Optimization of Layering Algorithm and Print Order in 3D Printing

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Abstract. 3D printing (3DP) is an emerging additive manufacturing technology, which has carried out a new change in the manufacturing industry and effectively promoted the related development of the intelligent manufacturing industry. However, traditional 3DP has limitations such as low accuracy, poor mechanical properties, and easy collision of nozzles when printing and printed products cannot meet some production needs. This paper begins with the two main types of algorithms used in 3DP technology: the adaptive algorithm and the equal thickness layering algorithm. It then further divides the adaptive algorithm into four categories based on different optimization focus directions. In this paper, the principles, benefits, and drawbacks of various algorithms as well as print order optimization are analyzed, and the prospects of 3DP are discussed. This paper illustrates the performance and improvement effect of hierarchical algorithm and order optimization in 3DP and provides a more comprehensive reference for scholars in the research field of algorithm optimization direction.

Keywords: 3D printing, layering algorithm, equal thickness layering, adaptive layering algorithm.

1. Introduction

Due to the rapid update and iteration of science and technology in this era, the market competition in various manufacturing industries is fierce, and more and more emerging manufacturing methods are constantly being born. Among them, the technology of 3DP has started to find use in the production sector and is now a significant component of the modern manufacturing field.

3DP, also known as additive manufacturing technology, is a technology that manufactures solid parts by adding material based on 3D computer-aided design (CAD) data. The material is accumulated in a bottom-up form through layer-by-layer additive manufacturing employing discrete ingredients, such as powder and liquid.

The modern manufacturing mode is developing from a single type, simple structure, and long cycle manufacturing to a multi-type, complex structure, low cost, and low consumable manufacturing trend. 3DP just meets most of the above needs, so it is widely used in different fields for applications [1]. Since the beginning of this century, various countries have vigorously developed 3DP-related technology research and development and policy support, such as China in the "14th Five-Year Plan" intelligent manufacturing development Plan proposed 3DP-related key tasks, provinces have also customized relevant policies and planning to support, and in the future, the technology still has a huge space for development [2].

The most classical equal thickness layering algorithms, such as those based on model topological information [3], are simple to implement, but very dependent on model quality, and the accuracy of some areas cannot meet the production demand. Therefore, adaptive algorithms such as auto-segmentation local adaptive algorithm [4], surface feature adaptive algorithm [5] based on shape-constrained geodesic distance field (SCGDF), and order optimization adaptive algorithm based on modified augmented contour tree (ACT) [6] are currently studied based on equal thickness algorithm, which respectively meets the needs of local high precision, effective reduction of support, and reduction of nozzle collision to achieve the best results. However, different adaptive algorithms have different emphasis. Therefore, many of the present algorithms are still complex, the operation requires a lot of resources, and there is a high dependence on the equipment's performance to obtain greater

accuracy and mechanical qualities. As a result, there are still restrictions, and the system cannot meet all needs.

This study analyzed the existing problems of 3DP, the principle of different layering algorithms and printing order optimization, optimization focus, optimization effect, advantages, and limitations, are summarized.

2. Current Problems with 3DP

In the process of 3DP, the STL model file needs to be read and layered to facilitate later cumulative manufacturing. At the same time, different algorithms, the selected layer thickness, and the printing order planning will greatly affect the number of supports required by the model, the finished product accuracy, and the printing efficiency. The improper thickness is more likely to lead to the staircase effect, affecting the accuracy of the finished product; Improper printing sequence can lead to nozzle collision and interference. Therefore, to increase accuracy and reduce volume error and interference, different scholars have developed optimization algorithms for layering and printing order, which are mainly divided into equal thickness layering and adaptive layering algorithms.

3. Layering Algorithms and Print Order Optimization

3.1. Equal Thickness Layering Algorithm

The equal thickness layering algorithm is one of the most traditional and widely used additive manufacturing methods. The layer thickness of the model is uniform. After the layer thickness is determined, the whole model will be divided layer by layer according to the fixed thickness. The later adaptive layering algorithms developed by most scholars are based on this research.

One of the more popular approaches involves the user selecting the proper layer thickness, h, taking the model's maximum height, zmax, and using n=zmax/h to get the layer number, n. All triangular surfaces that intersect the layered surface are chosen based on the current printing height z. Next, each layer's contour information is kept while the closed-loop contour information is derived based on the location where the triangular surface and each layer intersect. After that, the outer wall and inner wall are sorted in counterclockwise and clockwise order respectively to obtain comprehensive current layer coordinate information [7]. And so on, the whole model is segmented according to the layer thickness h.

