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The Collaborative Optimization Path of Lightweight Design and Additive

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Abstract. In the era of advanced manufacturing, lightweight design and additive manufacturing have become core elements for enhancing the performance of mechanical systems. Lightweight design optimizes material distribution and structural forms to effectively reduce product weight, thereby minimizing energy consumption and improving efficiency. Additive manufacturing, with its unique layer-by-layer fabrication process, enables the rapid production of complex structures and significantly expands design freedom. However, their independent applications face limitations: lightweight design may be constrained by traditional processing techniques, while additive manufacturing still needs improvements in material properties and production efficiency. Collaborative optimization integrates the two approaches, breaking through the bottlenecks of traditional design and manufacturing to create more efficient and economical innovative structures. This strongly promotes the leapfrog development of mechanical systems in aerospace, the automotive industry, medical devices, and other fields. This paper deeply focuses on the collaborative optimization path of the two, systematically exploring its revolutionary significance for the design and production of mechanical components.

Keywords: lightweighting design, additive manufacturing, collaborative optimization, Forearm of the mechanical arm, Altair Inspire, topology optimization

1. Introduction

Along with the continuous improvement of industrial automation, the mechanical structure of high performance and low energy consumption is in more and more urgent demand. The collaborative application of lightweight design and additive manufacturing technology provides a new direction for the innovative design and efficient production of mechanical parts. This paper takes the forearm of the robotic arm as the research object. The Print3D module is utilized to simulate the additive manufacturing process and solve the manufacturability problem of complex lightweight structures. The research results show that this collaborative optimization method not only significantly reduces the weight of the forearm of the robotic arm but also ensures the structural performance and manufacturing feasibility, providing an effective solution for the design and manufacture of key components of industrial robots.

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This article focuses on the research of lightweight structures for robotic arms. This research's robotic arm is a lightweight one developed based on the existing wheeled autonomous system. Under the condition of ensuring the strength and rigidity requirements of the mechanical arm, its weight can be significantly reduced. The overall design of the robotic arm is made of 6061T aluminum alloy. The structure is a typical cantilever beam. The research object is mainly determined to be the third arm segment of the mechanical arm. By conducting three-dimensional modeling of the third arm segment and by analyzing the forces under working conditions, it was determined that the web plate of the third arm section still has spare capacity. Optimization can be carried out. By combining explicit weight reduction method optimization with parametric size optimization. After numerous experiments, the areas of material that could be reduced were determined, and the size has been optimized. This enables the final robotic arm to reduce its weight by 21.97% while ensuring its strength and hardness [1].

2. Lightweight design theory and methods

2.1. Key points of lightweight design theory

First thing is the Material selection logic. Based on the actual working conditions of the forearm of the mechanical arm, materials with excellent specific strength/specific stiffness should be given priority to ensure the structural load-bearing capacity under the premise of controlling the weight.

Shape parametric design utilizes parametric modeling technology, performance index optimization, and algorithm-driven approaches to achieve a full-process digital design from geometric modeling to performance improvement and material optimization. This method effectively enhances product design quality and strengthens the competitiveness of products in the market. It has broad application prospects and significant practical value in numerous fields such as mechanical manufacturing, aerospace, and automobiles.

2.2. Finite element analysis application

The structure is decomposed into finite elements using discretization methods. By constructing the element stiffness matrix and load vector, the overall equilibrium equation is solved to obtain displacement, stress, and other field variables, achieving performance pre-evaluation under multiple working conditions. In the static mechanics analysis and lightweight design of the detector's mechanical structure, it is mentioned that a 3He tube detector module is the basic unit that constitutes a large area of detection surface. It requires high sealing to ensure that the 3He in the detector does not leak out under vacuum conditions, and also to guarantee that the detector equipment can have safe and stable working conditions. Therefore, it is very necessary to conduct static mechanics analysis and lightweight design on the mechanical structure of the detector [2].

In processes such as Selective Laser Melting, it is necessary to couple the temperature field, stress field, and flow field. For example, the characteristics of pool flow affect the heat transfer path, thereby changing the shape of the solidification front. Through a multiphysics coupling model, the performance of the formed part can be more accurately predicted.

2.3. The benefits of light-weighting

The weight of the robotic arm is a key factor affecting the overall performance of the machine. If the robotic arm of a robot can be made lighter, it can enhance the flexibility and energy efficiency of the robot. For instance, the launch of a rocket requires strict control over its mass. If the weight of the

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robotic arm can be reduced, it would be beneficial for a rocket carrying a robot on a mission to Mars. Robots can carry more batteries to Mars, which greatly enhances their endurance. Light-weighting helps robots achieve higher loads and longer endurance, while also reducing the wear and tear on joints and the power consumption of motors.

3. Lightweight design and additive manufacturing simulation of robotic arms based on Altair Inspire

3.1. Lightweight design and additive manufacturing simulation of the small arm of a mechanical arm based on Altair Inspire

With the development of industry, there is an increasing demand for high-load and low-energy consumption in industrial robots. Lightweight design has become increasingly important, especially in the design of robotic arms. This case takes the forearm of the robotic arm as the object.

