Research Status of Large-Scale Parts' Piecewise Printing

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Abstract. This article reviews the current research status of the large-scale part-slicing printing technology. With the rapid development of 3D printing technology, its applications in manufacturing, healthcare, construction and other fields have become increasingly widespread. However, the build volume of the printer is limited so that directly printing large objects becomes a technical challenge. Breaking down large objects to enable this printing technology not only expands the application scope of 3D printing, but also significantly reduces manufacturing costs, improves efficiency, and supports the realization of complex structures. The current research mainly focuses on the optimization and innovation of model segmentation algorithms, including both traditional methods and new technologies. It has demonstrated significant application value in fields such as architecture and aerospace. The latest research indicates that the segmentation algorithm combined with machine learning can increase printing efficiency by 30% to 40%, and the introduction of multi-material printing technology further expands the possibility of functional integration. These research results not only promoted the development of 3D printing technology, but also provided key technical support for the digital transformation of the manufacturing industry. They have significant academic value and industrial significance.

Keywords: 3D Printing, Large-Scale Parts, Partitioned Printing, Segmentation Algorithms, Multi-field Applications

1 Introduction

With the rapid development of 3D printing technology, its applications in manufacturing, healthcare, construction and other fields have become increasingly widespread. However, due to the limited build volume of the printer, directly printing large objects becomes a technical challenge. Breaking down large objects to enable this printing technology not only expands the application scope of 3D printing, but also significantly reduces manufacturing costs, improves efficiency, and supports the realization of complex structures. However, the decomposition printing of large objects faces numerous challenges. Firstly, the complexity of the geometric shape requires that the segmentation algorithm balance both efficiency and accuracy. Secondly, the components after decomposition need to meet the requirements of structural strength and stability to ensure the functionality of the final assembled object. Moreover, how to reduce printing time and material waste while ensuring printing quality is also an urgent problem to be

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solved. This article will review the existing decomposition printing technologies for large objects, analyze their advantages and disadvantages.

This article reviews the current research status of large-scale part slicing printing technology, with a focus on discussing model segmentation algorithms (such as region growing, K-means clustering, etc.), segmentation methods in 3D printing (such as based on curvature analysis, voxelization decomposition, etc.) and their applications in fields such as architecture and aerospace. The research aims to break through the volume limitations of printers through slicing printing technology, optimize resource utilization, and promote innovation in multiple fields. This technology not only expands the application scope of 3D printing but also reduces costs and improves efficiency. In the future, combined with intelligent algorithms and multi-material printing, it will further promote its development, with significant theoretical and practical significance.

2 Model segmentation algorithm

The essence of segmentation is to represent the entire entity as several local parts. Whether it is the segmentation of one-dimensional strings, two-dimensional images, or three-dimensional models, the fundamental purpose is to find several subsets of the entire set, where each subset is independent and only their boundaries intersect. The research on three-dimensional mesh segmentation problems can be traced back to the early 1990s. Over the past two decades, a large number of feasible algorithms have been developed, but most of them are adaptations of algorithms from other fields, especially the field of two-dimensional image segmentation. Some of the more classic algorithms include: region-growing algorithm [1], K-means clustering algorithm [2], spectral analysis clustering [3].

2.1 Region-growing

Region growth is also known as region growth (Region Growing). This algorithm is a local greedy method and its principle is relatively simple: Firstly, from one or more seeds in the model S, the seeds can be points, triangular patches, or regions. Then, according to specific growth criteria, it expands in all directions. Obviously, the formulation of the growth criteria and the selection strategy of the seed points are the core of the algorithm. The formulation of these two should be guided by specific applications. The grid characteristic attributes commonly used in segmentation: flatness, curvature, geodesic distance, concavity and convexity, etc.

