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Research Status of Adaptive Slicing Technology in Additive Manufacturing

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Abstract. 3D printing technology has gradually broken through the limitations of traditional subtractive manufacturing, providing unprecedented possibilities for the manufacturing of complex geometric shapes. Its core technology is to construct three-dimensional entities by layer-by-layer stacking of materials. In the current field of additive manufacturing, traditional fixed-layer thickness slicing can cause problems such as step effect, feature loss and efficiency bottleneck. The adaptive slicing technology effectively solves the above-mentioned printing problems caused by traditional fixed-layer thickness slicing by dynamically adjusting the printing thickness of each layer based on the different geometric features of the printing model. This paper systematically reviews the research progress of adaptive slicing technology in three dimensions around three major goals: optimization of forming accuracy (based on feature recognition algorithms such as surface slice tilt Angle and pixel change rate), improvement of printing efficiency (local adaptive layering and direct point cloud processing strategy), and enhancement of mechanical properties (surface layering and parametric control technology). The challenges in its practical application were analyzed and the future research directions and application prospects were prospected. Research shows that these new algorithms have significantly reduced the surface roughness of the printed models, shortened the printing time, and enhanced the bending strength of the models, successfully achieving the collaborative optimization between geometric accuracy and manufacturing efficiency in 3d printing technology.

INTRODUCTION

With the rapid development of 3D printing technology, adaptive slicing technology has become a key technology for improving printing efficiency and quality. Traditional 3D printing, which uses fixed-layer thickness slicing, can lead to obvious step effects on the surface of the printed parts, insufficient mechanical properties of the printed parts, and unsatisfactory printing effects of suspended model features [1-3]. For the various problems brought by the traditional fixed layer thickness slicing, relevant scientific researchers have proposed many optimization goals. For example, control and reduce the inclined plane features of the target printing model [4]. Optimize the contact area of the bottom surface of the model [5]. The model size is not uniformly scaled to fit the print size of the device [6]. Model static balance guarantee [7]. Optimize the surface roughness of the model [8]. Minimize the printing time as much as possible [5]. Economic optimization of the supporting structure [9]. The adaptive slicing technology can dynamically adjust the printing thickness of each layer according to the different geometric characteristics of the model, which can reduce the printing time while ensuring the printing accuracy. High print quality can be achieved when printing extremely complex models.

In terms of accuracy optimization, Huang Yunqing et al. proposed an adaptive slicing algorithm based on the fine layer thickness of veneer tilt Angle and dihedral Angle in the FDM printing process, aiming at the problems such as the step effect and model feature loss existing in the FDM printing process. Eventually, the effect of effectively reducing model feature loss was achieved [10]. Chen Lin et al. proposed an adaptive slicing algorithm based on the pixel change rate. By analyzing the change rate of the printed pixels to adjust the slice thickness, this algorithm successfully and effectively reduced the step effect and accurately depicted the fine features of the model [11]. Hope R L et al. proposed an adaptive slicing method based on the inclined boundary layer. Through Nurbs

surface modeling, cutting vector calculation and error prediction, the step effect and surface error were effectively reduced, and the accuracy and smoothness of the model were improved [12].

In terms of efficiency improvement, Mao H et al. proposed an adaptive slicing algorithm based on efficient metric contour analysis. Under the premise of meeting the geometric error constraints of each layer (such as surface roughness) and the limitation of manufacturing layer thickness, this algorithm minimizes the total number of layers, thereby shortening the printing time required [13].

Liang Yongtao proposed a fast adaptive layering algorithm based on point cloud, skipping the surface reconstruction step and directly processing the original point cloud data for layering. Experiments show that this algorithm can effectively shorten the printing time and improve the printing efficiency while ensuring the printing quality [14]. Tyberg J and Helge Bøhn J proposed a "local adaptive layering technique". By independently processing the local geometric characteristics of each feature, only thin layers are used for the feature areas that require high precision, and relatively thick layer thicknesses are used for the remaining areas. Thus, the total number of layers is greatly reduced, and the printing time is significantly reduced [15].

