number in order to be connected.
to the return path. This situation is not taken into account in the above two papers. Here, we propose the partition adjustment method. By introducing additional points and edges, we adjust each region to make it suitable for filling with closed parallel paths.

1. Define the height $H$ of each region, take $\omega$ as the filling line interval, and calculate the number of filling lines $n$ in the region.

2. Determine the lowest point of the area. If the point is also the maximum point in the whole contour point set, we select the point of $\Delta h$ distance on the up orientation as the new auxiliary point, as ①② in figure 4; if the point is the minimum point, select the point down $\Delta h$ as ③.

3. Judging the number of filling lines in each region. If $n$ is an odd number, in the case of the maximum point, $\Delta h = H - (n - 1) \times \omega$, and in the case of the minimum value, $\Delta h = (n + 1) \times \omega - H$; If $n$ is an even number, in the case of the maximum point, $\Delta h = H - n \times \omega$, and in the case of the minimum value, $\Delta h = (n + 2) \times \omega - H$.

After adjustment, the partition map and filling effect diagram are as follows. It can be seen that the underfilling phenomenon is greatly improved after the partition adjustment.

![Fig. 4. The underfill phenomenon in the path and its adjustment](image)

4. Results and discussion

The experiment is carried out on a basic graph which contains three kinds of holes: circle, square and triangle and compares it with the conventional scanning path planning algorithm in terms of the number of jumps, the number of path elements, and the path length.

The experimental results are shown in the table below

|                | Number of jumps | Number of path elements | Total path length |
|----------------|----------------|-------------------------|-------------------|
| the new algorithm | 0             | 400                     | 100347            |
| parallel path    | 9             | 430                     | 101032            |
| contour path     | 40            | 597                     | 98821             |

It can be seen that when the total path length is approximately equal, the path elements of the new algorithm in this paper are approximately the same as the parallel paths. The contour path contains many small polylines such as circles, so the path elements are greatly increased. Because the contours of each layer are not connected, the number of jumps is very large, and the algorithm in this paper realizes continuous filling without jump operations.

Finally, choose the three letters "S", "M", "T" (abbreviation of CAS Key Laboratory of Space Manufacturing Technology) to generate the path to show the effect.
Fig. 5. The application of the new algorithm in various graphics

5. Conclusions
In this paper, a new filling algorithm is proposed by studying the existing scanning path algorithm. The algorithm uses Fermat spiral and closed parallel path to achieve continuous path filling that guarantees contour accuracy. In the middle, optimization operations such as vector operations, extreme point partitioning and partition adjustment are added. Finally, the filling test was performed on several common graphics to prove its superiority.

Acknowledgments
The project is supported by National Natural Science Foundation of China (52005479 and 52005480) and Beijing Natural Science Foundation (3194063).

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