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Parametric Modeling-Driven Lightweight Design for 3D Printing

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Abstract. Due to the increasing demand for energy saving, emission reduction and efficient manufacturing, the role of lightweight design in automobiles, aerospace and other fields is gaining growing attention. With its high precision and rapid prototyping advantages, 3D printing technology offers novel approaches for lightweight design. In this paper, the application of 3D printing redesign technology based on parametric modeling in the field of lightweight is explored, and the research progress of key technologies such as topology optimization, path planning, and residual deformation control is discussed. By analyzing typical lightweight designs at home and abroad, the notable impacts of the combination of parametric modeling and 3D printing in weight reduction, material optimization and manufacturing efficiency improvement are outlined. Research indicates that this method can achieve significant weight reduction without compromising structural strength and functionality. Looking to the future, with the development of multi-material printing, artificial intelligence optimization and other technologies, 3D printing lightweight design is expected to further drive the transformation of the manufacturing industry to an intelligent and sustainable direction.

INTRODUCTION

With the increasing global environmental protection requirements, lightweight has become a research hotspot in various industries, especially in the fields of automobiles and aerospace. Lightweight technology not only helps to reduce the energy consumption of products, but also effectively improves the performance and service life of products. Lightweight design is particularly important in the automotive industry, as it directly affects the fuel efficiency, acceleration performance and emission levels of vehicles, especially in the field of electric vehicles, where lightweight design can significantly improve battery life. As a cutting-edge technology with high-precision and complex structure manufacturing capabilities, 3D printing technology is being widely used in automotive lightweight design. Through parametric modeling and optimized design, the design and printing time can be shortened, and more efficient lightweight design can be realized, and the complex structure and shape limitations that cannot be broken through by traditional manufacturing processes can be solved. The research topic of this paper is the application and development of 3D printing redesign technology based on parametric modeling in lightweight design, and the core goal is to drive the 3D printing process through parametric modeling to realize the lightweight, optimized design and efficient manufacturing of product structure.

RESEARCH STATUS AT HOME AND ABROAD

Research on the Lightweight Weight of BSC Racing Car Rear Column Based on Metal 3D Printing

Gao Peng et al. used UG to establish a simplified CAD model, completed the topology optimization design through the InspireOptiStruct module, used the finite element method to check the strength of the final model, and simulated and analyzed the metal 3D printing process based on the Print3D module, and obtained the best mass density distribution of the material in the form of cloud map. The results show that the weight of the parts is reduced by 22.47% after the lightweight design of the rear column of the BSC racing car, which meets the purpose of lightweight research in terms of material, structure and production technology. At the same time, the finite element analysis parameters all meet the design requirements, and the maximum increase in Mises's equivalent stress is 5.57%, which is small and does not exceed Aluminum (7075-T6) Yield stress for material properties. In the 3D printing process simulation, the deformation position and stress accumulation position of the behind column are obtained, which provides a reference for the further optimization of the part. The finite element analysis parameters all meet the design requirements, ensuring good safety, practicability, and effectiveness [1].

Structural Topology Optimization Design Considering 3D Printing Residual Deformation

Yan Xiaolei et al. carried out elastoplastic thermal-mechanical coupling finite element analysis during the melting process of metal powder in two adjacent printing layers, extracted the equivalent intrinsic strain load, realized the efficient simulation of the metal 3D printing process and the rapid prediction of residual deformation, and carried out experimental verification. Based on the Floating Projection topology optimization (FPTO) method, the P-norm of the overall residual deformation is introduced, the sensitivity of the residual deformation in the 3D printing process is derived, and a multi-condition and multi-objective optimization algorithm is proposed to minimize the structural compliance and residual deformation of 3D printing, so as to meet the design performance and improve the manufacturing performance. The effectiveness of the proposed method is verified by two-dimensional and three-dimensional examples. A multi-condition and multi-objective topology optimization model was established to minimize structural compliance and global residual deformation in 3D printing, and a structural topology optimization method for 3D printing manufacturing was studied [2].