In terms of enhancing mechanical properties, Huang B et al. proposed a curved layer adaptive slicing technology (CLAS). Through geometrically driven layer thickness adjustment and fiber continuity design, the thermodynamic process and the integrity of the structure were optimized, the mechanical properties of the model were enhanced, and the problems of weak interlayer adhesion and anisotropy of model parts in the FDM process were improved [16]. In their research in 2019, Rosa F and Graziosi S. introduced an innovative parametric adaptive slicing technology (PAS). Through parametric dynamic control of layer thickness and shape, the mechanical properties can be optimized specifically, significantly enhancing the mechanical performance of the printed model [17]. In their research in 2016, Li H et al. proposed an algorithm for automatically adjusting the layer thickness based on the model curvature. A small layer thickness was adopted in the area with a larger curvature, and a large layer thickness was adopted in the area with a smaller curvature. The results showed that the change in layer thickness significantly affected the tensile strength and elongation at break of the material [18].

This paper reviews the research progress of various adaptive slicing algorithms around the three major goals of "improving forming accuracy, improving printing efficiency, and enhancing the mechanical strength and performance of the model", and analyzes and compares their improvement and optimization in various directions.

IMPROVE THE FORMING ACCURACY

In terms of improving the forming accuracy of FDM technology, Huang Yunqing et al. proposed an improved adaptive layering algorithm for problems such as the step effect and feature loss caused by the traditional layering algorithm. Firstly, the top height method is adopted to roughly layer the model to obtain the initial contour. Then, the model features are identified through the geometric definitions of feature points, lines and surfaces. Finally, the layer thickness is dynamically adjusted based on the inclination Angle of the patches, the dihedral angles of adjacent patches and the complexity of the vertices [10]. In the pagoda model experiment, this method reduced the surface roughness at the feature points by 27.3% compared with the traditional adaptive algorithm and by 49.8% compared with the 0.3mm equal-thickness layering. Meanwhile, through the optimization of the STL file processing by the hash table, the redundant vertex data was reduced by 16.7%, laying the foundation for the improvement of accuracy. Experiments show that this algorithm achieves a surface quality similar to that of 0.1mm equal-thickness layers while maintaining the layering number only increasing by 12% compared to the traditional method, effectively balancing the contradiction between accuracy and efficiency. In terms of improving the forming accuracy of light-curing 3D printing, Chen Lin et al. proposed an adaptive slicing algorithm based on the rate of pixel change [11]. This algorithm analyzes the pixel change rate of adjacent slice layers. When the pixel change rate exceeds the critical value corresponding to the Angle threshold, the minimum layer thickness is used for local refinement; otherwise, the maximum layer thickness is adopted [11]. This method effectively balances the printing efficiency and accuracy. The final experiment shows that the number of printed layers has increased by 32% compared with pure fixed-thickness slices, and the surface smoothness has improved by 34%. This algorithm innovatively combines the curing characteristics of photosensitive resins and uses Beer-Lambert's law to calculate the projection depth. While ensuring the curing quality of each layer, it can be adapted to different resin parameters. Compared with the traditional methods based on normal vectors or area changes, this algorithm achieves cross-format (such as STL/OBJ/3MF, etc.) universality through pixel regression quantization, and shows significant advantages in preserving the structural features of complex models and reducing the step effect, providing an efficient solution for industrial-grade high-precision UV curing printing.

Hope R L et al. proposed an adaptive slicing method that uses an inclined boundary layer to more closely match the ideal geometric contour required on the model surface [12]. Based on the TruSurf system, this study directly analyzed the geometric features of the model using NURBS surface data and achieved error control by dynamically adjusting the layer thickness: the error was evaluated using dual indicators of normal "peak height" and layer plane deviation, and a mathematical model was established by combining the radius of curvature and the surface normal Angle to achieve adaptive optimization of the layer thickness. This research breaks through the traditional limitations of the horizontal layer. By calculating the cutting path through the vector cross product to generate the inclined layer, the fit degree between the layer boundary and the designed surface is increased by 60-80%, effectively reducing the step effect [12]. For complex geometric features, this study proposes an inter-layer alignment strategy at vertices and a multi-point calculation method for curvature in the inflection area, and introduces an internal and external tolerance control mechanism (OUTTOL/INTOL) to achieve active control of material allowance through the offset of the cutting path. Experiments show that in the manufacturing of 200mm axisymmetric workpieces, this method optimizes the number of layers from 113 layers of fixed slices to an adaptive 34 layers, while maintaining the surface deviation not exceeding the set threshold, providing an ideal solution to the contradiction between the manufacturing accuracy and efficiency of large-sized models.

