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Adaptive Layering Method for Improving Printing Accuracy and Efficiency

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Abstract. As a rapid prototyping technology, 3D printing is widely used in various fields. In the aspect of slicing, it is divided into equal thickness slicing and adaptive slicing. Most of the 3D printers on the market today use equal thickness slices, but equal thickness slicing cannot balance accuracy and efficiency, this paper need adaptive slicing to address this issue. This paper first introduces how to adjust the layer thickness through the triangular surface's normal vector of the STL model to weaken the adaptive slicing. Secondly, it introduces how to preserve more details of the model while ensuring efficiency on the basis of common adaptive slicing methods. Finally, some methods which are different from common adaptive slicing methods are introduced to adjust the layer thickness from different angles to achieve different purposes. The research in this paper provides ideas for the understanding and development of 3D printing adaptive slicing, and has important value for the research and application of adaptive slicing.

Keywords: 3D Printing; Adaptive Slicing; Accuracy; Efficiency

1 Introduction

Since the advent of 3D printing technology, it has shown great potential in manufacturing, medical and construction fields. However, the traditional equal thickness layered printing method has some contradictions between the printing accuracy and efficiency, and it is difficult to achieve a good balance. The adaptive layering technology has attracted much attention because it can flexibly adjust the layer thickness according to the characteristics of the model itself, so as to reduce the impact of the staircase effect on the model, improve the printing accuracy, and improve the printing efficiency. Scholars at home and abroad have conducted relevant research on adaptive layering. In Zhang Yisheng et al. reported adjacency topology relation, the topological relationship of discrete triangles is established through the linked list structure, so as to realize the fast layering of STL files [1]. The time complexity of the layering algorithm is changed from O (n^2) Reduce to O (n). In Chao Haiyuan et al. reported algorithm , non static

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linked lists are used to establish topological relationships and hierarchically synchronize [2]. In Chen Kun et al. reported adaptive layering algorithm [3]. By combining topological model construction with intersection tracking and marking methods, the layer thickness automatically adjusts based on the area difference ratio between adjacent slice layers. In Zhou Huiqun et al. reported adaptive contour layering method, adaptive layering is carried out through the curvature of the model surface contour [4]. The smaller layer thickness is used where the curvature is large, and the layering thickness is increased where the curvature is small. Tian Renqiang et al. reported adaptive triangulation algorithm can effectively reduce the influence of the step effect on the model by adjusting the layering thickness adaptively by considering the angle between the normal vector of the triangular patch in the STL model and the molding direction [5].

Although the above methods improve the efficiency of the overall layering of the printed model, they often neglect the geometric features of the local special structures in each layer. For instance, the algorithm for Improving Efficiency of FDM is difficult to deal with the field of personalized manufacturing and complex actual modelswhich, which may lead to the degradation of the printing accuracy. In the current study, it is challenging to improve the efficiency and accuracy of the overall printed parts. However, some studies focus on optimizing local structures. By separating and pre-processing these local special structures, it is expected to reduce the neglect of accuracy in the special structure features. This, in turn, should improve the overall quality and performance of the printed parts.

Based on the above research, this paper aims to summarize the key issues in 3D printing, paying special attention to the impact of the staircase effect, the importance of retaining details and exploring other possible improvement directions. This paper will introduce each topic and delve deeper in the following chapters, and aim to provide comprehensive theoretical support and practical guidance for the further advancement of 3D printing technology, and promote the research and application in this field to make greater progress.

2 Literature Review

2.1 Method to Reduce Staircase Effect

Reducing the staircase effect is an important part of preserving printing detail features because it can reduce surface errors of printed materials, especially in areas with small angles between the tangent plane and the horizontal plane. This is an advantage of adaptive layering algorithms over equal thickness slicing.

Most methods of adaptive slicing are based on the stereolithography (STL) model ,which records the printing model as triangle facets [6]. STL models only record the information about geometry, researchers can propose various printing methods based on STL model by reconstructing the STL model with different topological relationships between the facets.

