Lightweight Design of Six-dof Tandem Manipulator Based on Additive Manufacturing Technology

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Abstract. At present, topological optimization represents the most advanced structural design technology, and additive manufacturing represents the most advanced manufacturing technology. Combining the two technologies to provide a very effective way for the lightweight of the manipulator arm. Taking the six-degree-of-freedom series manipulator as the object, the lightweight design was carried out from the aspects of material lightweight and structure lightweight. Firstly, under the limit conditions, the exploratory topology optimization of the manipulator arm of the aluminum alloy material and the manipulator arm of the 3D printed plastic material was carried out respectively, and the optimization results were compared. 3D printing plastic material was selected as the design material of the manipulator. Then, under the condition that the stiffness and strength requirements are met, the manipulator of 3D printing plastic material is designed with the method of size optimization and topology optimization for the two limit working conditions, and the geometric reconstruction and simulation verification are carried out at last. The results show that the final manipulator arm meets the requirements of stiffness and strength, reduces the weight by 26.5%, and finally achieves the goal of lightweight.

1. Introduction
Domestic and foreign scholars have done a lot of research on structural lightweight technology, mainly reflected in the material lightweight and structural lightweight. Hu Hangzhou, et al., from Hunan University, used corrugated aluminum alloy plates to strengthen the structure to design the box-shaped automobile collision prevention beam, so as to achieve the goal of lightweight design of collision prevention beam [1]. By using topology optimization and shape optimization, Wang Xubao et al. of Beijing university of technology optimized the structure of aluminum alloy support for aviation, and made use of metal additive manufacturing technology, finally achieving the goal of reducing the mass by 24.5%, increasing the weighted rigidity by 38.3%, reducing the maximum displacement by 32.7%, and reducing the total volume by 12.2% [2]. Ma Guoqing of Harbin Institute of Technology used 7075-t6 aluminum alloy to lightweight the manipulator arm, and made topological optimization of the big arm of the manipulator arm, which reduced the weight by 15.06% on the premise of improving the stiffness of the big arm and enhancing its deformation resistance [3]. Ning Kunpeng et al. of Nanjing University
of Science and Technology carried out structural lightweight design for ER300 stacking manipulator arm, and finally obtained the stress distribution and displacement distribution of the optimized structure to ensure that the maximum stress and displacement after optimization meet the requirements, and finally make the overall weight reduction of manipulator arm 8.6%[4]. There are also some scholars in the fields of aerospace, manipulator arm, automobile industry, etc., who have also studied the lightweight materials and lightweight structures[5-11].

This paper takes the overall structure of the six-dof tandem manipulator as the object of lightweight design, and compares the materials of 6061 aluminum and 3d-printed plastic materials. Through calculation and analysis, the 3d-printed plastic materials are more suitable for the use of the overall structure of the manipulator. In addition, the overall structure of the manipulator was optimized by using the optimization method combining size optimization and topology optimization technology. Finally, a six-dof tandem manipulator overall structure meeting the requirements of stiffness and strength was obtained through geometric reconstruction.

2. Manipulator Arm Structure

As shown in Figure 1, the manipulator structure portion of the six-axis robot arm is composed of a base, six arms and six rotating joints. The base is mounted on the workbench, and six arms and six rotating joints are sequentially connected in series.

The joints a, d, and f can be rotated, and the joints b, c, and e can be pitched; the joint angles are θ₁, θ₂, θ₃, θ₄, θ₅ and θ₆, as shown in Figure 2. Through the joint control of the six rotating joints, the end of the arm can reach any position and posture in the working space. The D-H parameters of the manipulator are shown in Table 1. The configuration is shown in Figure 3. The maximum extension length of the arm is 655 mm and the maximum load is 0.5 kg.

