Topology optimization method and lightweight design of anthropomorphic manipulator

Haoting Wu1,2,4*, Meng Yin1,2,3, Zhiliang Zhao1,2,4, and Zhigang Xu1,2
1 Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China
2 Institutes for Robotics and Intelligent Manufacturing, Chinese Academy of Sciences, Shenyang 110016, China
3 University of Chinese Academy of sciences, Beijing 100049, China
4 School of Mechanical Engineering and Automation Northeastern University, Shenyang 110016, China
*Corresponding author’s e-mail: wuhaoting@139.com

Abstract. The topology optimization method is adopted to realize the weight reduction of the mechanical arm under the rigidity condition. The typical configuration and load conditions of the manipulator are analyzed. The stiffness mass model of the part is established by the finite element analysis method, and the topology optimization of the part is carried out. On this basis, the optimization of the manipulator system is completed. The optimized art quality is reduced by 6.2% compared with the original model, and the stiffness meets the standard requirements. The method of combining virtual joint method with working space of the manipulator is proposed. The amount of end deformation after optimization of the manipulator is analyzed. The maximum deformation is 0.27mm, which meets the requirements. The optimization process provides a reference for the selection of the drive joint parts of the mechanical arm. According to this, the physical design of the mechanical arm is completed and the load test is carried out. The experiment shows that the mechanical arm can still achieve rapid response under the condition of a 2kg end load.

1. Introduction
The use of mechanical arms in human social activities is becoming more and more extensive, and its development trend in human applications is becoming more and more obvious in the future[1]. The humanoid manipulator must have a humanized appearance, a certain amount of movement space and flexibility. In addition, in order to save manufacturing costs and energy-saving requirements, it is necessary to realize the lightweight design of the robot, in addition to the specific requirements of kinematics, dynamics and design space. The purpose of structural optimization is to make reasonable adjustments to the size, shape and topological parameters of the structure, so that the target performance of the structure can be optimized under the conditions of relevant constraints, such as meeting strength, stiffness, stability, manufacturability. Under the premise of design requirements, the best performance is achieved with the lightest weight and lowest cost[2].

In general, the process of robot design tends to increase the cross-section of the connecting rod to increase stiffness. However, this method will lead to an increase in the quality of the robot, which may increase the deformation and position error of the robot due to gravity[3]. In this case, topology
optimization is a better choice for lightweight architecture design because it does not simply modify existing models, but gives a new rational layout[4]. Especially in the design of robots, topology optimization can verify the problem of maximizing stiffness under mass constraints[5].

For the study of topology optimization of continuum structures, domestic and foreign scholars have proposed a variety of structural topology optimization models, including: homogenization method[6], variable density method[7], evolutionary structure optimization method[8], level set method[9]. In 1988, Bendson[10] proposed the homogenization theory based on the idea of "micro-structure", which marked the birth of continuum topology optimization design. Albers et al.[11] optimized the chest of the humanoid robot by mass minimizing compliance constraints. Lohmeier et al.[12] optimized the calf, thigh and pelvis of the walking robot in a similar way. Kwon et al.[13] optimized the lower body frame of the biped humanoid robot for stable walking by topology optimization. Among them, the variable density method has been deeply researched and applied due to the small design variables, simple program design and high iterative efficiency[14].

2. Mechanical arm structure introduction

The robot arm designed in this paper is located in the human-computer interaction service robot, as shown in Fig 1. The basic design requirement is that the arm structure and joint movement are similar to the upper limbs of the human body. The manipulator is driven by a tendon-sheath to be equivalent to the function of the human muscle. The traditional tandem arm directly mounts the drive motor at the moving joint, reducing the load capacity of the robot and making the robot inconvenient for high-speed motion and fast response. The mechanical arm that drives the joint movement with the tendon-sheath, the motor and the driver are arranged on the base, and the inertia of the moving parts is greatly reduced, and the load capacity is also improved. However, for the higher weight and strength requirements of the manipulator, the typical parts can be optimized by topology optimization.

