Research Status of Materials and Structural Design of 3D Printed Parts Considering the Factor of Gravity Balance

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Abstract. If 3D printing is a functional unit, making sure that it can remain stable is a main challenge from the model transforming into practical parts. This paper focuses on the co-design strategy for materials and structures to achieve gravitational balance during 3D printing processes. In terms of materials, choosing multi-material 3D printing and functional gradient material printing to realize density gradient printing. By distributing materials of different densities, a component with front heaviness similar to a toppling doll is achieved. This method takes advantage of the fact that the materials change the center of gravity position and moment of inertia of the component, and adds topological optimization in the low-density material area, which greatly reduces the influence of gravity on the printed component. In the structural section, the key structural design strategies that have emerged to solve this problem are systematically reviewed.First of all, discussing the static optimization method based on a single material, including the technology of controlling the center of mass through internal hollowing and fine-tuning the shape, as well as the scheme of achieving the coordinated optimization of lightweight and mechanical properties through density gradient filling. And then, introducing the dynamic balance design, which means the movable mass block method. It achieves adaptive stability under various complex working conditions through the displacement of internal mass blocks. These methods provide a new paradigm for enhancing design efficiency and structural performance.

Keywords: 3D printing, density gradient, density filling

1 Introduction

With the rapid development of additive manufacturing(3D printing), the complicated shape、light weight and function integration have become the core target of the manufacturing industry. Li Qian and Raise et al. all proposed that lightweight materials and structural optimization can significantly reduce the model quality without sacrificing performance [1][2]. However, during the practical printing processes, the 3D printed model often fails to be presented in the pre-set form due to the influence of gravity. Otherwise, long and slender

ICMEEA 2026, April 24-26, Singapore, Singapore

DOI 10.4108/eai.24-4-2026.2364883

cantilevers, thin-walled structures, or large-span components may also become unstable, sag, warp between layers due to the influence of gravity, and eventually lead to fracture. Therefore, achieving gravitational balance through the collaborative design of the inherent properties of materials and their structural layout has become a current research hotspot. On the one hand, the innovation of materials can significantly improve the mechanical properties of the printout. The core idea is to actively control the mass distribution and centroid position of components by utilizing the spatial distribution of materials, rather than merely relying on the optimization of geometric shapes. On the other hand, the optimization at the structural level makes the force path of the material more efficient through reasonable geometric layout, center of gravity projection constraints, and other means. The bending moment generated by gravity is effectively dispersed by the internal structure, thereby achieving the effect of gravity balance.

2 Material Innovation Design and Performance Trade-off

To satisfy the high stability requirements of 3D printed parts in high-end fields, a design method can be adopted by optimizing the material distribution during printing to adjust the center of gravity and moment of inertia, and then conducting internal topology optimization to achieve gravity balance.

2.1 Innovative Strategies for 3D Printing Materials with Density Gradients

The traditional 3D printing uses a single material, whose density is even. To achieve the gravity balance, it is important to break this homogeneity. Controlling the change of material density and mechanical properties in different areas within the component.

Multi-Material 3D Printing. Multi-material 3D printing is one of the most direct and flexible strategies for achieving the internal density gradient of components. The core lies in the utilization of multiple feeding systems of the printing equipment to selectively deposit materials of different densities during the manufacturing process, thereby constructing discrete or continuous density distributions in space. The successful implementation of this strategy is highly dependent on the specific technology principles, the match of material system, and precise path planning.

Multi-material printing is achieved by integrating multiple independently controlled extruders. To achieve density gradients, a combination of high-density filler composites and lightweight matrix materials is usually adopted.

During the process of multi-material 3D printing, the categories of materials and the differences of combination of materials should choose the different well-matched molding technology. Fused Filament Fabrication(FFF) is one of the most widely used 3D printing technologies. Through the specific program installation procedure, multiple nozzles are installed under the extrusion head to melt different polymer filaments and then spray them onto the construction platform. After the set number of printing layers is completed, the melting of the polymer will be stopped, and then the discharge nozzle will be switched to spray the second type of polymer melt [3].