![Figure 1. Mechanical composition of the manipulator arm](image1)

![Figure 2. Rotation degrees of freedom of the manipulator arm](image2)
Table 1. D-H parameters of manipulator

|   | $\theta_i$ | $d_i$ | $a_i$ | $\alpha_i$ | $\theta_i$ range   |
|---|-----------|------|------|-----------|------------------|
| 1 | $\theta_1$ | 0    | 0    | 90°       | -180°~180°       |
| 2 | $\theta_2$ | 0    | $a_2$| 0°        | -115°~90°        |
| 3 | $\theta_3$ | 0    | $a_3$| 90°       | -50°~195°        |
| 4 | $\theta_4$ | $d_4$| 0    | -90°      | -180°~180°       |
| 5 | $\theta_5$ | 0    | 0    | 90°       | -105°~105°       |
| 6 | $\theta_6$ | $d_6$| 0    | 0°        | -200°~200°       |

Figure 3. Configuration diagram of manipulator arm

3. Lightweight Design

3.1. Optimization Problem

An optimization problem consists of three elements: optimization goals, design variables, and constraints. The mathematical model is:

$$
\begin{align*}
\begin{cases}
\text{find} & \mathbf{x} = \{x_1, x_2, \ldots, x_n\} \\
\text{min} & f(x) \\
\text{s.t.} & g_j(x) \leq 0 & j = 1, 2, \ldots, J \\
& h_k(x) \leq 0 & k = 1, 2, \ldots, K \\
& x^i \leq x_i \leq x^u & i = 1, 2, \ldots, n
\end{cases}
\end{align*}
$$

Equation (1)

$x=\{x_1, x_2, \ldots, x_n\}$ means that there are $n$ design variables, $f(x)$ is the optimized objective function, $g_j(x)$ and $h_k(x)$ are the constraint functions of the variable.

Lightweight is a typical example of optimization problems. In the problem of lightweight design of the six-axis manipulator structure, the optimization objectives, design variables, and constraints are as follows:

1. Optimization goal: the smallest quality.
2. Design variables: material selection, structural form.
(3) Constraint conditions: Stiffness requirements under extreme conditions (maximum displacement of the end of the manipulator ≤ 4 mm), strength requirements under extreme conditions (safety factor ≥ 10).

Lightweight materials are an important way to reduce weight. In terms of material selection, comparing the 6061 aluminum and 3D printing visijet_M2R_BK* materials, the material mechanical parameters are shown in Table 2; in terms of structural weight reduction, based on the original structure, size optimization and topology optimization are used for weight reduction. The manipulator arm lightweight technology route is shown in Figure 4.

| Name            | Density/ (g·cm⁻³) | Elastic modulus/ (MPa) | Poisson ratio | Yield strength/ (MPa) |
|-----------------|-------------------|------------------------|---------------|----------------------|
| 6061 Al         | 2.9               | 689 00                 | 0.33          | 55.2                 |
| visijet_M2R_BK*| 1.2               | 225 0                  | 0.35          | 85                   |

By analyzing the characteristics of the manipulator, it can be seen that the state in which the arm is fully deployed horizontally is a limit condition, which is called the first limit condition, as shown in Figure 5(a). Rotating the joint d by 90 degrees yields another extreme condition, which is referred to as the second limit condition as shown in Figure 5(b).

Boundary conditions such as load and restraint are applied to the arm, as shown in Figure 5, F is the maximum load at the end of the arm, and the size is 5N. Secure the base. The green unit is the design area and the yellow unit is the non-design area.
3.2. *Comparison of two materials*

It can be known from the structural characteristics of the manipulator arm that the difference in the extreme position has little effect on the optimization result. Therefore, under the first limit condition, the 6061 aluminum alloy material and the 3D printed visijet_M2R_BK* material are used as the main structure of the manipulator arm for exploratory topology optimization. The three elements of optimized design are as follows:

1. **Design goal**: the lightest weight.
2. **Design variables**: the unit density of the design area.
3. **Constraint condition**: the end displacement of the arm ≤ 4mm.

Through topology optimization, the corresponding optimization results are obtained, as shown in Figure 6 and Figure 7.