3 D Printing Path Planning of Lightweight Infill Structures Based on Q-Learning

Xu Wenpeng et al. proposed a 3D printing path planning method based on Q-learning algorithm to improve the problem of many turns and start-stops in the path planning of the structure. Firstly, the model slices after filling and layering are preprocessed, and then with the goal of reducing the turning and start-stop actions of the print head, the corresponding Markov decision process mathematical model is constructed, and the action value function is iterated many times until it converges, and a set of action strategies to obtain the maximum return value are solved, and the strategies are escaped and output as print paths according to the set mathematical model, and finally verified by comparative experiments. Experimental results show that this method can effectively reduce the number of turns and starts and stops of the print head, increase the continuity of the printing path, save the printing time, and improve the printing quality to a certain extent. The Q-learning algorithm is used to find the optimal path planning scheme of the model slices under the constraints. According to the results of printing experiments, compared with the existing commercial software, this method can reduce the number of turns and starts and stops of the print head, effectively improve the printing efficiency, and ensure the basic shape of the product [3].

A Lightweight Design Method for Seats Based on Parametric Modeling and 3D Printing

The lightweight seat design method based on parametric modeling and 3D printing effectively simplifies the personalized design process and improves the modeling efficiency. Zheng Zufang et al. analyzed the force of the parameterized model through ANSYS finite element analysis software, and calculated the quality of the model according to the model volume, and found that the parameterized model can effectively achieve the lightweight of the seat structure and reduce the use of materials under the premise of ensuring the basic functions of the seat. The analysis results show that the scheme is stable under various working conditions, which verifies its feasibility in practical application. Finally, 3D printing technology is used to materialize the three-dimensional model of finite element analysis, which makes it possible to personalize the seat and meet the personalized emotional needs of consumers. Based on parametric and 3D printing technology, the design of the Pantone chair was carried out by using the parametric modeling method, and the feasibility of the technical route of this method was verified by finite element analysis, which realized the lightweight of the seat structure, gave product differentiation, and brought different personalized emotional experiences to consumers, so as to provide a reference for the development of digital design and manufacturing in the furniture industry [4].

Lightweight Design and Manufacturing of Mechanical Parts Based On 3D Printing

Huang Linqi et al. used the conceptual design tool Altair Inspire to reconstruct the geometric design space of the connector and the comparative analysis of the strength before and after the reconstruction, and then he used the new technology of sub-model in 3D printing and the method of reasonably setting the process parameters to carry out the lightweight design and manufacturing of mechanical parts. The experimental results show that under the condition of satisfying the actual stiffness and performance requirements and not changing the main structure of the model, the optimization results of the final model of the structural connector obtained in this study can achieve a weight reduction of 38.46%, which effectively reduces the mass and saves the material, solves the problem of difficult processing and many supports of the complex structure after topology optimization, and provides a feasible method for the lightweight design and manufacturing of mechanical parts. This experiment verifies the feasibility of the proposed method. At the same time, the design method of lightweight 3D printing has the outstanding advantages of not changing the main structure of the model, the model support is easy to remove, and it is suitable for various types of printers [5].

Real-time Topology Optimization Generative Design Method for Lightweight/3D Printing

The traditional topology optimization method of Zhao et al. relies on time-consuming finite element iterative algorithms, which increase exponentially with the size of the design domain and the increase of design variables, resulting in the so-called "dimensionality curse" problem. To solve this problem, this paper proposes a real-time topology optimization method based on denoising Conditional Generative Adversarial Network (CGAN), which uses the dataset composed of the topology optimization structure generated by the SIMP method and the corresponding conditional coding vector to train the model, and realizes the rapid iteration of the topology optimization generative design for lightweight 3D printing through the trained model. This method can generate topology-optimized structures in almost real time according to the design variable conditions, which is suitable for both two-dimensional and three-dimensional structures. Combined with GAN and CNN, a real-time topology optimization generation design method based on CGAN is proposed, which can generate the corresponding topology optimization structure according to the design requirements in almost real time. Compared with the traditional topology optimization method, the proposed method avoids the time-consuming finite element analysis and calculation process, and this method can help designers obtain the required topology optimization structure in almost real time in the generative design process for lightweight 3D printing, which is helpful to improve product design efficiency [6].