Wu, Y et al. reconstruct the STL model to sort out redundancy data and construct data about the vertex of the facets [7]. They propose an optimized method on basis of triangular plane normal vectors, a mainstream method of adaptive slicing. At first, they preprocess the STL model and add necessary topological relationships to the model. Then they divide each layer into 2 categories. If the current layer has few detailed features, the traditional method is used to calculate the layer thickness, which is determined by the angle between the normal vector of the triangular plane and the vertical direction, as shown in Fig. 1(a) and in Fig. 1(b), the thickness will get larger with the angel increasing until the angel turns into a right angel while the thickness achieve maximum value designed in advance. In cases where the current layer has quite a few details, they check the neighboring facets to find sharp corners and determine the thickness through a series of calculations. Finally, they choose the minimum value through the 2 categories mentioned above as the final slice thickness. After simulating with MATLAB, their method gets 19.3% higher accuracy than traditional method and only takes 4 min more time.

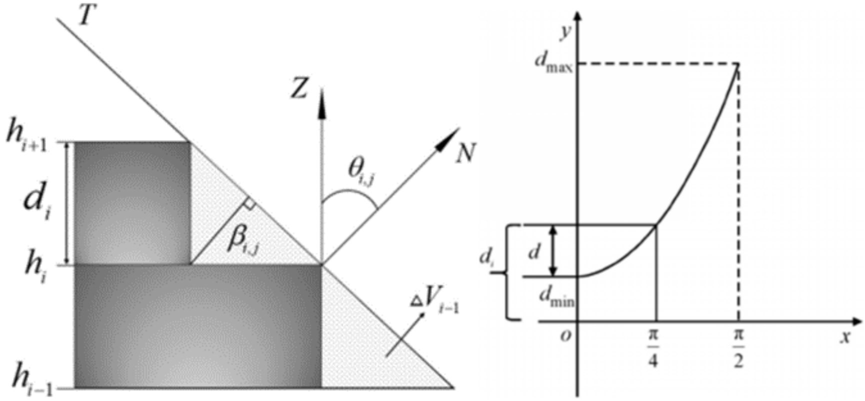

Fig. 1. (a)The normal vector; (b) The function of layer thickness with respect to angle [7].

Hu, Yifei et al. slice the STL model with constant layer thickness to acquire information about each layer [8]. Flat areas, for example, can be the basis to judge the existence of features between neighboring layers. As shown in Fig. 2, they compare the deviation of areas between several successive layers to obtain the deviations to judge whether can these layers be merged to one. Peaks, cusp heights and the number of contours can be the judgement basis as well. It's a unique way of adaptive slicing for its merging steps. Not only can this improved method reduce the staircase effect, it is more sensitive to details. Compared with other slicing methods, the new slicing method reduces the number of layers and keeps the accuracy of the model. After the experiment, researchers demonstrate the effectiveness and find that this slicing method reaches the balance between the efficiency and the accuracy.

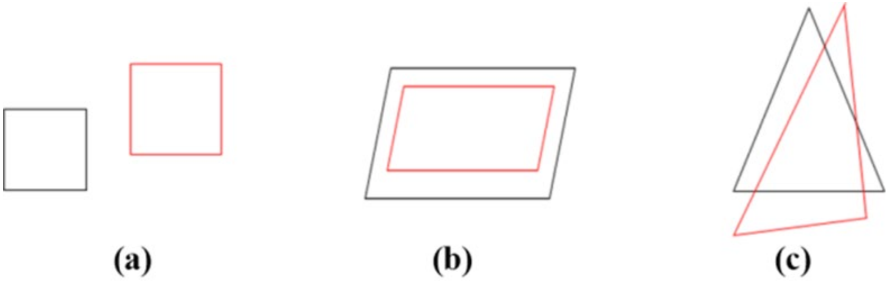

Fig. 2. The deviation of areas [8]. (a) No intersecting relationships; (b) contains relationships; (c) intersecting relationships

Besides the adaptive slicing method above, there are other slicing method which can reduce staircase error effectively. Zheng, X. et al. directly slice the CAD model instead of STL [9]. They use voxels, fictitious microstructures , to slice the model. Compared with traditonal slicing methods based on TPP, the innovation of their research is the tilted voxels. As shown in Fig. 3, the adjustable angels between voxels and vertical direction allow the microstructures to satisfy the changing contours, with voxels always parallelling to tangent plane of the contours. More fitting voxels lead to smaller number of layers. Quantitative analysis indicates that layer number decreases by 30% and the staircase effect is significantly reduced. Simultaneously, this method ensures the printing accuracy.

