Topology Optimization Design and Partitioning Methods for Multi-axis Support-free Printing

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Abstract. This paper explores the synergy of topology optimization and partitioning printing in multi-axis support-free printing. Traditional three-axis printing demands extensive supports for topology-optimized structures, causing low efficiency and high costs. While multi-axis printing enables support-free production via dynamic orientation adjustment, it is usually decoupled from topology optimization design, forming a design-manufacturing bottleneck that restricts its full potential. The research focuses on two core aspects: partitioning printing strategies involving model decomposition based on geometric features and performance requirements, and multi-axis-aware topology optimization. This optimization integrates dynamic overhang angle constraints and material anisotropy modeling to generate self-supporting high-performance structures. Findings show serial processes cause performance loss and higher iteration costs; two-step optimization and similar collaborative methods achieve basic block partitioning-optimization linkage but are limited to simplified 2D models, failing to exploit multi-axis printing's continuous direction-changing ability. Future research should focus on 3D continuous direction field planning, collision avoidance and complex geometry adaptation to advance this technology's practical application.

Keywords: Topology, Optimization, Partitioning

1 Introduction

Additive manufacturing (AM), often referred to as 3D printing, is a technology that uses layer-by-layer deposition or curing of materials to create objects. This technology breaks the geometric limitations of traditional manufacturing, offering immense flexibility for product design and production. Additive manufacturing employs a bottom-up processing approach, allowing it to create highly complex structures that are difficult to achieve with traditional manufacturing methods.

With the advancement of additive manufacturing (AM) technology, topology optimization is an advanced structural design method. It optimizes the distribution of materials to devise structures with optimal performance under predefined loads and constraints. This approach is capable of automatically generating innovative solutions, effectively reducing structural weight, enhancing

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mechanical strength, and optimizing other key performance metrics. Unlike size optimization and shape optimization, the initial configuration does not impose any restrictions on topology optimization. Therefore, it has a wider design space and can explore more diverse structural forms. Today, topology optimization has become an increasingly important method in engineering structural design[1].

In current engineering practice, structural lightweighting has become a core requirement for improving product performance and reducing energy consumption[2]. An ideal approach to attain this goal is provided by the combination of topology optimization and additive manufacturing. It can give full play to the advantages of additive manufacturing in manufacturing complex geometries, and can also ensure the optimality of the structure in terms of function through topology optimization [3]. There are many examples of successful applications of topology optimization and additive manufacturing, such as the antenna support of RUAG's Sentinel satellite, a cable support that is developed for the front beam section of the vertical tail assembly of the Airbus A350 XWB, and the aerospace support jointly developed by Northwestern Polytechnical University and China Aerospace Science and Industry Corporation[4].

However, traditional three-axis printing processes often require numerous support structures when dealing with complex structures generated through topology optimization. This not only significantly reduces manufacturing efficiency but also increases material costs, limiting the economic viability and applicability of the technology. Multi-axis additive manufacturing, by dynamically adjusting the building direction, offers a novel approach to solving the support challenges in traditional printing. Therefore, researching topology optimization structural design and partitioning methods for multi-axis unsupported printing is of great value in promoting the development of advanced structural manufacturing technologies. This research aims to establish an innovative method that integrates design and manufacturing requirements, achieving a synergistic improvement in structural performance and manufacturing efficiency through the effective connection between optimized design and process planning.

The core challenge currently facing this field is the disconnect between design and manufacturing. Existing research mainly addresses this issue from two directions. First, on the manufacturing side, researchers have proposed model partitioning methods, such as skeleton-based decomposition algorithms, which divide complex structures into independently printable parts [5]. Second, on the design side, scholars have tried to introduce manufacturing constraints into topology optimization, such as overhang angle constraints, and structures based on innovative configurations, such as hierarchical lattice structure optimization [1]. However, most existing methods treat design and manufacturing as sequential processes, lacking integrated approaches that consider multi-axis printing characteristics from the early stages of topology optimization. In recent years, some research has begun to emerge aiming to establish an integrated approach that coordinates design and manufacturing. This paper will explore the following: First, it systematically reviews partitioning printing strategies based on geometric features and performance requirements; second, it analyzes integrated methods for overhang angles and anisotropic factors in topology optimization under multi-axis constraints; finally, it discusses collaborative design paths combining partitioning printing and topology optimization, and points out current limitations and future challenges.