**Figure 6.** Comparison of quality optimization of the two materials

**Figure 7.** The end displacements of the two material manipulator arms

Figure 6 shows the mass change of the main structure of the manipulator during the optimization iteration. Figure 6(a) is the optimization iteration process of the 6061 aluminum material, and Figure 6(b) is the optimization iteration process of the visijet_M2R_BK* material.

Figure 7 shows the change of the end displacement of the manipulator during the optimization iteration. Figure 7(a) shows the optimized iterative process of aluminum and Figure 7(b) shows the iterative process of visijet_M2R_BK* material optimization. After optimization with 6061 aluminum material, the maximum displacement at the end is 3.834 mm and the mass is 1.492 kg. After optimization with visijet_M2R_BK* material, the maximum displacement at the end is 3.987 mm and the mass is 0.971 kg. The maximum displacement of the end of the arm using the two materials does not exceed 4 mm, but the difference in weight after optimization is large, so visijet_M2R_BK* is finally selected as the material of the main structure of the arm.
3.3. Size optimization
The visijet_M2R_BK* was selected as the material for the arm structure and the size optimization technique was used to determine the optimal size of the boom. Based on the first limit condition, a maximum displacement constraint of 2.5mm is applied to the end of the manipulator for optimization. The optimization result is shown in Figure 8. After optimization, the thickness of the arm 1–arm 6 is \{5.5mm, 4.3mm, 4.0mm, 3.5mm, 1.3mm, 2.9mm\}, which meets the stiffness requirements and strength requirements.

![Size optimization results](image)

**Figure 8.** Size optimization results

3.4. Topology optimization
Based on the size optimization results, the thickness of the arm 1–arm 6 is sequentially defined as \{6mm, 6mm, 3mm, 3mm, 1.5mm, 2mm\}, and topology optimization is performed under the first limit condition and the second limit condition. The topological cloud map and the corresponding stress cloud map and displacement cloud map are obtained, as shown in Figure 9 and Figure 10. The maximum vonMises stress of the arm under the first extreme conditions is 2.331Mpa, the maximum displacement of the end of the arm is 3.987mm; the maximum vonMises stress of the arm under the second limit condition is 2.334Mpa, and the maximum displacement of the end of the arm is 3.987mm. In summary, the topology optimization results under both limit conditions meet the design requirements.
Figure 9. Topological optimization results under the first limit condition

Figure 10. Topology optimization results under the second limit condition
4. Geometric Reconstruction and Simulation Verification

4.1. Geometric Reconstruction

According to the results of size optimization and topology optimization, the most important influence on the end displacement of the arm is the arm 2, the arm 3, the arm 4, and the arm 5, so the geometric model is modified and reconstructed to remove excess material. Figure 11 shows the new geometric model of each arm and the overall geometric model of the manipulator.

![Figure 11](image_url)

Figure 11. A new geometric model of the main structure of the manipulator arm

4.2. Geometric Reconstruction

The new geometric model of the main structure of the manipulator is simulated and verified, and the strength and stiffness of the manipulator under two limit conditions are obtained, as shown in Figure 12 and Figure 13.

![Figure 12](image_url)

Figure 12. Analysis results of the first limit working condition of the new model
The results in Figure 12 show that the maximum von Mises stress of the new structure under the first limit conditions is 2.028MPa and the maximum displacement at the end is 3.569mm. As shown in the results of Figure 13, the maximum von Mises stress of the new structure under the second limit conditions is 2.028MPa, and the maximum displacement at the end is 3.949mm. Under both limit conditions, the manipulator meets the stiffness requirements and strength requirements. The weight of the new structure of the manipulator is 1.337kg, which is 0.481kg less than the initial model weight, and the weight reduction ratio is 26.5%, achieving the goal of lightweight design.

5. Conclusion
In this paper, a six-degree-of-freedom series manipulator model is established. The lightweight structure of the manipulator arm is designed by combining the lightweight material and the lightweight structure. The simulation results show that the manipulator arm structure meets the design requirements, and the final weight is reduced by 26.5%. Achieved the purpose of lightweight.

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