

Design and Optimization of 3D Printing Self-supporting Structures

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Abstract. 3D printing technology has made the production of complex geometric shapes and personalized designs unprecedentedly simple, completely reshaping the pattern of manufacturing. A core challenge facing 3D printing technology is optimizing the printing of self-supporting structures, which can minimize material redundancy, shorten production cycles, and improve overall printing quality. This article delves into the time factors and optimization strategies of using 3D printing technology to produce self-supporting structures. The time factors and optimization strategies. This article discusses the design and optimization of self-supporting structures from two aspects. This paper delves into the strategies for enhancing the strength of self-supporting structures and reducing material consumption in the process of building self-supporting structures using 3D printing technology. The discussion is conducted from two dimensions design and optimization of self-supporting structures. This study conducts an in-depth analysis of the problems existing in structure design and explores the topology optimization scheme of optimizing the layout and algorithm in the same stress condition. This scheme ensures that the self-supporting structure has sufficient strength to maintain a stable printing process when printing complex components, thereby improving printing accuracy to some extent and reducing material consumption. It can effectively improve production efficiency and reduce costs.

Keywords: 3D printing, Self-supporting structure, Optimization, Application.

1. Introduction

The development of 3D printers can be traced back to the 1980s when American inventor Charles Hull created the world's first 3D printer [1]. Due to technological limitations, it was not until the 21st century that 3D printers experienced significant technological breakthroughs and gradually became widely used. Nowadays, 3D printing technology plays a significant role in fields such as automotive [2], aerospace [3], electronics [4], and medicine [5]. An important field of self-supporting structure 3D printers. Support plays an important role in the field of 3D printing, as it can support suspended parts, maintain printing accuracy, and solve suspension problems.

However, traditional support structures have significant flaws. It is limited by complexity and has an impact on component accuracy. Low production efficiency, high time cost, and accompanied by significant material waste [6]. These supports need to be manually removed after printing, greatly increasing the workload of subsequent processing [6]. Moreover, the disposal and abandonment of supporting structures will increase the cost of waste disposal and have an impact on the environment. Especially in large-scale production and rapid consumption of materials, this can cause significant environmental burdens.

To overcome these issues, researchers and engineers are committed to developing self-supporting technologies. Structures refer to complex geometric shapes and structures designed and manufactured during 3D printing that can support themselves without the need for additional supporting materials. Compared to traditional support structures, self-supporting structures do not require additional materials to support suspended or over-suspended parts, greatly reducing material waste [7]. Due to the lack of additional support structures, self-supporting structures can significantly improve production efficiency, and without considering the addition and influence of support structures, they can maximize design freedom and complexity, enabling 3D printing technology to be applied in a

wider range of fields. Meanwhile, self-supporting technology can improve the quality and accuracy of printing. technology can improve the quality and accuracy of printed surfaces.

Traditional printing may result in surface marks or residues [6], requiring additional processing work. However, by optimizing the self-supporting design, these problems can be avoided or reduced, improving the overall quality of printed materials. In addition, self-supporting technology can reduce cost-effectiveness and environmental pollution by reducing the use of materials [7], which is more in line with the requirements of sustainable development. With the development of algorithms and software, key self-supporting technologies such as topology optimization algorithms, internal structure design, adaptive path planning, and materials science have made significant breakthroughs, under the combined action of these technologies. Enable complex geometric shapes and suspension parts to be stably printed during the 3D printing process without the need for additional support structures.

This article is based on the innovative design of self-supporting structures and of self-supporting structures. The structural design utilizes a scheme of angular filling structure, crystal nucleus filling structure, and unsupported elliptical void structure to optimize the design scheme. The optimization of self-supporting structures utilizes topology optimization, layout optimization, and geometric optimization to enhance the performance of self-supporting structures.

2. Self-supporting Structure Design

2.1. Diamond-shaped Filling Structure

Wu and his team proposed a new method for generating application specific filling structures on diamond-shaped units [8], which enables the resulting structure to automatically meet manufacturing requirements for overhang angle and wall thickness. The general idea is shown in Fig. 1.