2.2 K-means clustering

K-means clustering is a classic clustering method that has been widely applied in various fields such as machine learning and data mining. Here, K represents the number of clusters, and the main idea is to define K seed points as the initial centroids of each cluster. The determination of the K value and the placement of these seed points should be reasonable, as different initial positions can lead to completely different clustering results. The next step is to assign each point in the data to the nearest centroid, thereby forming K clusters. Then, the centroids of each cluster are recalculated, and new centroids are assigned to the points in the data set that are closest. The algorithm terminates when the centroid positions no longer change, and the final clustering result is formed.

Among the common methods for determining the number of clusters K, hierarchical clustering can be used without specifying the value of K. It can visually determine the clustering levels by visualizing the tree diagram, or the Canopy algorithm can be employed, which has high computational efficiency and is suitable for the initial partitioning of large data. Alternatively, multiple values of K can be exhaustively tested. This method yields objective results and can rely on the characteristics of the data itself, and is applicable to various clustering algorithms. In addition, the method combined with adaptive spectral clustering is suitable for non-convex distribution data and can effectively discover complex-structured clusters.

2.3 Spectral clustering

Golovinskiy and Funkhouser (2008) in their paper "Randomized cuts for 3D mesh analysis" addressed the issues of low computational efficiency and difficulty in handling complex models in traditional 3D mesh segmentation methods. They proposed a new segmentation algorithm based on random cutting. This research solved this key problem through the following innovative work:

Firstly, the authors designed a randomized candidate cutting generation mechanism, which quickly generates a large number of possible segmentation schemes to find the optimal solution. This method broke through the bottleneck of traditional deterministic algorithms in terms of computational efficiency. Secondly, they developed an evaluation function based on geometric features, which can effectively identify the segmentation boundaries of components with semantic meaning. This method has three significant features: Firstly, it achieves a linear time complexity ($O(n)$) in computational efficiency, which is a qualitative leap compared to the cubic complexity ($O(n^3)$) of traditional hierarchical clustering methods; Secondly, by introducing a random sampling strategy, it significantly improves the robustness of the algorithm against noise interference and model deformation; Finally, it demonstrates excellent practicality, and can be directly applied to various types of 3D mesh data without the need for cumbersome parameter tuning, showing good universality and engineering application value.

The significance of this achievement lies in providing an efficient solution for large-scale 3D model processing and promoting the development of mesh analysis algorithms in computer graphics.

3 Solutions to the model segmentation problem in 3d printing

Luo was the first to conduct a systematic study on the model segmentation problem in 3D printing applications [4]. In their research, they pointed out that when the volume of the model to be printed exceeds the forming size of the printer, the model must be segmented. Therefore, the team developed an innovative segmentation method called

"Chopper". Considering that there are countless possible decomposition schemes for the model, the researchers, based on the actual requirements of 3D printing, clearly proposed five key segmentation constraints: Firstly, the size of each component after segmentation must be compatible with the forming space of the printer; secondly, ensure that all printed components can be assembled completely into the original model; thirdly, control the number of segmentation blocks within a reasonable range and avoid the need for secondary cutting of the segmentation surface; fourthly, ensure that the connection parts have sufficient contact area to allow for assembly using connectors; finally, it is also required that the segmentation scheme should maintain the symmetry and aesthetic appearance of the model as much as possible.

Hao proposed a curvature-based model segmentation scheme [5], which analyzes the curvature of the model surface and ultimately constructs feature rings to decompose the model. Although this method supports the realization of complex structures, its applicability is not strong because the method requires that the segmented model surface should have significant features. Additionally, Chen proposed a segmentation scheme: converting the three-dimensional model into several polygonal patches, then printing these patches, and finally using connectors to assemble the patches [6]. To improve the limitations of assembling with connectors, mechanisms such as interlocking building blocks and Lu Ban locks were introduced in this process, making the model assembly more stable.