Experimental Research on Structural Topology Optimization and 3D Printing Based on Python

Considering the needs of lightweight development and the improvement of the design efficiency of complex engineering structures, Fan Xiaonan et al. proposed a high-efficiency structural optimization design strategy. Taking the T-shaped structure as an example, the feasibility of the strategy is verified, and the following conclusions are obtained: a new type of bidirectional progressive optimization method can directly optimize the more complex 3D model, which is convenient for directly obtaining the topological CAD model, effectively reducing the structural quality and saving materials. After the optimization of the improved efficiency optimization strategy, the structural boundary is clear, the number of iterations is small, and the computational efficiency is high. The experimental analysis of 3D printing shows that the results obtained by the experiment and the computer simulation are consistent, and the proposed method can better guide the structural quality inspection under the condition of comprehensively considering the mechanical properties of the structure. The proposed structural optimization design strategy by him can greatly reduce the product design cycle and improve the design efficiency [7].

Topology Optimization and 3D Printing of Parts for Lightweighting

Taking the triangular bracket as an example, Zhou Yongping used SolidWorks Simulation to carry out finite element analysis and structural topology optimization of the triangular bracket, and carried out 3D printing manufacturing on the topology optimization results, and discussed the lightweight approach of parts based on 3D printing. Topology optimization realizes the lightweight design on the basis of satisfying the function and performance by redistributing the original part materials, and obtains the lightweight model. 3D printing breaks through the constraints of traditional manufacturing processes, has the manufacturing ability of complex shapes, and realizes the manufacturing of lightweight models. The convergence of 3D printing and topology optimization has significant advantages in terms of lightweighting, which can lead to higher efficiency, lower costs, and better product performance for the manufacturing industry [8].

Research on Topology Optimization And 3D Printing Application of Auto Parts Based on Reverse Engineering

Sun Xuemei et al. used a 3D digital scanner to scan and collect the shape features of the part, preprocessed the point cloud data with Geo-magic studio software, and then used Geo-magic Design X for reverse modeling. Then, the topology optimization of the reconstructed model was carried out by Solid thinking inspire optimization software to obtain the optimal design results of the part, and the mechanical analysis and verification of the optimization results were carried out and 3D printing experiments were carried out. It is proved that the topology optimized part structure can not only meet the mechanical property requirements, but also realize the lightweight requirements to the greatest extent. This experiment resulted in an innovation in a part with a better structure. This kind of topology optimization and 3D printing application research based on reverse engineering can not only quickly dissect and restore the original object, but also carry out secondary innovation on the original object to improve the value of the object. Through the topology optimization of the steering tie rod arm, the purpose of weight reduction can be achieved. The analysis of the finite element shows that the stress on the middle part of the steering tie rod arm is relatively small, so the internal structure can be changed to achieve lightweight design, and can be verified by 3D printing technology experiments to meet the force requirements of the parts.

The reverse design and topology optimization methods proposed in this paper have high practical value and are of guiding significance for the lightweight design of other components [9].

Research on the Integration of Topology Optimization Method of Spatial Structure Node and 3D Printing Technology

In order to solve the problems of excessive mass and uneven stress distribution of spatial structure joints, Du Wenfeng et al. used topology optimization method to study the optimal shape of cross-crossing joints commonly used in spatial structure, and applied 3D printing technology to fabricate a new type of cross-intersection joints obtained by topological optimization design. OptiStruct defines that the upper limit of the design volume of the optimization area is 40%, and the topology optimization analysis of the spatial structure nodes is carried out under the given working conditions, which solves the problem of excessive quality of the spatial structure nodes, and shows that it is feasible to apply the topology optimization method to reduce the self-weight of the nodes. By comparing the topology optimization node with the original node, it is proved that the topology optimization can achieve the purpose of greatly reducing the weight without compromising the good mechanical properties of the node. The development of 3D printing technology has improved the manufacturing technology of nodes. The use of 3D printing technology can significantly increase the production speed, reduce the production cost, improve the manufacturing accuracy, and solve the key problems that the topology is difficult to manufacture with traditional processes, so as to create high-precision nodes, and the integration technology combining topology optimization and 3D printing is conducive to the advanced design and intelligent manufacturing of nodes [10].