As for the selection of low-density materials, under the same weight, the strength and rigidity of continuous fiber reinforced polymer composites (CFRPCs) far exceed those of metals, making them the core material for achieving lightweighting. CFRPCs (Such as carbon fiber, glass fiber, etc) by embedding the plastic substrate, the strength, modulus, and load-bearing capacity of 3D printed parts can be significantly enhanced, thereby effectively improving their mechanical properties and overall stability[4]. Among them, the density of carbon fibers is approximately 1.41-1.3 g/cm³, the fiber diameter is about 400 μm, the tensile modulus is as high as 54 GPa, and the flexural modulus is 51 GPa, demonstrating extremely high rigidity and lightweight potential [5][6]; The density of glass fiber is 2.4 g/cm³, with a diameter of approximately 300 μm. Its tensile and flexural moduli are 21 GPa and 22 GPa, respectively, and it possesses excellent comprehensive mechanical properties and cost-effectiveness[7].

For the selection of high-density materials, it is often done by incorporating high-density materials into the body or using pure materials with inherently high density, such as tungsten-filled wires and stainless steel-filled wires.

The shell of the component is made of lightweight rigid materials, and high-density composite materials are used in the bottom area of the core to achieve the sinking of the center of gravity, thereby reducing the influence and effect of gravity on the component.

Functional Gradient Material Printing. Functionally graded materials (FGMs) represent a revolutionary material design concept. It is a heterogeneous engineering material that can be purposefully processed to make the elements constituting the material change in a gradient in space, thereby making the properties and functions of the material also change in a gradient [8]. And eliminating the abrupt interfaces existing in traditional composite materials. In the application of achieving gravitational balance of components, the core objective is to achieve a continuous gradient of the key performance of density. Thus, an optimized structure that outperforms the discrete multi-material scheme in both mechanical properties and weight distribution is obtained.

Internal Structure Topology.3D printing topology optimization is a design procedure that seeks the lightest, strongest, and most material-efficient parts while meeting performance requirements.

Thus, for the low-density part of the density gradient, the density can be changed through its internal structure. However, there is no denying that the stiffness and strength in low-density areas will decrease significantly. To make sure that the top sparse structure will not fail due to unexpected loads during normal use.

Zhou Yongping[9] conducted an analysis and comparison of the topology optimization of tripods before and after. It was finally determined to adopt a topology optimization scheme with a weight reduction of 60%. After geometric reconstruction and verification, the tripod successfully achieved a weight reduction of 54.08%. Finite element analysis confirmed that its performance met the standards: the maximum Mises equivalent stress was 11.66 MPa, which did not exceed the material's yield limit, the maximum displacement was 0.42 mm, and the minimum safety factor was 3.86. This structure not only significantly achieved lightweighting but also greatly reduced material costs. Also, it synchronously improved the severity, the strength, and the dynamic property. This solution not only ensured safety but also achieved remarkable lightweight effects.

So, topological optimization can be added in the low-density area. Under the premise of minimizing the material mass and reducing the total density of the component to the greatest extent, the stability and strength of the component can also be ensured.

2.2 Analysis of Advantages and Disadvantages

Gradient materials can effectively eliminate stress concentration, enhance fatigue life and damage tolerance, and more reasonably transfer and distribute loads through gradient zones. They also help achieve optimal weight distribution and precise center of gravity control, which may lead to better dynamic balance performance. However, the development of gradient materials also faces multiple challenges. For example, the chemical compatibility between materials is not properly handled, it can easily lead to deterioration or even cracking of the performance in the gradient zone, and the overall density variation range is limited by the density difference of the selected material pairs. Moreover, the process development, parameter optimization and process monitoring are extremely complex, which increases the equipment cost and the research and development threshold. In addition, the simulation and prediction of the complex mechanical behavior of gradient materials have become cutting-edge challenges, significantly increasing the uncertainty in the design stage.