Research Object: The small arm of the robotic arm (original weight 2.8kg), which carries typical working condition loads (maximum torque 120Nm, axial force 500N)

Core issue: In traditional design, to ensure safety and reserve redundancy with high quality, for example, by increasing part size, it leads to reduced motion efficiency and increased energy consumption. This not only incurs unnecessary costs but also hinders green development [3].

In the increase of material manufacturing technology-oriented mechanical arm lightweight design and process simulation, through the Altair Inspire software simulation module, the structure of the selected mechanical arm forearm is the research object. Under the premise of meeting the load requirements of the robotic arm and ensuring rigidity, the weight reduction reaches 60%, and the lightweight effect is obvious. Additive manufacturing process simulation can help designers correct potential structural defects before printing, improve product design, and reduce post-processing work. This study verified the effectiveness of topological optimization design combined with additive manufacturing technology, which can effectively reduce the processing difficulty and decrease the thermal deformation of the structure. It can provide references and ideas for the structural design of robotic arms and the innovative development of mechanical equipment [4].

In the topological optimization phase, the SIMP (Variable Density Method) is used as the core algorithm. The mathematical model is established with the dual optimization objectives of maximizing the overall structural stiffness and material volume constraint (retaining 40% of the initial material).

In the operation process of Altair Inspire, the finite element mesh is first established based on the CAD model of the forearm. Tetrahedral elements are used to discretize the structure, and the element size is controlled at 3mm to balance the calculation accuracy and efficiency. According to the actual working conditions, fixed constraints are applied at the joint connection part of the forearm, and a combined load of 120Nm torque and 500N axial force is loaded on the mounting surface of the end actuator. By setting optimization objectives and constraints, a multi-working condition iterative optimization calculation was initiated. After 28 iterations, a material distribution cloud map was obtained. The optimization results show that the materials are mainly concentrated in stress concentration areas and force flow transmission paths, forming a truss-like structure similar to bionic bones. This not only ensures the bearing capacity but also significantly reduces unnecessary materials.

To ensure the engineering feasibility of the optimization scheme, a sensitivity analysis module is introduced to make local adjustments to key areas. For transition fillet regions with high stress gradients, material thickness is appropriately increased through manual intervention to avoid structural failure risks caused by stress concentration. The final optimized scheme reduces the volume of materials by 60% compared to the original design, and the theoretical weight is reduced to 1.12 kilograms, while the fundamental frequency of the structure is increased by 23%, achieving dual optimization of lightweighting and dynamic performance.

3.2. A holistic technical framework for structural improvement

In this study, the technical approach mainly consists of three key components: structural topology optimization, mechanical verification, and process simulation.

The objective of structural topology optimization is to maximize the overall stiffness of the structure while retaining at most 40% of the initial material volume. The process simulation utilizes the 3D printing module to predict the supporting structures of additive manufacturing and estimate the deformation risks. At the same time, the simulation technology can also predict the deformation risks of the parts caused by factors such as material accumulation and temperature changes during the printing process. For example, when printing complex aviation components, by simulating the deformation situation, printing parameters can be adjusted in advance or compensation structures can be designed, thereby effectively reducing the deformation of the parts after printing, improving the printing accuracy and product quality.

3.3. General overview of lightweight design

The approaches to achieving lightweight mechanical arms mainly include two aspects: structural optimization design and lightweight material selection. Good materials such as titanium alloy and carbon fiber can directly affect the use of robotic arms and play a crucial role in the lightweighting of robotic arms. Structural optimization mainly includes size optimization, shape optimization, and topology optimization. This time, based on these two aspects, it will discuss how to make the robotic arm lightweight.

4. Challenges and improvement directions of lightweight design

4.1. Design level bottlenecks

In practical operations, the topology optimization solutions output by Altair Inspire often present complex and irregular shapes, with numerous sharp corners and non-standard surfaces. These geometric features are difficult to directly apply in production, requiring engineers to manually adjust them through processes such as chamfering and surface smoothing to complete structural repairs. This process relies on individual experience judgment and lacks standardized procedures; automation tools also struggle to fully cover it, leading to significantly extended design cycles.

4.2. Strengthen data practice verification

Establish a dedicated database for the performance of additive manufacturing materials, and obtain real performance data through systematic tensile tests, fatigue tests, etc. Combining in-situ detection technologies such as X-ray real-time monitoring, dynamically capture changes in the material forming process, and reverse correct simulation parameters.

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4.3. Material defects and suggested defects of the robotic arm

There are some shortcomings in the above-mentioned method that combines topological optimization with aluminum alloy materials. Firstly, the insufficiency in materials is mentioned. The material chosen in the above-mentioned paper is aluminum alloy. Aluminum alloy materials do have advantages [5]. They possess high strength and low density, and the cost is also relatively low. Compared with traditional steel materials, using aluminum alloy materials can reduce the weight by one-third. However, aluminum alloy materials are inherently prone to corrosion, which makes aluminum alloys prone to corrosion when exposed to humid environments or in contact with other metals. This limits the working environment of robots, preventing them from operating in humid conditions. Moreover, in structures with high requirements for vibration control, mechanical arms made of aluminum alloy may cause vibration and modal resonance problems.