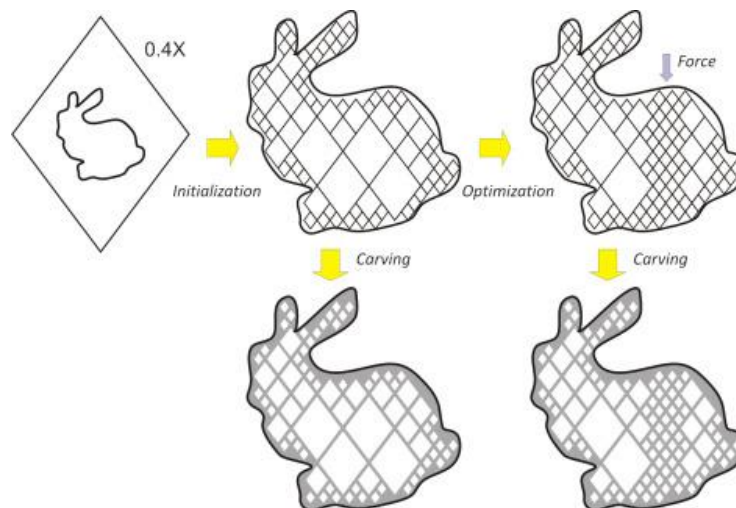


Figure 1. Overview of filling optimization using diamond structure [8]

As shown in Fig. 1, an overview of filling optimization using diamond-shaped structures is presented. The initial model (left) covering the diamond shape, i.e. the root, is adaptively optimized to fit the geometric shape of the input model. Only retain leaf nodes that are completely located within the model. Then, the diamond tree is transformed into a self-supporting structure formed by diamond shells. In the optimization process for specific physical objectives, the structure (and material) is added by recursively refining the diamond-shaped elements represented by the affected leaf nodes [8].

This method introduces a tree structure with diamond-shaped units, which is self-supporting and has a controllable minimum feature size. Adaptive spatial refinement similar to octree can be used to modify the topology of the tree structure, but it will subdivide diamond-shaped cells [8]. This method can completely avoid additional support structures and achieve the goal of self-supporting.

As shown in Fig. 2, the optimized structure effectively reduces the internal stress of the object in two situations.

In summary, through adaptive optimization of the diamond frame, the filling material has better mechanical properties.

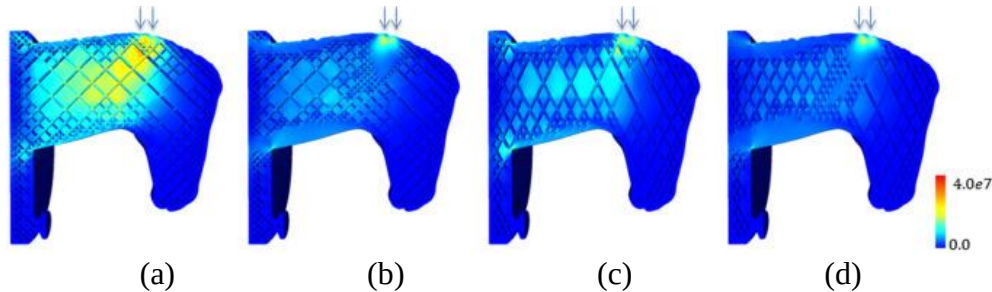


Figure 2. Stress testing and distribution on the horsehead model [8]. (a) Initial diamond structure with an aspect ratio of 1; (b) optimized diamond structure with an aspect ratio of 1; (c) initial diamond structure with an aspect ratio of 2; (d) optimized diamond structure with an aspect ratio of 2

2.2. Elliptical Filling Structure

Lee and his team proposed a new method for hollowing out 3D shapes with unsupported smooth elliptical internal voids based on diamond-shaped filling structures [9]. The concept is shown in Fig. 3.



Figure 3. Model with elliptical filling structure [9]

Diamond-shaped filling structures can achieve the goal of saving 3D printing materials and improving the overall mechanical performance of the model while meeting self-supporting conditions.

But at the same time, there are also drawbacks, the most prominent of which is the problem of stress concentration.

As shown in Fig. 4, the internal stress distribution maps of different filling structures under the same stress conditions were compared. At the structural corners of the 'P' - shaped model, there is a problem of excessive stress concentration under the diamond-shaped filling structure, while the use of an elliptical filling structure effectively solves this problem. Therefore, the elliptical filling structure can be regarded as an improved method of the diamond filling structure.