![Figure 1. Seven-degree-of-freedom humanoid manipulator model](image)

3. Topology optimization method based on RAMP variable density method

For the structural optimization of the parts of the moving mechanism, the common method is to extract several sets of boundary loads of the parts to be optimized, and then apply them on the parts to optimize the static multi-conditions. When considering the flexibility of the member, the displacement of the object is:

\[ Y(x,t) = y(t) + w(x,t) \]  
\[ w(x,t) = \sum_{i} W_i(x) q_i(t) \]

Where \( y(t) \) is the rigid body displacement, \( w(x,t) \) is the displacement of the object due to flexibility, \( q_i(t) \) is the \( i \)-th generalized coordinate, and \( W_i(t) \) is the \( i \)-th orthogonal mode.

The lagrangian function is:

\[ \frac{d}{dt} \left( \frac{\partial T}{\partial q_i} \right) - \frac{\partial T}{\partial q_i} = Q_i \]
\[ Q = \int_{0}^{L} f(x,t)w(x)dx = my(t)\int_{0}^{L} w(x)dx \] 

(4)

When the damping is not considered, the dynamic equation of the dynamic load structure is:

\[ M\ddot{q}(t) + Kq(t) = \ddot{y}(t)(m - \rho A)\int_{0}^{L} w(x)dx \]

(5)

The topology optimization problem of continuum structure is essentially to optimize the iterative calculation, retain the structural unit favorable to the structural force transmission path, and delete the unit that has little effect on the structural force transmission path. The corresponding mathematical model is as follows:

\[
\begin{align*}
\text{Find } & \quad \rho = (\rho_1, \rho_2, \cdots, \rho_N)^T \\
\text{Min } & \quad c(\rho) = F^T U \\
\text{s.t. } & \quad V \leq V_0 \\
& \quad F = KU \\
& \quad \rho_i \in \{0,1\} (i = 1, \cdots, N)
\end{align*}
\]

(6)

Where \(\rho_i\) is a design variable, 0 means deleting the unit, and 1 means that the reserved unit is an entity. \(K\) is the total stiffness matrix; \(U\) is the displacement vector of the structure. \(F\) is the external force vector to which the structure is subjected, \(V\) is the optimized structural volume, \(V_0\) is the initial volume of the structure, and \(f\) is the volume constraint parameter. \(f_{\text{vol}}\) is the upper limit of the optimized volume.

RAMP is very similar to the SIMP method, and it is necessary to introduce a continuous variable \(x\), a coefficient \(p\), and an intermediate density unit, where \(0 \leq x \leq 1\), and \(p\) is a penalty factor. The relationship between the elastic modulus of the material before and after optimization is different:

\[ E(x) = E_{\text{min}} + \frac{x_i}{1 + p(1 - x_i)}(E_0 - E_{\text{min}}) \]

(7)

When \(E_{\text{min}}\) is much less than \(E\), \(E_{\text{min}}\) can be ignored. The above formula is simplified as:

\[ E(x) = \frac{x_i}{1 + p(1 - x_i)}E_0 \]

(8)

![Penalty effect diagram of different p values in the SIMP model](image)
If the optimization results only have a density of 0 and 1, this model is completely correct. But in fact there is always an intermediate density, so the penalty factor $p$ needs to be introduced. When $p$ is large enough, a material without intermediate density can be obtained. The selection of $p$ is related to the Poisson’s ratio $\nu_0$ of the raw material, and its main form of expression is in a two-dimensional structure, $p \geq \max\{2/(1-\nu_0), 1/(2-\nu_0)\}$, and in a three-dimensional structure, $p \geq \max\{15(1-\nu_0)(7-5\nu_0), 1.5(1-\nu_0)(1-2\nu_0)\}$.

4. Topology optimization

The system optimization design of the robot is divided into part topology optimization and parameter system optimization. For multi-body system optimization, it is very time-consuming to apply topology optimization to the whole system. Therefore, topology optimization of parts can greatly save the optimization process. The required calculation time[15].

4.1. Topology optimization process

Figure 3. Typical parts of the robot arm

Figure 4. Optimized components

The typical arm of the arm is a typical object. The model is a cylinder with a diameter of 75mm, a length of 110mm and a thickness of 15mm. As shown in Fig 3, the material density is 2730kg/m$^3$ and the elastic modulus is 68.9GPa. The pine ratio is 0.33. Topology optimization issues do not take into account the effects of material or geometric nonlinearities.

