Self-Supporting Structure Technology in 3D Printing Applications

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Abstract. In recent years, with the rapid development of additive manufacturing technology, the design and manufacture of self-supporting structures have entered a brand-new stage, which significantly reduces the dependence on support materials through the layer-by-layer molding characteristics, opening up a new path for the lightweight and efficient production of complex geometric structures. This paper systematically reviews the research progress of self-supporting structures. At the level of mechanical analysis, methods such as Thrust Network Analysis (TNA), Force Density Method (FDM) and Extended Limit Analysis (ELA), and discrete homogenization are used to optimize the structural compression and tension balance through numerical models. Algorithmic techniques such as parametric design, automated mesh generation, and artificial intelligence optimization fuel the realization of more complex and refined designs of structures. In addition, some engineering ideas of self-supporting structures also provide technical references for fields such as 3D printing, demonstrating their potential in the manufacturing field. Topology optimization, as a major research hotspot in additive manufacturing, also provides an important technical basis for the realization of self-supporting structures. Despite the many advances in self-supporting structure technology, it still faces challenges such as high computational cost, limited manufacturing accuracy, and difficulty in modeling the nonlinear behavior of materials.

Keywords:. Self-supporting structures, 3D Printing, Thrust Network Analysis, Parametric and Intelligent Optimization

1 Introduction

The design of self-supporting structures can be traced back to ancient architecture. For example, arch bridges in ancient Rome and loess kiln dwellings in China utilized gravity and the compressive properties of the materials to achieve mechanical equilibrium without relying on additional support structures [1].

After entering the 20th century, structural mechanics, material science and computer technology were developed. Self-supporting structures in architectural design have gradually evolved into more complex and refined forms, especially with the emergence

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of modern computational mechanics, which enables architects and engineers to design and optimize these structures through accurate numerical models [2].

As additive manufacturing technology continues to advance, the design of self-supporting structures is also being used in it. While traditional self-supporting structures usually rely on tedious process steps such as molds, support materials and post-correction, 3D printing technology can directly print self-supporting structures through layer-by-layer manufacturing, which greatly simplifies the manufacturing process and improves the degree of design freedom. In recent years, the rapid development of 3D printing technology has brought the design, optimization and manufacturing of self-supporting structures into a completely new stage. The application in 3D printing can significantly reduce the dependence on support materials, thus improving manufacturing efficiency and reducing costs.

Despite the many advances in the study of self-supporting structures, challenges such as computational efficiency, physical consistency, and fabrication feasibility are still faced. In this paper, we will systematically review the research results on self-supporting structures in recent years, especially those applied in additive manufacturing, from the perspectives of mechanical analysis, algorithmic optimization and engineering optimization, to provide theoretical support and technical reference for related research and engineering practice in the field of additive manufacturing.

2 Mechanical analysis and structure generation

The generation and validation of self-supporting structures rely on mechanical equilibrium theory, in which Thrust Network Analysis (TNA) has become a core methodology for the study of Compression-Only Structures (COS).

2.1 Presentation of thrust network analysis

Block and Ochsendorf first proposed three-dimensional thrust network analysis (TNA) [3]. The method extends graphic statics to three dimensions by calculating the pressure-only equilibrium form of the structure through linear optimization and projective geometry theory. The concept of funicular polygon is also adopted to extend the force analysis from traditional two-dimensional curved structures to complex spatial structures such as vaults and domes.

2.2 Extended optimization of thrust network analysis

Rippmann et al. proposed an interactive framework based on TNA [4]. This method controls the geometry and internal force distribution in both directions, and allows the user to view the thrust flow inside the structure in real time while adjusting the morphology. In another research, Marmo and Rosati have optimized and extended the computational functions of TNA, improved the original mathematical modeling, and discarded the traditional dual grid of TNA, which reduces redundant computations and improves the solution efficiency [5]. The adaptation of this method to free boundaries and voids allows 3D printing to be more flexible for manufacturing lightweight and skeletonized self-supporting forms, such as large-span domes, skeletonized architectural components, and biomimetic structures.

2.3 Verification of thrust network analysis by 3d printing

Based on the original TNA theory, Block et al. experimentally validated the TNA method by 3D printing physical models [6]. Using a bondless 3D printed model, they simulated the force state of a historic masonry vault and demonstrated the effectiveness of the TNA method in optimizing 3D printed self-supporting structures.

2.4 Adaptive force density method

Zhang and Ohsaki proposed adaptive FDM, which is an adaptive force density method. This method improves the solution efficiency by transforming the nonlinear system of equilibrium equations into linear equations through the ratio constraints of the force density [7]. Eigenvalue analysis and spectral decomposition are used to stabilize the structure by iteratively searching for new force density configurations. FDM is applicable to both tensile structures and tensegrity structures, and can be used to optimize the morphology generation in the design of self-supporting structures.

2.5 Extended limit analysis

Lopez et al. proposed Extended Limit Analysis (ELA) based on the traditional limit analysis, which considers the force contribution of reinforced masonry and is applicable to a wider range of structural types. The ELA is extended from 2D to full 3D structures using 3D solution methods and numerical iterations for optimizing the design and analysis of structures such as reinforced masonry and thin concrete shells [8].