3 Research Status of Gravity Balance in Structural Design

3.1 Voxel-Centroid Double Iteration

The internal hollowing algorithm provides a quality theoretical basis for high-precision printing of single materials. Prévost proposed to alternately optimize the internal volume in the engraving stage and the geometric shape of the object's outer surface in the deformation stage through an iterative form. This algorithm can collaboratively utilize two degrees of freedom and generate two networks, namely MO representing the outer surface and MI representing the inner surface, ultimately creating a 3D printing model that is both stable and aesthetically pleasing [10]. For the internal volume optimization of the sculpting stage, by discretizing the input mesh into a voxel grid, it is possible to clearly observe the impact of hollowing out the object on the object's center of mass in real time. Then, by fixing the deformation parameters, the geometry of the outer surface MO can be maintained unchanged. After that, the optimization objective is simplified to only minimize the centroid error term. Initially, all the voxels are in a filled state. Then, based on the distance from the outer surface, the interior is divided into two parts: the part that can be carved and the part that cannot be carved. Sort the voxels according to the cutting plane, then remove the voxels one by one in sequence. During this process, calculate the centroid position and the energy ECOM of the model in real time, and record the carving mode when the energy is at its minimum. During the internal carving process, the divergence theorem is used to convert the volume integral into a surface integral. Therefore, when removing voxels, only the surface contributions need to be updated, rather than recalculating the entire volume integral. This significantly improves the carving efficiency. After each round of carving, recalculate the center of mass and the cutting plane, rearrange the voxels, and continue the carving until the energy cannot decrease any further.

For the geometric optimization stage of the outer surface, after the internal cavity is fixed, the algorithm enters the deformation stage. The low-degree parameterized deformation of the model is controlled by the user-defined "handle", and a deformation function based on Laplacian energy is introduced to constrain the smoothness of the surface changes and prevent geometric distortion. Ultimately, the vertex positions were fine-tuned using the gradient descent method to ensure that the external deformation was in harmony with the internal cavity and to avoid errors such as self-intersection. The core of Prevost's[11] research focuses on the computational design issues of 3D models for manufacturing. Specifically, it involves how to automatically modify the internal structure and external geometry of a given 3D model through computational means, so that it can meet specific physical performance requirements after printing - that is, static stability under the influence of gravity. Furthermore, this study employed an alternating iterative optimization algorithm, which decomposed the complex problem into two relatively independent sub-problems. By discretizing the continuous geometric bodies into voxel grids, the internal optimization was transformed into a discrete voxel selection problem. The sequence carving is carried out using a mathematical algorithm based on cutting plane guidance, which efficiently approximates the optimal solution. Prévost's research effectively addresses the issues of automated design, computational complexity, and the realization of functions with a single material. It transforms the previously manual trial-and-error model balance design process, which relied on designers, into an automatic computational optimization process. Without using materials of different densities, the physical function (stability) is achieved merely by changing the distribution of a single material within the model. In terms of computation, through a series of methods such as voxel discretization, divergence theorem, and parametric deformation, a computationally extremely complex joint optimization problem of geometry and physics is made solvable and efficient.

In the optimization of the stable balance of 3D printed objects, the research conducted by Wu Fenfen's institute adopted a technical approach that fundamentally utilized voxelization, center of mass adjustment, and local deformation methods. Under the premise of local deformation, it achieved the standability of 3D printed parts through the redistribution of internal quality [11]. The proposed solution in Wu Fenfen's research mainly adopts an offline automatic optimization method. During the operation, the operator only needs to provide parameters such as the model, wall thickness, and inclination angle threshold. After that, the algorithm will iteratively run until the energy no longer decreases.

However, Wu Fenfen's research employed algorithms to construct a mathematical model, on which the stable equilibrium angle was defined, and the centroid error was divided into two components: horizontal and vertical. During the internal quality adjustment, voxelization and voxel-based heuristic hollowing are also employed. However, the voxels are sorted based on the distance from the plane to ensure that the centroid height increases as the inclination angle increases. The distance of each voxel is calculated explicitly. This technology has established a more comprehensive "stable balance optimization" problem definition and solution process.

3.2 Density-Centroid Dual Optimization

Li Dawei's[12] research was conducted based on two major requirements: the static balance of 3D printed parts and the lightweighting of materials. The model was voxelized and sliced along the direction of gravity. The maximum tensile stress of each section was calculated to obtain the stress distribution map, which was used as the basis for sensing the density distribution [11]. Next, the algorithm calculates the theoretical minimum filling rate, generates a variable internal density distribution that matches the mechanical requirements, and uses implicit functions to construct the corresponding internal support structure. On the basis of achieving lightweighting, the algorithm introduces an optimization loop. While maintaining the basic geometric features of the model, it continuously adjusts the internal structure, ultimately ensuring that the centroid projection of the model precisely falls on a single point support, thereby achieving stable balance. Li Dawei's research systematically addressed the contradiction between lightweighting and structural efficiency. This research achieved "on-demand material allocation" through stress-driven density distribution. While ensuring the strength of critical areas, it removed the redundant materials to the greatest extent, resulting in significant weight reduction. In addition, the problems of functionality and balance were also resolved: the printed piece not only serves as a lightweight model, but also functions as a component with specific physical capabilities (such as maintaining a stable standing position). It successfully integrated the physical objective of centroid control with the structural generation process, achieving static stability under demanding conditions such as single-point support.