IMPROVE PRINTING EFFICIENCY

In terms of improving the efficiency of additive manufacturing, Mao H et al. proposed an adaptive slicing method based on efficient metric contour analysis in their 2019 study, which demonstrated significant advantages [13]. This technology transforms the traditional hierarchical optimization method based on local geometric evaluation into a global optimization method by constructing a geometric error density function (measuring contour) along the printing direction, and combines GPU-accelerated sampling technology to achieve efficient contour construction [13]. The dynamic programming algorithm is adopted to globally optimize the hierarchical scheme on the premise that the geometric error of each layer does not exceed the set threshold. Compared with the traditional greedy algorithm, the number of layers is reduced by 16% and the error constraints are strictly satisfied. Experiments show that while maintaining the surface quality, this algorithm shortens the slicing calculation time from several minutes of direct slicing of the traditional CAD model to within one second, significantly reducing the printing time [13].

In the field of 3D printing, the key to improving printing efficiency lies in optimizing the layering algorithm and data processing flow. In his research in 2015, Liang Yongtao proposed a fast adaptive hierarchical algorithm based on point cloud [14]. Traditional hierarchical algorithms have the problem of long time when processing models. The algorithm designed by Liang Yongtao skips the traditional surface reconstruction (i.e., triangular patching) and directly stratifies based on the original point cloud data of the model, shortening the preprocessing time. The efficient management of point cloud data is achieved by adopting the hybrid data structure of "pre-grouping + quadtree". The layer thickness is dynamically optimized through spatial feature analysis. Within the allowable error range, the average layer thickness is increased by 42% and the total number of layers is reduced by 30%[14]. The innovative projective contour extraction technology combined with cubic B-spline fast fitting increases the single-layer processing speed by 40%, significantly reduces the algorithm complexity, and shows significant efficiency advantages in 10^6 level point cloud processing, providing a new paradigm for the rapid prototyping of complex models.

In terms of improving the efficiency of 3D printing, local adaptive slicing technology can significantly reduce manufacturing time through innovative layering strategies. The traditional adaptive slicing method adopts a uniform layer thickness for all components within the same height layer, resulting in some simple structures being forced to use unnecessary thin layers, causing efficiency losses. The local adaptive slicing technique proposed by Tyberg and Bohn divides the model into independent sublayers through topological analysis, and dynamically adjusts the layer thickness for the geometric features of each sublayer (based on the vertical component of the surface normal vector) to achieve local optimization [15]. This method adopts a multi-stage contour matching algorithm, including direction detection, proximity verification and gradient tracking, to ensure the accuracy of sublayer partitioning. Experiments show that this technology reduces the printing time by 17-37% compared with the traditional methods [15]. This hierarchical strategy of decoupling local features provides an innovative solution for the efficient forming of complex structures.

ENHANCE THE MECHANICAL STRENGTH AND PERFORMANCE OF THE MODEL

In terms of enhancing the mechanical strength of the model, the surface layering adaptive slicing (CLAS) method proposed by Huang and Singamneni in 2015 significantly improved the mechanical properties of fused deposition modeling components by integrating surface layering and adaptive slicing techniques [16].This algorithm generates continuous surface layers based on the surface offset method of the intersection of three planes, and combines the adaptive layering strategy based on the residual height and the inclination Angle of the patches to achieve fiber continuity while reducing the step effect. Experiments show that the thicker curved surface layer increases the three-point bending strength to 32.2MPa by enhancing interlayer thermal diffusion and prolonging the curing time, which is 30% higher than the traditional uniform layering [16]. This method effectively balances the contradiction between surface quality and internal structural integrity by dynamically adjusting the layer thickness. Thin layers are adopted in steep areas to maintain geometric accuracy, and thick layers are used in gentle areas to strengthen the interlayer bonding.