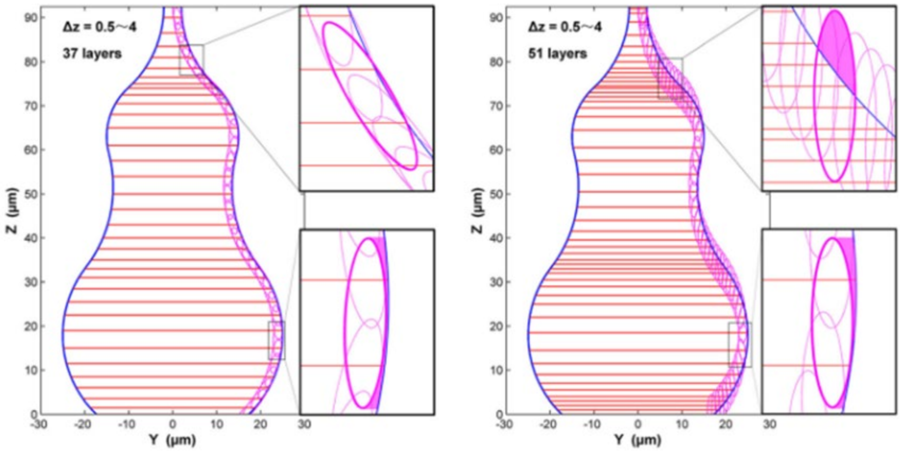

Fig. 3. Comparison of Tilted and Vertical Voxels [9]. (a) Adaptive Slicing Method with Tilted Voxels; (b) Adaptive Slicing Method with Vertical Voxels;

2.2 Methods for Preserving Detailed Features

In Xia Lingwei et al. reported collaborative optimization [10]. The author proposed a new porous structure design method and path optimization algorithm based on Voronoi diagram, which is a continuous polygon consisting of vertical bisectors connecting line segments of two adjacent points, as shown in Fig. 4.

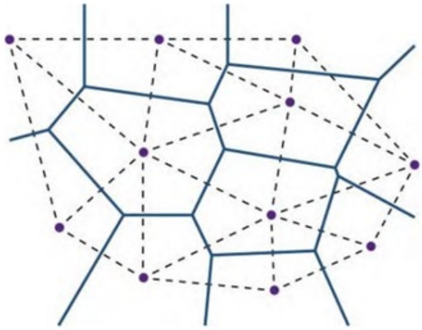

Fig. 4. Voronoi polygon [10].

In particular, it was mentioned in the literature that Voronoi diagram was used to generate optimized porous structure, and different density material distribution was generated by offsetting Voronoi skeleton, which can improve printing accuracy very well. However, the discussion does not sufficiently consider the specific problems that may occur during the actual printing process:

The path optimization algorithm proposed by the author aims to reduce printing interruption. It also seeks to improve path continuity. However, in the actual 3D printing process, the algorithm needs to consider printing speed, heating temperature, and material fluidity comprehensively. It seems that the algorithms proposed in the literature do not fully consider these important parameters that affect print quality, which may lead to material accumulation and uneven cooling during actual printing, affecting the quality of the final product.

While path continuity has a direct impact on reducing print time and support material usage, the physical properties of the material are also critical to path planning. Further ways to consider physical properties include evaluating material properties such as fluidity, hardness, and viscosity. In addition, the shrinkage, adhesion, and response to temperature and velocity changes of the material should be considered. By considering these factors together, the path planning can be adjusted to ensure the compatibility of physical properties with the path during printing, thus minimizing the printing time and the use of support materials. For example, an overly compact print path can lead to heat buildup, which affects the cooling and curing process of the material and thus the structural integrity of the printed object. In addition, the literature does not explicitly mention how to take into account the properties of different materials when optimizing the path, e.g., some materials may require specific cooling times and temperature control to achieve the desired print results.

Therefore, when improving the path optimization algorithm, the team should take into account the physical and chemical properties of different 3D printing materials, such as plasticity, heat capacity, thermal conductivity, etc. Implement dynamic path planning, adjust printing speed and path spacing according to material characteristics, ensure normal curing and cooling of materials during printing, and avoid printing failure caused by internal stress accumulation.

The Lv N et al. reported Adaptive Layering Algorithm is to enhance the quality of FDM-3D printing [11]. Propose an adaptive layering algorithm based on optimal volume error. This algorithm minimizes volume errors resulting from step effects between layers by adjusting layer thickness, as shown in Fig. 5, thus optimizing printing surface accuracy and reducing printing time. In the experiment part, the author compares the effect of the equal thickness layering method. They also verify that the adaptive layering algorithm can reduce the printing time while ensuring the printing quality.