In order to find the optimal structure in the topology optimization process, the final topology features are as obvious as possible. The constraint volume fraction of the set model is small enough to be 10% of the original design area, and the optimization target is the largest overall stiffness of the structure. When the difference between the objective functions of two consecutive iterations is less than the given convergence tolerance, the program determines that the solution converges, and the defined convergence tolerance is 0.5%. The OptiStruct optimization results can be post-processed in HyperView to determine the display threshold for the optimization results. Units with a relative density below this value will not be displayed.

According to the load and constraint conditions, six degrees of freedom constraint are applied on one end face of the model as the complete support, and on the other end face, the load under different working conditions is applied. The load of a single working condition is divided into three types: axial force, bending and shearing force. The topology optimization results under three working conditions are shown in Fig. 5.

Figure 5. Three working conditions optimization analysis results

After optimizing the part design area under different volume constraints, it is found that when the volume constraint is too small, the optimization result is highly separated and the geometric expression is not clear; when the volume constraint is too large, the topology optimization target of the part cannot be achieved.
4.2. Deformation analysis

Stiffness is one of the main factors affecting the performance of the robot. Therefore, stiffness should be considered to achieve the optimal design of the robot. The stiffness model established for the part by finite element analysis is shown in Fig. 6.

In order to clearly express the characteristics of topology optimization, it is found that the volume constraint of the design region is 60%, and the result with good topological characteristics can be obtained. Therefore, the volume constraint for defining the maximum stiffness design is 60%. The remodeling of the part structure is shown in Fig. 4.

Figure 6. Stiffness-quality model
5. Analysis of the end motion error of the manipulator after optimization

![Diagram of robotic virtual joint model]

Figure 7. Seven-degree-of-freedom humanoid robotic virtual joint model

After the optimization of each part is completed, the robot arm system can be optimized, and the virtual joint method is used to detect the end motion error of the optimized manipulator. The virtual joint method is based on the traditional rigid model by adding virtual joints (equivalent virtual springs) to simulate joints as shown in Fig. 7. Combining the finite element method with the virtual joint method can improve the calculation accuracy while maintaining high computational efficiency.

![Graph showing robot arm working space error]

Figure 8. Robot arm working space error

The deformation of the manipulator can be expressed as a function of the mass of the part. After optimization, the mass of the arm is reduced by 6.2% compared with the original model. The D-H parameters of the mechanical arm link are shown in Table 1. The maximum position deformation of the end of the arm is calculated by the robot working space combined with the virtual joint method to be 1.14 mm, which meets the standard requirements.

| link $i$ | variable $\theta_i$ | $a_i$ | $a_i$ | $d_i$ |
|----------|---------------------|-------|-------|-------|
| 1        | $\theta_1$         | 90°   | 0     | 0     |
| 2        | $\theta_2$         | -90°  | 0     | 0     |
| 3        | $\theta_3$         | -90°  | 0     | 0     |
| 4        | $\theta_4$         | 90°   | 320   | 0     |
| 5        | $\theta_5$         | 90°   | 0     | 0     |
| 6        | $\theta_6$         | 90°   | 250   | 0     |
| 7        | $\theta_7$         | 90°   | 100   | 0     |
6. Prototype positioning accuracy and load capacity test

According to the above topology optimization results, the structure of the humanoid manipulator is determined, and the parameters of the configuration motor and the parameters of the transmission system are determined through joint calculations such as joint torque, and the prototype of the design arm is shown in Fig. 9. The synchronous motor and the harmonic reducer are placed outside the arm, which greatly improves the load capacity of the mechanical arm, and effectively improves the positioning accuracy of the mechanical arm, and the repeating positioning accuracy of the end is less than 1 mm.

7. Conclusion
(1) After optimization, the quality of the arm is reduced by 6.2% compared with the original model, and the maximum position deformation at the end is 1.14mm, which meets the design requirements.

(2) According to the optimized model, the physical design was completed, and the end positioning accuracy and load capacity test were carried out. The repeatability of the end of the arm is less than 1mm, and good signal tracking can be achieved with a load of 2kg at the end. It also has the advantages of low manufacturing cost and low cost, and the ratio of self-weight to load capacity reaches 1.85:1.

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