2.6 Discrete homogenization and mechanistic network optimization

Based on numerical homogenization, de Goes et al. proposed the equilibrium theory for discrete masonry structures. Its core lies in transforming the continuous stress field into a finite-dimensional model through an orthogonal force network, thus revealing the mathematical relationship between simplicial meshes and self-supporting capacity, and improving the computational efficiency and design freedom [9].

3 Algorithm optimization and parametric design

Algorithmic optimization of self-supporting structures aims to improve computational efficiency, enhance design freedom, and optimize mechanical properties. Taken together, these methods can be used to effectively enhance the design accuracy, manufacturing efficiency, and material utilization of self-supporting structures in 3D printing, especially for the design and production of complex geometries.

3.1 Regular triangular sections and parameterized methods

Liu et al. proposed a parametric method based on regular triangular dissections to optimize the force density distribution of self-supporting meshes through power diagram mapping [10]. The method implicitly encodes the network topology, which breaks through the limitation of the fixed topology of the traditional network analysis and makes the optimization of free form structures more flexible.

3.2 Automated masonry structure generation

Panozzo et al. proposed an automated masonry modeling approach based on TNA combined with hexagonal meshing to ensure structural stability [11]. The study uses Field-Aligned Remeshing to optimize the discrete force patterns and proposes a hexagonal block delineation strategy without sliding failure that can be applied in 3D printing.

3.3 Self-supporting parametric polyhedral structures for 3d printing

Yi Liu et al. proposed a lightweight self-supporting structure design method based on polyhedral units specifically for 3D printing [12]. The method meets the structural requirement of supporting overhanging surfaces through stress optimization, while optimizing the center of mass, number, and wall thickness of the cells to reduce the internal forces in the structure and support the inner surface. The cross-section of each unit consists of simple geometries that are easy to fabricate, and the optimized structure can be fabricated by 3D printing technology, and its effectiveness is verified by numerical simulations and physical experiments.

3.4 AI-based self-supporting structure optimization for additive manufacturing

Marshall V. Johnson et al. proposed an artificial intelligence (AI)-based optimization method for self-supporting structures, specifically for 3D periodic structures in additive manufacturing (AM) [13]. The method classifies the simplest spanning structures in self-supporting geometries by using image analysis and machine learning models (random forest classifier), and automatically adjusts the process parameters using a closed-loop optimization strategy. The researchers proposed two optimization strategies: one to adjust the print speed and nozzle height step by step, and the other to find the optimal parameters quickly by dichotomy. The AI tool obtained through optimization was successfully applied to different additive manufacturing systems including DIW and FFF, and was able to be generalized across multiple printer platforms. 3.5 Self-supporting Diamond-filled Structures for Additive Manufacturing.

3.5 Self-supporting diamond-filled structures for additive manufacturing

Jun Wu et al. proposed a rhombic mesh-based optimization method for self-supporting internal infill structures in additive manufacturing [14]. The method utilizes an adaptive rhombic mesh to generate infill structures to ensure that the maximum overhang angle and minimum wall thickness requirements are met during the manufacturing process, thus avoiding additional support structures altogether. The study employs a numerical optimization method to make the structure satisfy different mechanical stiffness and static stability requirements by progressively refining the rhombic mesh. Experiments show that the method can effectively improve the structural strength while reducing material consumption and fabrication time, and is applicable to different 3D printing processes.

3.6 Fabrication and optimization of self-supporting suspension structures under ebm technology

Ameen et al. investigated the fabrication limits and deformation of self-supporting overhanging structures under electron beam melting (EBM) technology [15]. The study experimentally analyzed different geometries of drape structures such as convex surface, concave surface, slope, bridge drape, and overhanging drape, assess their feasibility and deformation characteristics under unsupported conditions. The results show that different types of overhang structures have their own self-supporting limits, beyond which deformation, buckling or material loss may occur. In addition, the study proposes a segmental bracing strategy, which effectively reduces the use of bracing materials and post-processing time, while ensuring fabrication accuracy.

4 Engineering practice and topology optimization

The actual construction of self-supporting structures faces the key challenge of how to minimize additional support during construction and fabrication. As a whole, these research techniques provide certain technical references for the application of 3D printing-based technologies in large-scale engineering. Topology optimization is a major research hotspot in recent years for the design of 3D printed self-supporting structures, where mathematical algorithms are used to calculate the optimal material distribution to reduce the weight and improve the structural performance, which is expected to be applied in engineering and manufacturing.

4.1 Real-time optimization of self-supporting structures in engineering

Deuss et al. investigated the sparse chain construction strategy, using chains instead of formwork to support masonry buildings [16]. The method is optimized by staged assembly to ensure that the structure is always in equilibrium during construction and to reduce the reliance on formwork. It is suitable for masonry buildings but has limited applicability to non-discrete structures. This idea of engineering optimization is also reflected in 3D-printed self-supporting structures: the design and construction methodology for building self-supporting curvilinear-geometry buildings, for example, multipurpose pavilions, using 3D printing by Lapyote Prasittisopin et al. In the study, concrete structures were printed by FDM (Fused Deposition Modeling) technology and a self-supporting curved geometry was designed so that it could self-support without the need for additional support systems. A modular construction method was used to disassemble the large structure into small modules, build them layer by layer using 3D printing, and connect these modules through on-site assembly to form the final building [17].