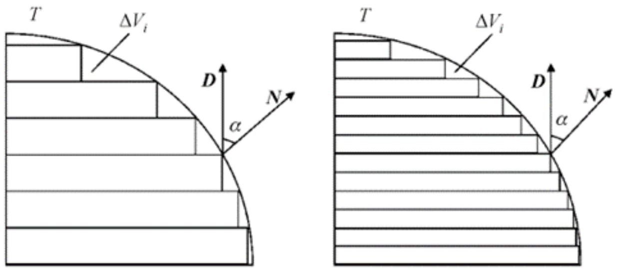

Fig. 5. Schematic diagram of the staircase effect of the STL model with different layer thicknesses [12]. (a)The thinner layers (b) The thicker layers

A careful analysis of the mathematical model and formulas proposed in the paper, especially the calculation of volumetric errors and the layer thickness adjustment strategy, reveals the following potential problems and directions for improvement.

The first assumption for the calculation of volumetric error is the formula $S_i \approx \frac{h^2}{2\tan\beta_i}$, which in the literature assumes the cross-sectional area of a planar triangular segment in the derivation, as shown in Fig. 6. However, this assumption may not be precise enough when dealing with larger triangular segments or complex surfaces. For instance, larger triangular segments may introduce greater uncertainty in the calculation of cross-sectional areas due to their increased size. Additionally, when dealing with complex surfaces, such as curved or irregular shapes, using the same formula may overlook variations in curvature, leading to inaccuracies in volume calculations. In fact, triangular segments of complex surfaces may have more complex geometries.

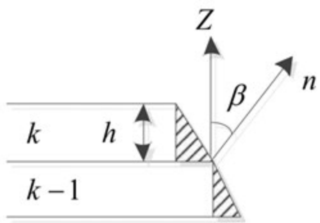

Fig. 6. Schematic diagram of volume error [11].

Secondly, considering the limitations of the angle calculation, the method used in the paper to calculate the angle β is only applicable to normal printing situations, and may not take into account the changes in the relative position of the printhead to the printing surface, which is common during the printing process.

In this regard, the team suggests a number of measures for improvement. Firstly, more complex geometric calculations were used to accurately calculate the volumetric error of each triangular segment, especially on complex surfaces. Secondly, a more sophisticated dynamic layer thickness adjustment algorithm was developed to take into account the balance between local geometry and features and global print results. Finally, real-time angle adjustment is performed to develop a more advanced algorithm that monitors and adjusts the position of the printhead relative to the print surface in real-time to achieve more accurate β angle calculations.

In general, although the proposed method is theoretically feasible, in practical applications, further improvements may be needed to accommodate complex geometries and different printing conditions. In particular, more in-depth research and development should be carried out in terms of the accuracy of geometric calculation and the flexibility of layer thickness adjustment.

In Yi Yingmin et al. reported Adaptive Layering Algorithm [12]. The author focused on solving the step effect between layers in FDM 3D printing, and proposed an adaptive layering algorithm based on optimal volume error. The algorithm aims to minimize the volume error caused by bevel by adjusting the printing thickness of each layer, so as to improve the printing accuracy and surface smoothness. Shown is a schematic diagram of the dihedral Angle of two triangular mesh with common edge L, where the normal vectors of the two triangular mesh are N_i and N_{i+1}, respectively, and the Angle between the normal vector N_i and N_{i+1} is θ. The calculation formula can be written as: $\theta = \cos^{-1}\frac{N_i N_{i+1}}{|N_i||N_{i+1}|}$, as shown in Fig.7.

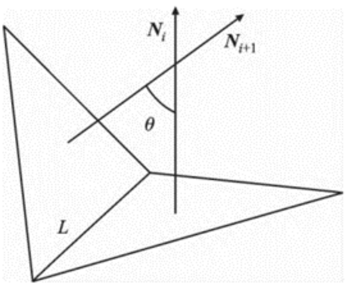

Fig. 7. Schematic diagram of the dihedral angles of a mesh of two triangular facets [12].