So it recommend magnesium alloy. Magnesium alloy is a highly promising metallic material. Magnesium alloys make up for some of the shortcomings of aluminum alloys. For instance, magnesium alloys are lighter than aluminum alloys and have excellent shock absorption capabilities. However, its tensile strength is slightly lower than that of aluminum alloy. Magnesium is inherently a highly corrosive material and is even more susceptible to humid environments than aluminum. However, with the technological advancements in recent years, magnesium alloys have achieved good corrosion resistance. This has led to an increasing number of robot manufacturing companies being willing to use materials like magnesium alloys in recent years. In terms of engineering practice, the Chinese enterprise Estun and Baowu Magnesium Industry jointly launched a new magnesium alloy industrial robot model, ER4-550-MI, in 2024. Compared with the original aluminum alloy version, it has reduced its weight by 11%, increased the operation cycle speed by 5%, and lowered the overall energy consumption by 10% .Overall, it is "functional decomposition, with sequential progress in space and overlapping and concurrent in time"[6].

Moreover, it also demonstrates better heat dissipation and shock absorption performance. Although this material is excellent, due to the poor processing performance of magnesium alloys and the difficulty in mass production, it is suitable for use in precision work robots. The research results show that the weight of the mechanical arm gripper parts has been reduced by 83.4%, and the structural strength and stability meet the requirements. Reducing the weight of the gripper parts can lower their manufacturing costs, have a favorable impact on the load capacity and movement speed of the mechanical arm, and enhance its application range and flexibility. This method provides new ideas and solutions for the design and manufacture of mechanical systems, offering an effective lightweight optimization design engineering practice approach for reducing the cost of complex structural components, and has certain practical application value. Finally, the ANSYS software was used to conduct modal analysis on the optimized boom, verifying the rationality of the optimization scheme. The study shows that when the plate thickness of the boom is 18 mm, the volume retained in the topology is 68%, and the hole depth of the bolt holes at the tail of the boom is 27 mm, the average maximum stress is the smallest, which is the optimal lightweight structure. Moreover, the lowest frequency has increased, and the total mass of the boom has decreased by 52.18%, and the maximum stress it bears has decreased by 56.83% [7, 8].

4.4. Structural defects and suggested improvements of the robotic arm

For the structure, the paper did not employ topological methods. All weight reduction optimizations were achieved through perforation, which falls under the category of explicit weight reduction methods. The global optimal form was not sought by using mathematical topology optimization

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technology. Topology optimization can achieve the maximum weight reduction. Topology optimization is a method that does not predefine the shape of a structure. It uses mathematical optimization to find the optimal distribution of materials within a given design domain, achieving the maximum weight reduction. Intuitively speaking, it is to create a skeleton-like distribution by drilling holes in the solid to achieve a higher stiffness-to-mass ratio. During this process, commonly used algorithms include SIMP and ESO. Therefore, it is recommended to use topological optimization to find the best lightweight structure on a computer. The paper also made some simplified assumptions about the joint connections and other parts. However, in reality, the joints have a significant impact on the structure of the robot. Long-term activities and force transmission can all have an impact. The author only considered static force but failed to take into account the force of acceleration and deceleration, as well as metal fatigue caused by long-term use. In real life, robots that move their arms for a long time may have problems with their joints. Therefore, for the light-weighting of robotic arms, magnesium alloys can be considered as a substitute for aluminum alloys in terms of materials. However, while using light materials, the process and cost should also be taken into consideration. For the structure, intelligent optimization algorithms can be applied. Combining topological optimization, size optimization, and other methods, a comprehensive assessment of the robotic arm is conducted.

5. Conclusion

With the rapid development of intelligent AI in recent years and the advancement of robot applications, there is an increasing trend towards the integration of the two. Therefore, lightweighting is a problem that must be taken seriously. The lightweight design of robotic arms has become a key approach to enhancing performance, reducing energy consumption, and expanding operational capabilities. Based on the summary above, it is understood that in the past, the lightweight design of robotic arms focused more on the optimization of traditional structural geometry and was limited by some material constraints. This may result in the weight not changing much. For further optimization, the topology optimization and material manufacturing simulation platform adopted not only breaks free from the constraints of traditional structures, the optimization of material allocation was also achieved based on algorithms. Magnesium alloy, a lighter material, was also selected for the materials. It can be seen from this that the lightweighting of the mechanical arm has shifted from empirical and structural approaches to data-driven and intelligent computing. The future research objective should further integrate multi-material design and dynamic collaborative modeling. This will make the robotic arm lighter while ensuring performance and safety, thereby promoting its practical application in various fields.

Authors contribution

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

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