The topology optimization time is reduced to the shortest time and cannot be adjusted repeatedly, and the topology optimization correction needs to be recalculated.

Adapting the design structure minimizes material usage while meeting functional and strength requirements. Using parametric modeling for rapid design iteration to improve design efficiency and flexibility.

PARAMETRIC MODELING-DRIVEN 3D PRINTING REDESIGN PROCESS

The establishment of parametric modeling is a key step in the 3D printing redesign process, which needs to be combined with the structural characteristics and design requirements of the product, and reasonably set the parameters to ensure the accuracy and adjustability of the model, so as to provide a basis for subsequent optimization. In the establishment and adjustment stage of parametric modeling, the model needs to be dynamically adjusted according to the design goals and optimization results to meet the specific design requirements. In addition, through the optimization of parametric modeling, the lightweight and performance improvement of the model can be further realized, that is, the structural performance can be optimized by adjusting key parameters, so as to improve the overall efficiency and functionality of the model. This process encompasses the entire loop from initial modeling to dynamic tuning to performance optimization, ensuring that the design is both technically compliant and operational. Parametric modeling is more time-saving, faster and more convenient, which can minimize material use and weight, so that the efficiency in the 3D printing process is significantly improved, and the computational efficiency is improved.

FUTURE OUTLOOK

3D printing technology is accelerating its evolution from prototype manufacturing to large-scale production, and its future development trend will revolve around technological innovation, application expansion and ecological construction, profoundly changing the traditional manufacturing model. Technical level: multi-material hybrid printing and intelligent upgrading will become the core direction. The research and development of new composite materials and biocompatible materials will break through the application boundary, such as the application of cermet composite printing in the aerospace field; The AI-driven intelligent printing system can realize automatic parameter optimization and real-time defect detection, and combine with Internet of Things technology to form a closed-loop production system. Breakthroughs in nano-precision printing and ultra-high-speed printing technologies will promote the development of precision manufacturing of microelectronic devices and optical components.

3D printing is breaking through the physical concept of "additive" and evolving to a digital manufacturing hub. With the collaborative innovation of the industrial chain and the improvement of policy standards, this technology will become the core pillar of flexible manufacturing in the era of Industry 4.0, and promote the transformation of the global manufacturing industry to a distributed, personalized and sustainable direction.

CONCLUSION

This study systematically summarizes the research progress, technical methods and future trends of 3D printing technology in lightweight design, and highlights the efficiency and innovation of the combination of parametric modeling and 3D printing.

3D printing technology has been widely used in many industries due to its advantages of rapid prototyping, personalized customization and complex structure manufacturing. In manufacturing, 3D printing is being used for rapid prototyping, lightweight part production (e.g., aerospace components), and custom tooling, significantly shortening development cycles and reducing costs. Applications in the medical field are particularly prominent, including the study of personalized prostheses, dental restorations, surgical guides and even bioprinted organ tissues to provide patients with more precise treatment options. The construction industry uses 3D printing technology to build houses and bridges, which not only improves construction efficiency, but also enables the design of complex structures that are difficult to complete with traditional processes. In addition, the automotive industry is promoting the development of new energy vehicles through 3D printing to produce lightweight parts and customized interiors. In the fields of education, art, and consumer goods, 3D printing is also widely used in model making, creative design, and personalized product production. With the advancement of material technology and printing process, 3D printing will further expand to industries such as energy, electronics and food, and become one of the important technologies to promote Industry 4.0 and intelligent manufacturing.

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