The core method of this paper is to reduce the volume error caused by the angle difference between layers. By calculating the volume error and angle of each triangle segment, the algorithm adaptively adjusts the thickness of each layer to improve the print quality. This process involves a series of mathematical models, including the approximation of triangle areas, the calculation of angles, and the layer-by-layer adjustment of layer thickness.

However, simplified geometric approximations are used in the calculation of triangular area and step volume errors, which may lead to a loss of accuracy when dealing with highly curved surfaces or complex geometries. Moreover, the calculation of angles in the paper is based on specific geometric assumptions and may not be applicable to all types of triangular meshes, especially on highly irregular models.

The team suggests that the optimization of geometric processing, improving the calculation of triangular area and volume errors, may require more accurate geometric analysis methods, such as using surface integration or numerical integration methods for complex surfaces. As for the selection of automated layer thickness parameters, this may be achieved through machine learning or optimization algorithms, which can reduce the reliance on specialized knowledge and make the algorithms more robust and pervasive.The application of machine learning in automatic selection of layer thickness parameters can optimize the efficiency and quality of the 3D printing process by using supervised learning methods, training models to predict the best parameters, or discovering patterns from data through unsupervised learning methods to automatically determine the best layer thickness parameters.

If this paper wants to achieve the transformation from theory to practice, it also needs to refine the existing model, and ensure that the algorithm can remain efficient and accurate in different print environments and models. By integrating advanced geometric calculation methods, automatic parameter adjustment and improving algorithm performance, this technology can be more suitable for industrial 3D printing applications.

2.3 Other Methods for Adaptive Slicing.

Y. Yang suggested an adaptive slicing technique where the slicing criterion is the volume difference between two neighboring layers [13]. It separated the two-layer slice's region into common and difference areas. In the common area, the machine's maximum permitted thickness can be deposited. Additionally, the different areas require distinct approaches. As shown in Fig. 8. There might be a key plane for the difference where the mutations happen at that height. It doesn't take any more deposition to keep the model accurate. To lower the model's slicing error, it should be deposited for the difference area of moderate value. No more deposition is needed for minor difference areas since the slicing error falls within the tolerance. Testing the sample model reveals that, in comparison to the conventional adaptive slicing, building time can be slashed by 40%. By applying adaptive slicing just where it is necessary, and by using distinct sedimentation techniques in areas that are common and areas that are differential. The suggested approach has increased efficiency while reducing the volumetric error between the constructed layered manufacturing part and the original CAD model. It works well with the majority of commercial layered manufacturing systems because of its simple implementation.

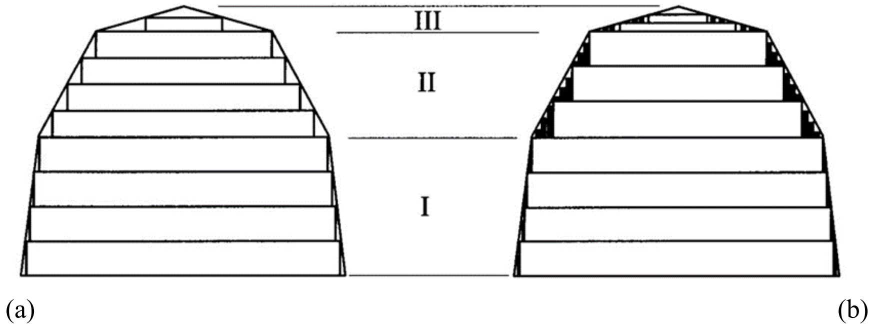

Fig. 8. (a) Conventional slicing and deposition method and (b) high-precision exterior, high-speed interior deposition method [13].

S. Rianmora used image processing techniques for adaptive slicing [14]. In this method, image processing techniques have been used. The 3D model's complexity determines the relative thicknesses and slicing positions of the layers from the bottom up. A layer's simplicity is determined by how similar its top and bottom shapes are. If the two contours of the layer are the same, or if their maximum variation is within tolerance, the layer is said to be simple. If not, the thickness should be decreased until the minimal layer thickness is reached or a simple layer thickness is achieved. As shown in Fig. 9. The model's front and side views are used, along with the Canny edge detection technique to identify the image boundary containing the full part and the edges of the front and side images of the example CAD drawing. Layer by layer examination of the photos locally. Identify the position of the slice. The outcomes of the uniform direct slicing strategy with thicknesses of 1 and 3 mm and the uniform cusp height approach were compared to the new adaptive direct slicing results. In comparison to the thick uniform and the uniform cusp height sliced models, the surfaces of the thin uniform and adaptive sliced models are smoother. The number of layers was lowered by roughly 25.33% by employing the adaptive direct slicing technique, which directly affected build time.