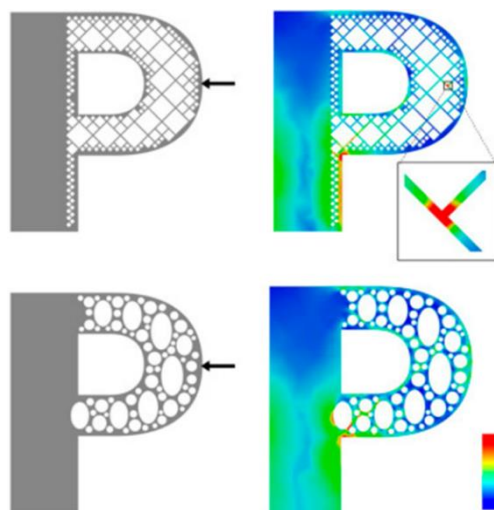


Figure 4. Stress distribution diagram of different filling structures [9]

2.3. Crystal Nucleus Filling Structure

Zhou and his team proposed a self-supporting lattice design strategy based on symmetric operations and mechanical constitutive relationships of lattice-structured materials.

The lattice unit cell is defined as the smallest repeating unit with complete symmetry of the crystal structure. Design self-supporting 3D lattice units for additive manufacturing using multiple (three-fold, four-fold, and six-fold) rotational symmetry operations.

As shown in Fig. 5, first-level lattice units with triple, quadruple, and six-fold rotational symmetry were designed. The node connectivity of the first-level lattice composed of all diagonal braces should be increased to improve the efficiency of the structure in terms of stiffness and strength performance. Subsequently, by gradually increasing node connectivity, the lattice of the other three levels was designed [10].

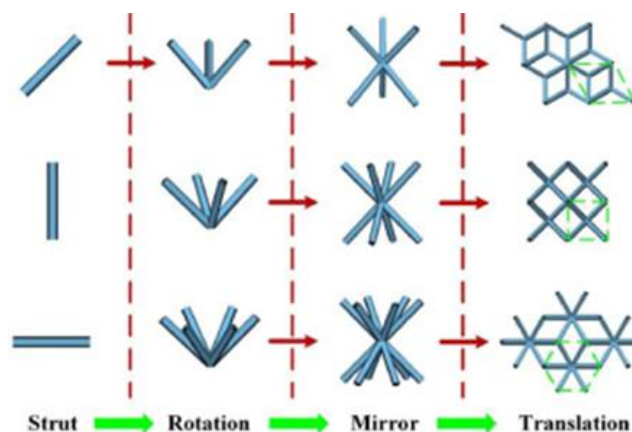


Figure 5. First-level lattice unit [10]

As shown in Fig. 6, structures with different mechanical stiffness can be obtained by designing different L3-1, L4-1, and L6-1 level lattices. In short, by designing and adding support columns in the lattice, the stiffness in this direction will gradually increase.

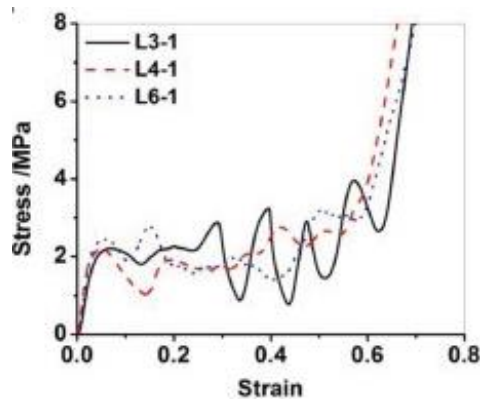


Figure 6. Experimental stress-strain curve of the first layer secondary self-supporting lattice structure [10]

This method proposes three types of self-supporting lattices with triple, quadruple, and quadruple rotational symmetry. Each type of lattice can be divided into four levels, which enables the structure to gradually transition from a bent-dominated lattice to a stretched-dominated lattice. Thus, they possess high strength, high stiffness, high energy absorption, and low-density performance.

Although the diamond-shaped self-supporting structure can effectively reduce the waste of printing materials and provide better mechanical performance without the need for additional support during printing, there are also problems with the diamond-shaped structure, such as stress concentration. So, a new structure, the elliptical filling structure is mentioned. This structure is based on the technique of diamond filling structure, replacing diamonds with ellipses as filling structures. The advantage of this method is that it can effectively solve the problem of stress concentration.

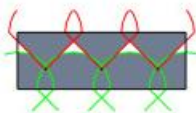
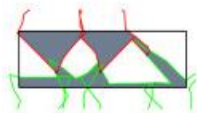
There are also many directions for future research. Firstly, by optimizing the position and size of the ellipse, the filling result can be further optimized to improve the filling rate.

3. Optimization of Self-supporting Structures

3.1. Feature Driven Topology Optimization

Zhou and his team have developed a topology optimization method for additive manufacturing (AM) of 2D and 3D self-supporting structures [11]. Solved three important issues, namely control of suspension angle, avoidance of so-called V-shaped regions, and minimum length scale control. The general concept is shown in Table 1.