2 Partitioned Multi-axis printing

Multi-axis sectional printing is a core process strategy for solving the manufacturing dilemma of large-size and highly complex structures. Its development is highly compatible with the evolution of additive manufacturing technology. Although the traditional 2.5-axis fused deposition modeling (FDM) technology has the advantage of simple operation, it has significant limitations in the processing of complex structures. The emergence of multi-axis printing technology provides a new path to solve these problems. It can flexibly adjust the relative angle between the nozzle and the workpiece, and theoretically can achieve supportless printing and weaken the staircase effect[6]. However, current volume decomposition strategies for multi-axis printing still have shortcomings. Against this backdrop, the core idea of modular multi-axis printing, which breaks down a complete digital model into smaller, geometrically simple sub-parts, and independently plans the optimal multi-axis printing path for each sub-part, fundamentally reduces the manufacturing difficulty of complex structures, and ultimately obtains the finished product through physical assembly.

2.1 Geometry Feature-based Decomposition

Multi-axis segmented printing is based on the decomposition of geometric features. In the process of multi-axis 3D printing, the overall model is decomposed into several sub-segments that are adapted to multi-axis printing motion, based on the geometric properties of the model. This solves the problems of inaccessible hidden areas, significant staircase effect, and high support requirements in traditional printing. At the same time, it adapts to non-horizontal printing directions to optimize printing accuracy and efficiency[7]. These methods primarily focus on the model's geometry, aiming to generate easily printable sub-blocks. Early research emphasized planar segmentation, cutting the model along specific planes, with each sub-block printed along a 2.5-axis orientation. However, planar segmentation introduces significant geometric discontinuities at the seams when dealing with freeform surfaces. Skeleton-based decomposition methods emerged to address this issue.For the goal of 3D printing without any support structures, Wei et al. devised a skeleton-based algorithm to decompose a 3D surface model into the smallest number of segments. The algorithm is applicable to shell models as well as solid models, further expanding the application scope of the skeleton decomposition method in supportless printing scenarios[5]. Kanada et al. proposed a decomposition method driven by two types of geometric features: one is geometric features based on printability. The other is geometric features based on a specified printing direction vector field, which, together with the attitude adjustment of the multi-axis print head, achieves unsupported or weakened staircase effect printing. It uses a delta-type 3D printer to design, segment and print the Olympic rings. The design of these rings is reasonable and the printing effect is good [7]. Although some unresolved issues remain, including the difficulty in determining part segmentation points and the weakness at these points, these geometric feature-based decompositions provide a more suitable sub-block partitioning scheme for block-based multi-axis printing, conforming to the topology of complex models.

2.2 Performance Requirement-based Decomposition

Performance requirement-based decomposition considers not only geometric printability during partitioning, but also the functionality of the final product. Its goal is to optimize the performance of the overall structure through partitioning. A typical direction is decomposition oriented towards mechanical performance. For example, some studies have attempted to set the partition interfaces in low-stress areas of the structure to avoid the connection interfaces becoming performance bottlenecks [8]. Another cutting-edge direction is multi-material and functionally graded partitioning, which involves decomposing the model according to functional requirements, printing each part separately using different materials, and finally assembling them into a single structure with multiple functions. To address the performance optimization issue of multi-material block printing, Markovic's team proposed that the printing direction and post-processing method should be matched according to the material characteristics of the sub-blocks. For example, a 0° printing direction can enable the sub-blocks to obtain the optimal tensile strength, while targeted thermochemical post-processing can reduce stress concentration at the interface of the blocks and avoid the connection part becoming a performance bottleneck [9]. This fully demonstrates the great potential of block printing in realizing complex functions.