Other common equal-thickness partitioning methods are equal-thickness partitioning algorithms based on the position of triangular surfaces, and triangular topological relationships [3] or adjacency slices [8].

3.2. Adaptive Layering Algorithms

3.2.1 Local adaptive layering

Local adaptive layering is to change the slice thickness through the geometric features of different regions of the model, such as distinguishing the inner and outer contours and sorting them according to specific rules, and topologically reconstructing the nested model, to optimize the printing accuracy and efficiency [5].

Zhao et al. [9] proposed a tolerance-based local adaptive algorithm. Through the requirements of geometric dimensions and tolerances in mechanical components and combined with algorithms, the method of balancing time and finished product accuracy can be obtained. Firstly, the part with geometric dimensioning and tolerancing (GD&T) requirements and the rest of the parts are optimized separately to achieve the local optimization effect. For example, for parts such as bore shafts that require higher precision, a thinner layer thickness is used to reduce volumetric errors. Then, the particle swarm optimization algorithm was used to optimize the layer thickness, and the fitness value of each particle was calculated to check whether the number of iterations met the minimum limit, and the GD&T error of each particle was calculated to minimize the manufacturing time. This algorithm's

benefit is that it reduces superfluous support material while improving the part's assembly performance. Its drawback is that when it involves several geometric and tolerance limitations, it's challenging to implement in increasingly complicated real-world scenarios.

An approach for automatic segmentation local adaptive layering algorithm was suggested by Wang [4]. By reading the model file, the constant thickness pre-layered is performed, and then the number and height of the contour are calculated to determine the height of the horizontal triangular patches. The triangular patches of the corresponding heights are then divided, and the layer heights of the variations in the number of contours are noted. The various components of the separation are then adaptively layered, with the upper and lower layers not overlapping, the layer thickness being modified in accordance with the contour features, and the minimum thickness variation range being somewhat larger than the initial pre-layered thickness. One benefit is that the layer's thickness is more adjustable and sensible, and the balance of accuracy and efficiency is considered, but the disadvantage is that the data structure is complex, the process of determining the segmentation position is more cumbersome, and the effect of mixed layering of multiple layering methods needs to be explored. Table 1 shows the implementation of the algorithm.

Table 1. Comparison of the test model formation between the automatic segmentation local adaptive layering algorithm and the equal-thickness layering algorithm [4]

The layer thickness of the adaptive layering algorithm/mm	Adaptive layering algorithms Molding time/min	The layer thickness of the equal-thickness layering algorithm/mm	Equal-thickness layering algorithms Molding time/min
0.02-0.3	245	0.1	194
		0.3	571
0.02-0.3	268	0.1	201
		0.3	593
0.02-0.3	223	0.1	182
		0.3	529

3.2.2 Surface adaptive layering algorithm

The surface adaptive layering algorithm changes the thickness of the slice layer by calculating the surface shape characteristics [10], the correlated normal curvature [11-12], the tangent angle perpendicular to the point on the contour line [13], or the angle between the normal and the printing direction [14] to accommodate a variety of surface models and reduce the number or need for support structures.

Xu et al. [15] proposed a surface adaptive layering algorithm based on SCGDF. Firstly, the contour l_0 of the initial underlying planar layer is set, the shortest distance from each point on the surface of the model to this contour is analyzed, and a scalar field $\delta_{*(q)}$ is formed. Different distance values can generate different equidistant contours. The surface layer is then obtained by projecting the contour line onto the target plane, triangulating it, and using the least squares method to map the triangular mesh on the plane on the three-dimensional surface. The advancing front technique and the Delaunay triangulation are used here. At the same time, to ensure a stable Harsdorff distance, the adaptive interval is selected to generate the surface layer, and the projection direction of the equidistant profile is obtained by combining the principal component analysis method, and finally, the average thickness of the two adjacent layers is obtained, which could be adjusted as needed. The algorithm can effectively reduce the support structure and can handle complex geometries such as multi-branched and multi-genus feature models. However, the layer is non-planar, and interference may happen in some places because of the harmonic mapping concept, and the nozzle direction needs to be constantly changed, which increases the time-consuming.

Rodriguez-Padilla et al. [16] proposed a surface adaptive algorithm based on point projection. As shown in Fig. 1, the trajectory points are projected from other initial positions to the target surface

through the projection vector, and the new trajectory points are generated by calculating the intersection of each projection point and the target surface. Subsequently, the exact projected position of the trajectory points needs to be obtained, which can be computed by using the plane equation and each target triangle face's center of gravity to ensure the continuity and smoothness of the path, additional parameterized points are generated between the track points and nozzle collisions are also avoided. At the same time, the positioning of the nozzle can be obtained by calculating the projection point normal vector. This approach has the advantage of being able to be used for various additive processes instead of just fused deposition molding (FDM), and the higher the mesh resolution, the lower the volume error. The drawback is that it depends more on the mesh's resolution, and to ensure accuracy, the triangular faces will increase more, resulting in more complex and time-consuming calculations.