Table 1. Feature-driven topology optimization process diagram [11]

initial structure	Initial feature distribution	Final support design	Final feature distribution
			

Firstly, in 3D printing, topology optimization is a design and manufacturing technique aimed at rethinking and optimizing the structure of parts to achieve more efficient, lightweight, and functional components. Through topology optimization, parts with complex internal structures can be designed, typically consisting of slender support structures or mesh structures that reduce overall weight while maintaining part strength and stiffness.

However, at the same time, topology optimization can cause problems, such as generating difficult-to-print V-shaped regions, which can be solved by feature-driven topology optimization methods.

3.2. Layout and Geometry Optimization

Jun Ye and his team proposed an end-to-end pilot line for obtaining self-supporting optimized structures by combining previous topology optimization methods. The method considers the influence of material properties and printing parameters on printing through adjustable parameters with the minimum allowable sag angle. Manufacturing constraints are taken into account in both layout and geometric optimization processes, and the effectiveness of the algorithm is verified through printing examples based on FDM and WAAM. The research results are shown in Fig. 7.

As shown in Fig. 7, the optimization steps are divided into (a) allocating design domains, loads, and supports; (b) Discretize the domain into a node grid; (c) Generate ground structures; (d) Solve the layout optimization problem and obtain the optimal layout; (e) Identify the optimized node positions in geometric optimization. Due to the difficulty in manufacturing and applying geometric structures resulting from layout optimization, geometric optimization was carried out to further rationalize the optimized structures obtained from layout optimization [12].

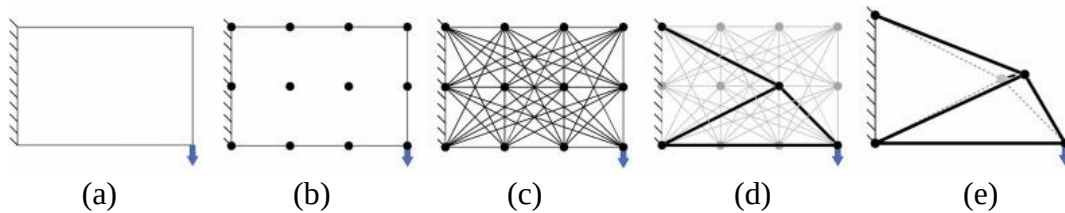


Figure 7. Layout and Geometry Optimization Steps Diagram [12]. (a) assign the design domain, load, and supports; (b) discretize the domain into a node grid; (c) generate ground structure; (d) solve the layout optimization problem and get the optimal layout; (e) identify optimized nodal positions in geometry optimization

During the optimization process of layout and geometry, the overhang angle of components is limited, so that the optimized structure can be 3D printed without additional supporting materials. Geometric optimization can effectively reduce the number of redundant bars and nodes, thereby simplifying the layout without excessive use of materials.

4. Introduction to Applications of Self-supporting Structures

4.1. Aerospace Field

Self-supporting technology is widely used in many fields, especially in the aerospace field, where it can significantly reduce the weight of the vehicle, thereby improving its payload and maneuverability. Therefore, more and more thin-walled components are being adopted in the aerospace field [13], which usually have a support structure made of honeycomb layer boards inside, as shown in Figs. 8, 9, and 10. Honeycomb layer boards are favored for their low density, high strength, and relatively simple manufacturing process [10]. For example, the grid sandwich plate structure was used for the first time in the Strong Victory-1 satellite launched on August 17, 2019, and the momentum wheel support structure on the China-Brazil Earth Resources Satellite 04A launched on December 20, 2019, which consists of a topology-optimized thin-walled structure and a grid filling material. The application of self-supporting technology has achieved a breakthrough in the aerospace field.

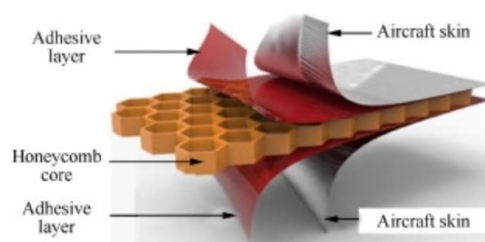


Figure 8. Honeycomb core [14]



Figure 9. Fuselage panel [14]

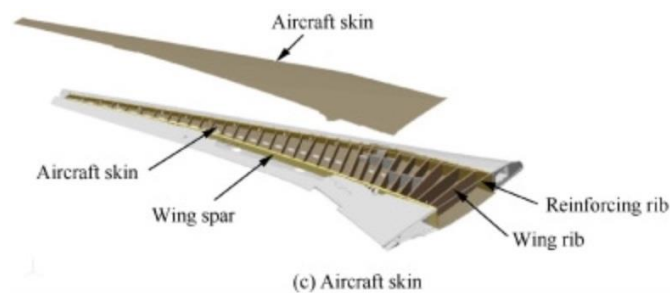


Figure 10. Aircraft skin [14]