3 Topology Optimization Design

Multi-axis topology optimization design aims to consider and leverage the technological characteristics of multi-axis printing during the topology optimization stage, thereby creating novel structures that possess both excellent performance and are fundamentally easy to manufacture using multi-axis technology. In this domain, the central focus of cutting-edge research pertains to the methodologies for modeling the manufacturing constraints inherent to multi-axis printing, as well as the strategies for their seamless integration into the mathematical framework underlying topology optimization. Currently, the main constraint types include overhang angle constraint integration, printing path and anisotropy constraint consideration, etc.

3.1 Integration of Overhang Angle Constraints

Overhang angle constraints are the most direct and universal manufacturing constraints. Unlike traditional overhang angle constraints applied in a single Z-axis direction, overhang angle constraints in multi-axis scenarios are dynamic and direction-dependent. When applying an overhang angle in a traditional single Z-axis direction, the lower surface becomes rougher as the overhang angle decreases, eventually leading to part failure.Therefore, researchers establish a local construction direction field—and in the course of the optimization process, they impose restrictions on the angle that exists between the growth direction of an individual material point and the local direction associated with it, thereby guiding the structure to grow along one or more optimal paths, thus naturally avoiding the generation of large overhang structures. Ye et al. believe that in the collaborative optimization study of Truss structure and construction direction, by defining a local construction direction field and constraining the growth angle of the component, the generation of large overhang structures can be effectively avoided, the structure and printing surface can be optimized to further improve the structural efficiency and minimize overhang, and the self-supporting manufacturing can be realized through physical printing verification [10]. A method for fitting the local element density distribution of linear surfaces is proposed by Zhang et al., which is designed to estimate the boundary normals of both optimal and intermediate design structures in SIMP where serrated and fuzzy boundaries are present. This method can suppress overhangs and overly thin components, combine constraints to limit the volume fraction of illegal elements, and solve the topology optimization problem through a multimodal algorithm [11].

3.2 Considerations For Print Path and Anisotropy Constraints

If the printing path planning and process-induced material anisotropy constraints of additive manufacturing are ignored during the topology optimization stage, the optimized design may face the risk of iteration or even failure due to insufficient manufacturability or shortcomings in mechanical properties. In particular, the development of multi-axis additive manufacturing technology has enhanced design freedom by flexibly adjusting the printing path. However, more rigorous demands are also placed on the integrated design of topology optimization by the differences in material anisotropy that are generated by distinct printing paths. In the field of multi-axis topology optimization manufacturing, Shin et al. first proposed to construct a spatiotemporal topology optimization framework, providing a solution for the deep integration of multi-axis printing manufacturing constraints and topology optimization mathematical models. This study directly addresses the challenges brought by material anisotropy to structural performance in multi-axis AM, and innovatively uses pseudo-time field as a design variable to simultaneously optimize material density distribution and multi-axis construction direction [12].Ichihara and Ueda proposed a design framework for fiber-reinforced polymer composites, and put forward a printing path planning method based on anisotropic topology optimization, which generates high-toughness structures by optimizing material orientation and path spacing [13].

4 Combination of Partitioning multi-axis manufacturing and multi-axis topology optimization manufacturing

4.1 Existing Serial Processes and Limitations

While the combination of topology optimization and AM offers the possibility of high-performance structures, the linear disconnect between design and manufacturing remains a core bottleneck. This problem is particularly prominent in two scenarios: first, the sequential approach of 3-axis AM and topology optimization. Existing research mostly follows the logic of first generating the theoretically optimal structure through topology optimization, and then adapting it to manufacturing constraints. However, the topology optimization stage does not incorporate conditions such as overhang angle restrictions and fixed vertical printing directions, resulting in the initial structure often requiring secondary modifications due to a large number of overhang areas that cannot be directly printed, accompanied by significant performance sacrifices. For example, the core objective of the AM filtering method proposed by Langeraar is to directly generate self-supporting structures through topology optimization, thereby avoiding the drawbacks of temporary supports from the root. Such temporary supports also increase material consumption and post-processing costs. The removal of supports in metal AM is more difficult, and even residual stress affects safety [14]. Secondly, the serial limitations of early multi-axis AM research. Some studies have reduced overhang by decomposing the structure into multiple regions and assigning local printing directions as proposed by Gao et al. or by using customized curved surface printing layers proposed by Dai's team, but they have not yet broken away from the framework of topology optimization to process planning and then to structural modification [15][16].