3.3 Multi-Posture Static Balance

Regarding the issue of balancing gravity and stability, Prévost's research has proposed a novel approach, which is to utilize a design and optimization framework involving a set of movable mass blocks (metallic balls) and internal capsules (capsule channels) to enable 3D printed models to achieve static balance in various user-defined postures such as standing, hanging, and immersion in liquids. And it maintains almost no change in appearance [10]. The core idea in Prevost's research is to reserve several movable mass blocks within the model. Through the capsule channels, metal balls are sent to different positions, thereby generating multiple centroids in different postures. In this study, the model was first imported, and the initial settings for the linear capsules were made. Then, three different objective functions were used to mathematically define the three forms of standing, suspension, and immersion in liquid. Finally, the optimal capsule parameters were obtained through geometric and manufacturing constraints. This research has revolutionarily overcome the limitations of a single posture. It has broken through the fundamental restriction of "one model, one posture". It also solved the problem of adaptability in complex environments. This method achieved adaptive stability in various physical environments, such as air and liquid, by defining different objective functions for different environments. Prévost's research achieved this by installing an internal "balance gyroscope" in the model, allowing users to dynamically switch to the optimal configuration for the target posture by changing the position of the mass blocks as needed. In addition, this research has opened up new paths for "4D printing" and "adaptive structures", providing important ideas for the future of true 4D printing (where the printed objects can autonomously change their shape and function over time or in response to external stimuli).

4 Conclusion

This article systematically reviews the "material-structure" collaborative research for gravity balance in 3D printing: On the material side, through material innovation, the gravity balance of 3D printed components is achieved. The core lies in using multi-material additive manufacturing and functional gradient material design to achieve active control of the quality distribution and center of mass of the components. In terms of structure, the three algorithms of internal hollowing, density gradient, and movable mass blocks were the first to incorporate "centroid" as a variable in topological optimization, enabling the same model to maintain static stability in multiple postures such as standing, suspension, and immersion in liquid. These studies have broken the traditional limitation of CAD design, which only focused on geometric shapes, marking the maturity of the "physics-driven design" paradigm. The design process is no longer merely the deduction of form, but the precise solution of physical properties, laying an important theoretical foundation for the field of computational manufacturing. These studies have successfully overcome the inherent contradiction between functionality and aesthetics through technological breakthroughs. By intelligently optimizing the internal structure, the model has achieved stable performance in various postures such as standing, suspension, and immersion in liquids, while maintaining almost no change in its external geometric shape. This provides a reliable technical path for achieving the integration of structural function and material design and manufacturing, significantly expanding the application potential of 3D printing technology in functional end parts. The ability to dynamically adjust the balance of static objects has also initially demonstrated the rudimentary form of 4D printing (where the function of the object changes over time or in response to the environment).

The research on 3D printing structure design for gravitational balance has demonstrated a significant potential for transitioning from passive geometric replication to active functional creation. Its future development will exhibit a trend of multi-dimensional deep integration. The core direction is to shift from the current single static balance optimization to the collaborative design and coupled optimization of multiple physical fields such as gravity, inertia, stiffness and vibration modes, aiming to meet the comprehensive requirements for component performance under complex working conditions. The deep involvement of artificial intelligence, especially in generative models and reinforcement learning, is expected to break through the limitations of traditional algorithms and achieve intelligent configuration creation that surpasses empirical intuition. Furthermore, the research will expand from static structures to dynamic reconfigurable systems. By integrating built-in actuation mechanisms such as microfluids and phase change materials, it will achieve adaptive balance based on environmental perception, promoting the practical application of the 4D printing concept. Ultimately, these technological advancements must be deeply integrated with the integrated design platform for material structure and processing, and incorporated into the sustainability considerations throughout the entire life cycle, in order to achieve the crucial leap from laboratory innovation to industrial application, and truly unleash the revolutionary potential of 3D printing in the manufacturing of high-performance, multi-functional intelligent components.

Authors Contribution

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

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