4.2. Steel Structure Field

In the field of steel structure construction, metal additive manufacturing technology has been widely used in industrial project practice, As shown in Figs. 11 and 12, the AM pedestrian bridge successfully built by MX3D in Amsterdam and the small pedestrian bridge developed by Darmstadt University of Technology in Germany [12]. By using self-supporting topology optimization technology, the same performance of the structure is ensured while significantly reducing the material used in (a) and (b) bridges. This achievement fully demonstrates the huge potential of metal additive manufacturing technology in structural engineering and also reveals the in-depth research on metal additive manufacturing materials, connection methods, and other structural components' mechanical properties.



Figure 11. AM footbridge in Amsterdam [12]



Figure 12. AM footbridge at TU Darmstadt [12]

5. Challenges and Future Development of 3D Printing

5.1. Challenges of 3D Printed Self-supporting Structures

With the development of technology, the demand for high-performance structures is increasing. The complexity of engineering structures continues to increase, requiring more complex and intricate AM processes. Although layout optimization methods based on ground structure technology can produce optimized designs, the overhang effect usually requires the use of auxiliary support materials [12].

5.2. Design and Optimization of 3D Printed Self-supporting Structures for Future Development

Although many studies have explored the self-supporting design of structures and examined 2D and 3D cases, limitations still exist. This study mainly focuses on the design and optimization of 3D-printed self-supporting structures.

(1) Improve sensitivity calculation efficiency

Sensitivity analysis plays a crucial role in structural optimization, and the computational efficiency of sensitivity analysis can be improved by adopting more effective analysis methods. In 2021, Zou et al. [15] used a gradient optimization algorithm to improve the computational efficiency of sensitivity analysis. In addition, they also implemented a parallel solution to significantly reduce computational costs.

(2) Consider the drape characteristics and printing direction

Compared to considering only suspension constraints, taking into account both printing direction and tilt structure has greater advantages in achieving larger design space and improving structural performance. Zhang et al. proposed a topology optimization method that simultaneously considers the characteristics of cantilever angle and cantilever length [16]. This method has shown effectiveness in preventing the creation of thin components. In 2020, Wang et al. [17] introduced a topology optimization method that considers both cantilever angle and cantilever height simultaneously. Compared with methods based solely on cantilever angle constraints, this method aims to achieve structural self-supporting while improving structural performance. Zou et al. conducted a thorough inspection of the printing direction and hanging angle [18]. Improved results were achieved by discretizing the design domain and automatically adjusting the unit length ratio to accommodate various suspension angles. They also considered different printing directions during the topology optimization process. By considering the printing direction and suspension angle, the performance degradation of MBB beams is minimized under the same filtering radius, and in the optimal case, the flexibility loss is only reduced by 0.4% [7].

6. Conclusion

This study used survey and literature research methods to obtain information about self-supporting through a literature review, to discover the deficiencies of self-supporting. The survey method was used to purposefully collect relevant information to find ways to make up for the deficiencies.

The self-supporting structure can improve the stability and accuracy of 3D printing, ensuring the successful manufacturing of 3D objects. The function of the support mechanism is to prevent the deformation of the printed object, firmly anchor it in the appropriate position, and maintain the connection between the printed objects, especially when the printed object contains complex design elements such as suspension or bridge structures. The supporting structure is crucial for preventing the collapse of printed objects. The function of the supporting structure is to prevent the collapse of the formed parts and improve printing performance.

Self-supporting materials are commonly used in practical applications and are commonly used in the aerospace industry to protect aerospace components, including complex combustion chambers, engine nozzles, and turbine blades. In the automotive industry, it is often used to fix complex parts

of locomotive components, including engine exhaust systems, seat structures, and brake components. In the medical field, it is commonly used to fix human organs and tissues such as the heart, teeth, lungs, etc.

The integration of self-supporting structures with other design structures is beneficial for the advancement of self-supporting structures and improves their stability. In the additive manufacturing process of metal materials, the melting and solidification processes often result in residual stress and deformation. These factors lead to a decrease in the accuracy of printed objects and may result in serious printing failures. Therefore, enhancing the lightweight and stability of self-supporting structures and combining them with other design structures is a key approach for future development.

Authors Contribution

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

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