On the one hand, multi-axis AM core constraints such as material anisotropy and nozzle collision risk only intervene in the process stage. For example, the decomposition method proposed by Wu et al. caused anisotropic failure because the partitioning and printing direction were not designed simultaneously[17]. In addition, in triaxial additive manufacturing, the collision risk of convex and shallow concave surfaces can be ignored, but the risk increases when a deep concave printing surface is used[18]. On the other hand, process planning passively adapts to the completed topology. As an illustration, the curved printing layer developed by Li et al. necessitates range reduction for collision avoidance, yet the optimal force transmission path is still compromised in this process[6]. To encapsulate, the primary contradiction in the existing serial process arises from the spatiotemporal gap between optimized design performance and manufacturing feasibility; this gap contributes to performance trade-offs, increased iteration costs, and failure to maximize the adaptability of multi-axis AM. An integrated optimization framework is thus required to resolve this limitation.

4.2 An Initial Attempt at Integration Exploration

To overcome the drawbacks of sequential processes, researchers have begun exploring collaborative design methods. Current cutting-edge research focuses on the collaborative optimization of structural performance and manufacturing feasibility. The two-step optimization method proposed by Ye et al. is a typical example of this approach. In contrast to prior studies that focus on triaxial additive manufacturing, the present method achieves concurrent optimization of both the structural design and its associated printing strategy—specifically, the geometric configuration of the printed surface. This method proposes a two-step optimization approach that combines structural topology optimization with modular printing planning: starting with a high-performance structure obtained through traditional topology optimization, the design domain is partitioned into a set of mutually independent regions, where each region is allocated a local printing direction. To maximize the printable fraction of the structure, linear programming is employed to determine the optimal printing direction for each individual region. This method decomposes the complex structure into sub-regions and adapts the structure geometry to regional printing parameters to avoid overhangs. The second step is to re-optimize the structure under the block printing constraint. This is to perform secondary topology optimization on the structure based on the determined block printing direction constraint and adjust the structure shape to eliminate unprintable areas. At this time, the block printing direction constraint becomes the core manufacturing constraint of topology optimization and directly guides the iterative optimization of the structure morphology [18]. Although it still focuses on 2D scenes, and the Partitioning direction has the risk of sudden changes at the joints, it has provided a feasible paradigm for collaborative design and laid the foundation for working in 3D scenes.

4.3 Future Trends

In the integration of partitioning multi-axis manufacturing and multi-axis topology optimization manufacturing, current preliminary explorations centered on collaborative design have broken the limitations of traditional serial processes. However, from technology implementation to large-scale application, breakthroughs are still needed in scenario expansion and engineering adaptation, while addressing multi-dimensional technical challenges. The future development trend will move from 2D collaboration to 3D global collaboration, breaking through structural dimensional limitations, which presents a significant challenge for researchers.

5 Conclusion

This study reviews the manufacturability design and partitioning methods for topology-optimized structures in multi-axis unsupported printing. It systematically outlines the technological development of block-based multi-axis printing, topology optimization design, and their integration. It demonstrates that achieving integrated design-to-manufacturing to unleash the full potential of multi-axis printing is a promising research direction. However, the current research paradigm still has significant limitations. First, the aforementioned collaborative design methods significantly simplify the model, reducing computational complexity but sacrificing the core flexibility of continuous direction changes in multi-axis printing. Second, its research scope is limited to two-dimensional problems, and its feasibility has not yet been verified in more complex three-dimensional scenarios.

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