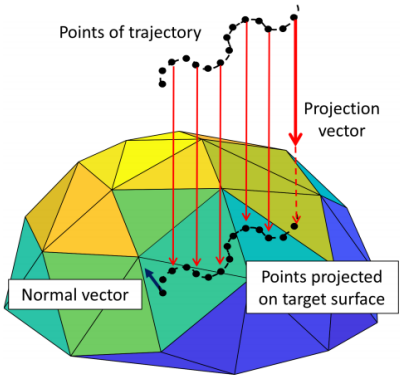


Figure 1. Projecting the ordered points of the trajectory onto a non-planar surface in a surface adaptation algorithm based on point projection [16]

3.2.3 Adaptive layering for mechanical property optimization

Adaptive layering for mechanical property optimization is a method that relies on finite element analysis (FEA) [17-18] and strain energy analysis [19] to reduce the structural support in the printing process, improve the printing efficiency, and optimize the printing path and mechanical properties by optimizing the deposition direction and thickness of each layer, to achieve better printing quality and efficiency.

Tam et al. [18] proposed a method to solve the problems of stress line discontinuities in the traditional method and generate a topology with appropriate connectivity to improve the mechanical properties of the finished product. The design domain is meshed, and the structure is analyzed on the domain to obtain stress line-related data. The FEA data is used to determine the primary stress directions. Line segments are then produced using interpolation, and the process is repeated until the design boundary is achieved. After the correction, the stress line layout is optimized by the strain energy minimization objective function to maximize the stiffness and ensure the continuity and accuracy of the stress. The benefit is that this approach, which works well with planar and 2.5D membrane structures, greatly increases stiffness and strength while lowering the anisotropy issue. The initial yield capacity is low because of inconsistent production technology, which is a drawback.

Li et al. [19] proposed an algorithm that can maximize the stiffness of prints. Import the CAD model into the FEA and analyze each element. The strain energy of each discrete element is obtained by analyzing the displacements and stresses due to boundary conditions and loads in the software, as shown in Fig. 2. Then, a new pseudo-density and building direction (BD) is generated by using the globally convergent method of moving asymptotes (GCMMA). The advantage is that it converges quickly through GCMMA, and the number of iterations is short, but the disadvantage is that the computational complexity is high, and the result may only be a locally optimal solution rather than a globally optimal solution.

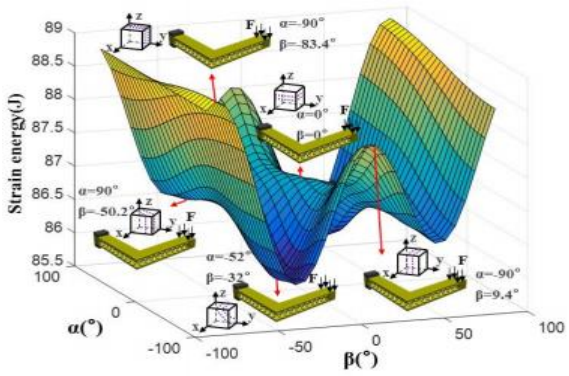


Figure 2. Strain energies of all BDs in the algorithm for maximizing the stiffness of the print [19]

Beattie et al. [20] proposed that the mechanical properties of FDM components would be greatly affected by different construction directions. The experimental results show that the ultimate tensile strength of the edge construction direction is the highest, and the bending test shows that the ultimate stress in the plane direction is the highest. After scanning the parts by scanning electron microscope, it was found that the fracture and failure modes were significantly different due to the different construction directions. For example, the fiber fracture mode is a stratified failure because the combination between the component layers in the vertical direction is weaker than that parallel to the load direction. Therefore, optimization in the direction of construction is crucial. The specific bending stress-strain curve is shown in Fig. 3.