In their research in 2019, Rosa F and Graziosi S. introduced an innovative parametric adaptive slicing technology (PAS). Through parametric dynamic control of layer thickness and shape, it can specifically optimize mechanical properties, the distribution of materials, interlayer bonding force and microstructure. Thereby significantly enhancing the mechanical performance of the printed model [17]. Experiments show that the three-point bending stiffness of the bent specimens using PAS technology is increased by 17% compared with the vertically oriented specimens of the traditional planar sections, and the maximum load is increased by 14%, demonstrating a better bearing capacity [17]. This strategy of actively regulating the direction and density of material deposition through path planning breaks through the anisotropic limitation caused by traditional planar layering and provides theoretical support for the directional strengthening of key areas of components.

In fused deposition modeling technology, the adaptive layering algorithm significantly improves the collaborative optimization of the mechanical properties and forming efficiency of the model by dynamically adjusting the layer thickness. In their research in 2016, Li H et al. proposed an algorithm for automatically adjusting the layer thickness based on the model curvature. Small layer thicknesses were adopted in areas with greater curvature, and large layer thicknesses were adopted in areas with smaller curvature [18]. This algorithm is based on the curvature characteristics of the model. In the area with a larger curvature, a smaller layer thickness is adopted to enhance the interlayer bonding, improve the surface quality and tensile strength, while in the area with a lower curvature, a larger layer thickness is used to reduce the number of layers. Experiments show that the layer thickness directly affects the neck growth length of adjacent silk materials. Through temperature monitoring, it is found that a thinner layer thickness can promote heat transfer to the lower layer and enhance molecular penetration bonding [18]. Compared with the single-layer thickness process, the adaptive layering reduces the molding time by 40% while ensuring the mechanical properties of the key areas, achieving the best balance between surface roughness and mechanical properties. This intelligent layering strategy provides an effective solution for performance-oriented manufacturing of complex structural components.

CHALLENGES AND DEVELOPMENT

Through various studies, it has been found that the adaptive slicing technology can significantly reduce the printing time compared with the traditional methods, while improving the printing accuracy and surface quality. However, the adaptive slicing of complex geometric models relies on a relatively high algorithmic computing power, thereby restricting the promotion of this technology to industrial-level applications. Models in industrial-grade application scenarios often have the characteristics of ultra-high precision requirements and coexistence of multi-scale structures. Ultra-high precision requirements include models such as aero engine blades and biomedical prostheses, which contain micron-level features and need to process millions of point clouds or surface data in real time. Coexistence of multi-scale structures, such as automotive parts, simultaneously have support frames (centimeter-level) and heat dissipation microchannels (sub-millimeter-level). The hierarchical algorithm requires millions of surface intersection operations. Moreover, at present, scholars studying this field pay more attention to the geometric characteristics of printed models, but still have insufficient consideration of the adaptive regulation of dynamic processes such as thermal stress and material phase transformation.

In the future, adaptive slicing technology may integrate lightweight AI and quantum optimization to reduce the computational load of feature recognition and layer thickness allocation. It will also, from the perspective of

hardware acceleration, perform core operations such as GPU/ photonic chip acceleration of pixel change rate and surface modeling.

CONCLUSION

This paper systematically reviews the latest progress of adaptive slicing technology in the field of 3D printing. Research shows that the adaptive algorithm based on strategies such as geometric feature recognition, pixel change rate analysis, and local hierarchical optimization has successfully reduced the step effect and improved the feature resolution of complex models in terms of forming accuracy. In terms of printing efficiency, the manufacturing cycle has been significantly shortened through dynamic layer thickness allocation and point cloud data processing. The curved layer technology and parametric slicing have achieved a breakthrough improvement in the mechanical properties of the printed model by optimizing the interlayer bonding and material distribution.These technological breakthroughs not only solve the problem that traditional fixed-layer thickness slicing cannot simultaneously balance printing efficiency and quality, but also provide a new paradigm for the manufacturing of complex structures. However, the existing algorithms still face the challenges of computational efficiency and multi-physics field coupling in the processing of industrial-grade complex models. In the future, with the integration of artificial intelligence lightweight algorithms, quantum computing optimization and hardware acceleration technologies, adaptive slicing is expected to achieve real-time high-precision processing, promoting the in-depth penetration of 3D printing into high-performance demand fields such as aerospace and biomedicine.The continuous development of this technology will reshape the intelligent manufacturing system, promote the transformation and upgrading of the industrial ecosystem from standardized production to personalized and function-driven manufacturing, and ultimately become one of the core engines of the Fourth Industrial revolution.Acknowledgments

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