4.2 Topology optimization and self-supporting structures

Wang et al. explored topology optimization and 3D printing methods for Three Branch Joints (TBJs). They used OptiStruct solver for topology optimization to generate the optimal morphology that conforms to the stress distribution of the structure, and used 3D printing technology to fabricate the optimized structure. The experimental results show that the topology-optimized trident nodes outperform the conventional hollow ball nodes and bionic nodes in terms of force equalization and stiffness, while significantly reducing the material usage [18]. This study highlights the advantages of combining topology optimization with additive manufacturing, especially in the optimization and fabrication of complex connected nodes, which can provide lighter weight structures with better mechanical properties.

Xu et al. proposed a topology optimization framework for multiaxial additive manufacturing to generate optimized slicing paths through heat diffusion and Poisson's equation to enable self-supporting of layers during the printing process. To further optimize the structure, the study employed a boundary gradient method to identify self-supporting geometric features and determine which surfaces can self-support without relying on the support structure. This method has been validated for use in the design of self-supporting structures for short cantilever beams as well as bridge structures [19].

Guo et al. proposed two other methods for designing self-supporting structures based on topology optimization. These methods are based on the moveable deformable component (MMC) and moveable deformable void (MMV) frameworks, respectively, where the MMC method optimizes the size, position, and tilt angle of the components during the design process by introducing deformable components, thereby ensure that the structure is self-supporting and avoid excessive overhang angles in additive manufacturing. Whereas, the MMV approach focuses on avoiding the disadvantage of the need to introduce additional complex functions in the traditional level set approach by optimizing the geometry of the voids [20].

Overall, topology optimization enables the design of lightweight, self-supporting structures that meet specific functional requirements in areas where performance is critical, resulting in improved product performance and longevity.

5 Challenges and trends

Some current mechanical or geometric optimization algorithms still suffer from high computational cost and slow convergence when dealing with large-scale complex structures. For example, although the Thrust Network Analysis simplifies the equilibrium equation solution through linear optimization, its dyadic mesh model still suffers from redundant computational problems in 3D free-form surfaces [6]. Existing methods focus on structural stability, in the actual additive manufacturing process, thermal stress caused by deformation may affect the self-supporting performance, the future can be more concerned to the consideration of temperature, hydrodynamics, and other factors. Masonry structural materials and 3D printed materials often exhibit complex nonlinear behaviors such as cracking and strain hardening, but most of the existing models are based on linear assumptions. For example, although the force density method improves the efficiency by linearization, it may have insufficient adaptability to nonlinear materials [7]. The prediction for different nonlinear materials is still a major challenge if the relevant techniques are to be applied in the field of additive manufacturing in the future. In addition, the optimization of material distribution and interfacial bonding remains a major challenge when multi-material 3D printing is involved. Some self-supporting structures may be more difficult to realize. Overall, the application of self-supporting structure technology in 3D printing is full of potential, but still faces several challenges such as manufacturing accuracy, optimization algorithms, and material selection. With the advancement of intelligent optimization technology, the application of multi material printing technology, and the integration of additive manufacturing systems, more subsequent studies are expected to address the related technical difficulties and deficiencies [21].

6 Conclusion

This paper reviews the research progress of self-supporting structures in 3D printing, focusing on three aspects: mechanical analysis, algorithm optimization and engineering implementation. By reviewing the core theoretical methods such as Thrust Network Analysis (TNA), Force Density Method (FDM) and Extended Limit Analysis (ELA), combined with parametric design, AI optimization and topology optimization strategies, it reveals the current key technological paths and results of self-supported structure design in additive manufacturing. The paper also introduces the application cases of self-supporting structures for engineering practice, and summarizes the unique advantages of topology optimization for self-supporting structures in enhancing structural efficiency and reducing the use of support materials. Its research has become a multidisciplinary cross-hotspot connecting mechanics theory, modeling computation and advanced manufacturing, which has important theoretical significance and engineering value.

Self-supporting structures, as a key support technology to promote the high efficiency of 3D printing, and its related research results not only show great potential in structural optimization and material utilization, but also provide new possibilities for the construction of complex geometries. Looking ahead, the development of self-supporting structures in the field of 3D printing is expected to deepen in the following directions: first, at the algorithm level, more consideration will be given to the complex physical factors in the manufacturing process, such as thermal effects, residual stresses and material nonlinearities, to promote a more realistic simulation and design optimization. At the level of the manufacturing process, the use of multi-materials, multi-axis and in-situ monitoring and other advanced printing technologies, to achieve a higher degree of precision and stronger functionality. The third is the system integration level, through hardware and software collaboration and artificial intelligence integration, to realize the whole process of self-supporting structure from design to manufacturing intelligence and automation. Self-supporting structures will not only be limited to experimental components or prototype manufacturing, but are also expected to realize large-scale and practical applications in construction, aviation, medical and other engineering fields.

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