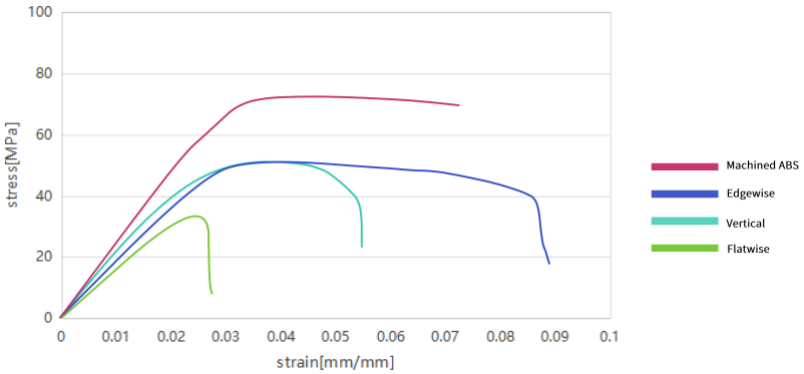


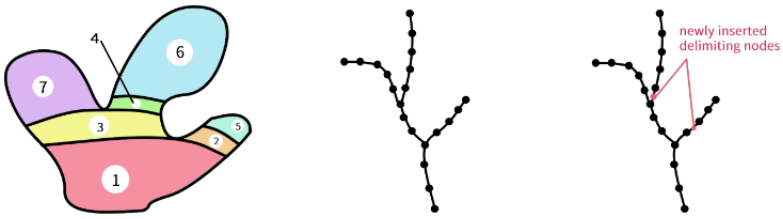
Figure 3. Flexural stress-strain curves of a sample in different construction directions based on the adaptive algorithm [20]

3.2.4 Adaptive algorithm of print sequence planning based on partition

Sometimes, the above algorithms cannot perfectly solve all problems. For example, in the surface adaptive algorithm, although the model of a complex structure can be processed numerically by the curvature of the surface, it will still cause interference and nozzle collision problems due to harmonic mapping. Therefore, in the printing of many complex structures, the printing sequence planning algorithm based on partition plays an important role.

Lau et al. [6] proposed an adaptive algorithm based on partition sequential planning. First, because the overhang angle of the boundary surface directly can cause excessive calculation in slicing, the ACT is used to identify and draw the iso-surface of the model vertices, and the maximum overhang angle of each equivalent field value is obtained. The ACT and modified ACT are shown in Fig. 4. And the layer thickness is determined by the maximum overhang angle, which has the advantage of reducing the staircase effect and decreasing the additional support required. The algorithm gradually removes the partition from the top node by inputting the partition tree. At the same time, it ensures that all the lower iso-surfaces in the nozzle movement space are cleared, and the printed nozzle movement space is also removed. Output the final partition and print order to ensure no hangs or interference. The algorithm maximizes the surface accuracy while drastically cutting down on the overall printing time and the interference issue it causes. However, it largely depends on the scalar

field defined in the model, the performance of the hardware device, the printer accuracy, the number of axes, and the nozzle design.



(a) (b) (c)

Figure 4. Sequential optimization based on the modified ACT. (a) subdivided components; (b) ACT; (c) Modified ACT [6]

4. Conclusion

At present, 3DP is in a stage of continuous innovation. To illustrate how different algorithms optimize the layering effect and print order, this paper combined with typical cases of different algorithms divided the algorithms into equal thickness layering algorithm and adaptive layering algorithm, and subdivided the adaptive layering into four categories: local adaptive layering, surface adaptive layering, adaptive layering for mechanical property optimization and print sequence planning adaptive algorithm based on partitions. Important factors including printing precision, mechanical characteristics, computing time, and algorithm complexity are analyzed, and the relationships and realization needs of various printing methods are expounded, which provides future researchers with references and further research directions of previous algorithms in the direction of layering algorithms and print order optimization.

The conclusion of this research is that the equal thickness layering algorithm is simple to implement, but it greatly depends on model quality. In the adaptive algorithm, the local adaptive algorithm can realize the local accuracy better to meet the production demand, but the calculation is more complicated when the demand is complicated. The surface adaptive algorithm can effectively reduce the volume error according to the surface feature, but the method based on projection mapping may have some problems such as nozzle collision. The adaptive algorithm based on mechanical properties can effectively improve the mechanical properties of the model, but there are some problems such as the predicted effect of the algorithm is different from the actual, and it is only a locally optimal solution. The adaptive algorithm related to order optimization can effectively reduce the collision interference problem, but it is more dependent on the performance of the printing equipment.

The layering algorithm still has a large optimization space, and its shortcomings mainly lie in the fact that it consumes a lot of computing resources to achieve good product quality in complex cases and depends on the performance of equipment and the number of axes to a large extent. More thorough research is necessary to figure out how to optimize future aspects of printing accuracy and mechanical qualities, decrease reliance on equipment performance and computation complexity, and minimize resource consumption.

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