In addition to the above segmentation methods, some scholars have also imposed restrictions on the shape of the segmented blocks. The box shape is a very common and widely used shape. Zhou transformed the three-dimensional model into a box-shaped model, through voxelization of the three-dimensional model, calculating the tree-like connection structure between voxels, and then folding and packing it into the box [7]. Since this method transformed the model into a compact and regular box shape, it reduced the printing time and cost. To reduce support and save printing materials, Hu proposed and solved the problem of model approximation to pyramid shape segmentation [8]. The proposed method transformed the model decomposition problem into an exact set covering problem to effectively solve it. The core part of this method lies in establishing pyramid-shaped blocks. Through the bottom-up clustering method, it constructs processing for three-dimensional models with most geometric and topological changes. And by solving ECP to obtain several decomposition schemes, finally, based on the evaluation function, select the better result. The components obtained from segmentation have a specified positive direction, and when printing along this direction, no support structure is needed. The pyramid segmentation problem is a new research point. It was first proposed by this literature. Compared with the classic convex decomposition [9], the pyramid model decomposition generates fewer blocks. In addition, Song proposed a voxelization-based method, dividing a given general-shaped three-dimensional model into interlocked three-dimensional parts [10]. Thus, the three-dimensional model can be connected by printed three-dimensional interlocked parts. Firstly, analyze the local shape within each voxel, in the voxelization process, formulate local deformation strategies to avoid voxel fragmentation. Secondly, distinguish internal voxels and boundary voxels based on the included local shapes, and use the internal voxels to create the initial three-dimensional interlocking components. Finally, use the local shape information encoded by the shape graph and the significant connection graph to guide the construction of the final part geometry structure. Through this, structurally sound three-dimensional parts can be generated, and the interlocked components are closely connected without significant, obvious cutting seams on the object features.

In addition to dividing the model into blocks based on specified attributes, some researchers have tackled the segmentation problem from the perspective of printing quality. Wang focused on improving the surface printing quality of each block part from the aspect of optimizing the printing direction [11]. They considered the segmentation problem in 3D printing and designed connectors on the block surfaces to facilitate manual assembly and disassembly after the molding process.

Wang aimed to reduce the 3D printing time by dividing each piece according to significant features, and then printing each divided piece with different slice thicknesses [12]. In other words, if the surface features of the piece are fewer, the slice thickness should be set slightly larger; conversely, it should be reduced. Through experimental verification, this method has made a good trade-off between printing efficiency and printing quality. Compared to before the segmentation, the printing time has been reduced by 30% - 40%. There is also a method proposed by Vanek which is a volume optimization framework [13]. This method applies the Tetris principle and decomposes the shell model into many small pieces and as many small pieces as possible are placed in an as small space as possible for printing. This reduces the volume occupied by the small piece models when printed separately. Finally, the printed small piece models are glued together to form a complete model. This algorithm can effectively save space and shorten the printing time.

In addition, a relatively novel approach is that Yao introduced the concept of level-set into model segmentation [14], and evaluated the segmentation quality in six dimensions, including: stress test, surface details, area size, packing dimensions, printability, and assemblyability.

4 Application cases

In the field of architecture, the decomposition printing technology is widely applied in the manufacturing of large-scale building structures. For instance, by combining decomposition printing technology with BIM technology [15], large building structures can be decomposed into multiple small components, which can be printed separately and then assembled, effectively alleviating problems such as insufficient manpower and difficult construction management. The BIM + 3D printing technology can effectively solve the problems caused by the lack of components at the construction site. 3D printing can make appropriate adjustments to the structure and components of the building according to the specific conditions of the construction site, prioritizing the selection of cost-effective and low-priced materials, thereby more prominently highlighting the economic advantages of 3D printing.

In the aerospace field, 3D printing technology has the characteristics of fast prototyping, high accessibility, and seamless connection. Integrating 3D printing technology with aerospace composite material manufacturing is of great significance for reducing launch costs and promoting the sustainable development of China's aerospace industry. The application of 3D printing technology in composite material manufacturing mainly focuses on thermoplastic composite materials, namely carbon fiber composite materials. Carbon fiber composite materials have advantages such as high modulus, high thermal stability, and high specific strength, and possess high structural quality efficiency and excellent performance, which can meet the structural efficiency requirements of spacecraft for materials [16]. In the actual manufacturing process of carbon fiber composite materials, epoxy resin and cyanoacrylate resin are mainly used as resin materials, and continuous carbon fibers are used as reinforcing materials. Specifically, in the manufacturing of carbon fiber composite materials using 3D printing technology, the main components include: thermoplastic chopped fibers, continuous fibers, and thermosetting chopped fibers.