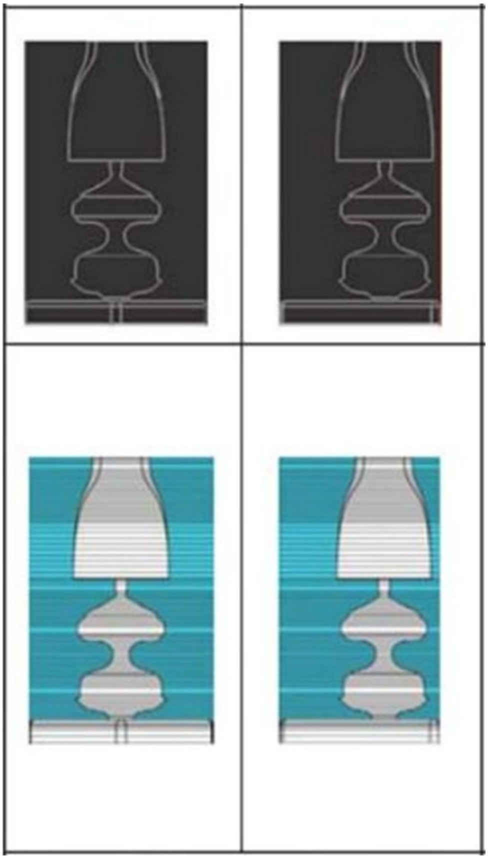

Fig. 9. Application steps of new adaptive direct slicing on the curvature lamp model [14].

R. C. Luo adaptively slices the model, by comparing the contour's center of gravity or circumference with those of the surrounding layer [15]. The points of contour are created because the scan horizontal plane intersects the triangle edges. Using those point data, the contour circumference of the layer may be computed. In a similar manner, it is possible to compute the contour circumference of neighboring layers and subsequently determine the difference in contour circumference between them with ease. Determine the center of gravity positions of the two neighboring layers, as well as the obtained center of gravity distance ΔG. The thickness of the layer is obtained through the contour circumference difference and the center of gravity distance and a series of formulas related to them, and the thickness is between the upper limit and the lower limit. This innovative method can be applied to fast prototyping systems that are based on LCD panel displays. The article conducts experiments through two cases. The model of Case 1 is composed of a cylinder and an ellipsoid, and the model of Case 2 is an oblique cylinder. The results are shown in Table 1. According to the experimental findings, the suggested adaptive slicing approach can reduce the number of layers by about 50% compared to the uniform slicing method without sacrificing model accuracy.

Table 1. Layer numbers comparison: uniform slicing method and adaptive slicing method [15].

	Method	Layer thickness (inch)	Number of layers	Relative ratio of layers (%)
Case 1	Uniform thin layers	0.005	600	100
	New adaptive slicing	0.005~0.02	297	49.5
Case 2	Uniform thin layers	0.005	600	100
	New adaptive slicing	0.005~0.02	300	50

3 Conclusion

This article introduces various adaptive layering methods, with a focus on reducing step effects, preserving the detailed features of printed models, and other layering methods. Compared to current mainstream layering methods, this paper focus more on preserving detailed features.

Most adaptive layering methods have the function of weakening the staircase effect. Since the STL model was proposed, it has been a mainstream research tool. This paper introduced several adaptive layering methods based on the STL model and provided an overview of their principles. Many of these methods, which are based on the normal vector method of triangular patches, have improved efficiency or accuracy. In the hierarchical methods that preserve detailed features, unlike the first part, most methods classify and discuss local details, focusing more on local geometric features and even studying them separately. There are also printing methods based on the printing materials.

Among the stratification methods based on other influencing factors, researchers did not focus on a specific function of the stratification method, but chose a specific variable as the stratification basis, and then judged the effectiveness of the stratification method and identified its advantages compared to other schemes based on the results. Many of these layering methods are also based on the STL model.

At present, adaptive layering methods based on the STL model are still mainstream, but most new solutions are optimization methods, and new layering methods based on the STL model are very rare. With the advancement of computer technology, more software is in the development stage, and these new tools have unique advantages over STL models. In the future, there will be more new models and more innovative layering ideas.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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