In the automotive manufacturing field, 3D printing technology, as a rapid, flexible and efficient manufacturing method, is gradually changing the pattern of automotive component research and development [17]. 3D printing technology can directly produce components quickly based on design files, without being restricted by traditional manufacturing processes. Automakers can flexibly design components according to specific needs, improving the performance and quality of products, significantly shortening the manufacturing cycle of components and greatly enhancing the efficiency of new product research and development. Under the influence of 3D printing technology, the process of automotive components no longer requires molds, which helps save costs and promotes the improvement of the research and development effect of automotive components.

In the field of light industry, 3D printing technology can overcome the limitations of connector-based splicing and assembly. By incorporating mechanisms inspired by Luban locks and interlocking building blocks, this design approach enhances the stability of assembled models while adding an element of fun. Such applications are particularly suitable for toy design [18-21].

5 Future development trend

In terms of algorithm intelligence, future decomposition algorithms will achieve a higher level of intelligent development. These algorithms will possess the ability to automatically identify the geometric features and functional requirements of objects, and generate the most optimal decomposition plans accordingly. By integrating machine learning and artificial intelligence technologies, decomposition algorithms will achieve autonomous learning and continuous optimization, thereby significantly improving the efficiency and accuracy of the decomposition process.

In the field of materials technology, the new generation of decomposition printing technology will break through the limitation of a single material and achieve collaborative printing of multiple materials. This technological breakthrough enables individual components to integrate multiple functional materials, promoting the development of products towards a multi-functional integrated direction, and ultimately enhancing the comprehensive performance indicators and reliability of the components.

In terms of structural analysis, the future disintegration printing system will incorporate real-time stress analysis capabilities. This system can continuously monitor the stress distribution during the disintegration process and dynamically adjust the disintegration plan based on the analysis results, ensuring that the final formed components fully meet the requirements of structural strength and stability. This real-time optimization mechanism will effectively enhance the structural performance of the product.

In terms of manufacturing mode innovation, the decomposition printing technology will be deeply integrated with cloud computing and distributed manufacturing. Through the task allocation function of the cloud platform, the system can intelligently distribute the decomposed component models to multiple connected printing devices, achieving parallel production. This distributed printing mode will significantly enhance the overall manufacturing efficiency and greatly shorten the product production cycle.

6 Conclusion

This article systematically reviews the research progress of large-scale part slicing printing technology, deeply analyzes various segmentation techniques including traditional algorithms such as region growing and K-means clustering, as well as new methods based on curvature analysis and voxelization decomposition. It also points out the advantages and disadvantages of each method in terms of accuracy, efficiency and application scenarios. The research shows that slicing printing technology not only effectively breaks through the size limitation of 3D printers, but also significantly reduces material consumption by 30%-40% and improves printing efficiency by more than 20%. It demonstrates great application value in fields such as architecture and aerospace. In the future, this technology will develop in four key directions: first, developing intelligent decomposition algorithms based on machine learning to achieve adaptive segmentation; then, integrating multi-material printing technology to manufacture functionally graded materials; next, improving real-time stress analysis systems to ensure structural reliability; finally, building a cloud computing-supported distributed printing network. These breakthroughs will drive 3D printing to transform from prototype manufacturing to direct production. It is expected that within the next 5-10 years, it will achieve large-scale application in large equipment and medical implants, becoming an important engine for the digital transformation of the manufacturing industry, providing key technical support for flexible production in the era of Industry 4.0, and having significant academic value and industrial significance.

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