

Current Status of Research on Lightweight Design and Manufacturing of Robot Joint Modules Based on Topology Optimization

Zonghan Wu

*School of International Education, Beijing University of Chemical Technology, Beijing, China
2022090077@buct.edu.cn*

Abstract. The lightweight design of robotic joint modules is a key breakthrough in improving motion performance. The core challenge lies in the fact that traditional manufacturing processes (casting/milling) cannot achieve the theoretically optimal topological optimization structure, resulting in persistent issues such as high joint inertia, slow response speeds, and high energy consumption. 3D printing technology, through its layer-by-layer manufacturing process, can overcome geometric constraints, making the engineering application of complex topological and lattice structures possible, thereby providing an irreplaceable solution for joint lightweighting. This paper reviews the current state of research on lightweight design and manufacturing of robotic joint modules based on topology optimization, with a focus on the design and manufacturing collaboration of robotic joints through topology optimization. Through this study, it was found that the collaborative application of topology optimization technology with 3D printing, CNC machining, and other processes has already achieved weight reduction in joint modules across industries such as industrial, medical, and humanoid robotics, while simultaneously enhancing stiffness and heat dissipation performance, providing diverse technical pathways for the high-performance development of robotic joint modules.

Keywords: Robot joint modules, lightweight design, traditional manufacturing processes, topology optimization, high-performance development

1. Introduction

With the rapid development of robotics technology, its applications have expanded from traditional industrial workshops to multiple fields such as medical rehabilitation, home services, and aerospace, with increasingly stringent requirements for robot performance. As the core component connecting various limbs and enabling motion and force transmission, the balance between the weight and performance of robot joint modules has become a key bottleneck constraining robot development.

In recent years, topologically optimized robot joints have emerged in various forms, such as wearable knee joint robots that reduce user burden through lightweight design [1]. Lightweight industrial robot arm joints that enhance production efficiency and flexibility [2]. Additionally, topological optimization technology achieves significant weight reduction by optimizing material

distribution while maintaining joint strength and stiffness, providing an effective solution to the traditional design dilemma of “balancing weight and performance.”

This paper aims to systematically review the diverse application paths of topology optimization technology in robot joint lightweighting, providing theoretical references and practical insights for joint design in various scenarios. Additionally, by analyzing the bottlenecks in design and manufacturing collaboration, it offers directional guidance to promote the transition of topology optimization technology from laboratory research to industrial application, thereby assisting the robotics industry in overcoming core performance bottlenecks.

2. Overview of robot joint modules

2.1. Classification of robot joint modules

Robot joint module classification as shown in Table 1.

Table 1. Classification of robot joint modules [1-5]

Application scenarios	Representative Types
Medical rehabilitation	Wearable knee joint, finger exoskeleton
Humanoid robot	Bionic thigh joint, bipedal robot
Industrial robot	Robotic arm joints (such as ABB, IRB4600)

In medical rehabilitation scenarios, wearable knee joints and finger exoskeletons are typical examples [1,3]. These joints come into direct contact with the human body and must closely follow human movement patterns. Therefore, their design emphasizes lightweight construction and smooth movement to reduce the burden on users, while also providing sufficient assistive force to help patients complete rehabilitation training or daily activities.

In the field of humanoid robots, the design of biomimetic thigh joints and bipedal robot joints focuses on simulating the coordination and stability of human limb movements [4,5]. Biomimetic thigh joints must support the weight of the upper body while enabling flexible flexion and extension movements to ensure natural and smooth robot walking and turning actions; bipedal robot joints place greater emphasis on overall motion balance control to address complex situations such as uneven ground and center of gravity shifts during walking.

The core requirement for industrial robots is efficient and precise operational capability, exemplified by robotic arm joints (such as those used in ABB and IRB4600) [2]. These joints must possess high stiffness and load-bearing capacity, maintain motion precision at high speeds, meet the demands of high-intensity industrial production tasks such as welding, material handling, and assembly, and have a long service life to accommodate continuous production environments.

Although joint types vary in function across different scenarios, they are all critical to a robot's core motion capabilities. Their design characteristics also provide targeted directions for the application of topology optimization technology.

2.2. Structural composition and mechanical properties of joint modules

A typical robot joint module consists of a drive unit, a transmission mechanism, a connection frame and a sensing unit. The drive unit includes motors, hydraulic devices, etc., to provide power for the joint movement; the transmission mechanism is responsible for transmitting power to the actuating parts to realize the conversion of motion and force; the connection frame plays the role of supporting

and connecting the components; the sensing unit is used to detect the position, speed, force and other parameters of the joints, to ensure the accuracy of motion control.

Joint modules in different application scenarios need to meet specific mechanical characteristics. In the field of medical rehabilitation, the knee joint needs to bear the body weight, while ensuring the flexibility of the movement to adapt to the human body movement [1]. Industrial robotic arm joints need to withstand a certain amount of torque, to ensure the stiffness of the operation process and movement accuracy [6]. Multi-fingered robots of the palmar joints in the grasping of the object, need to cope with multi-directional force, the structure of the synergistic performance requirements of the force is higher [7]. Soft robot joints need to be flexible enough to adapt to complex environments while also having enough stiffness to resist interference and keep movements stable [8].

2.3. Problems with existing robot joint module designs

Currently, there are still some issues with the design of robotic joint modules. First, traditional design methods often rely on experience, leading to unreasonable material distribution and excessive redundancy, resulting in overly heavy joint modules. This not only increases energy consumption but also reduces motion flexibility [2].

Second, most robot thermal designs are based on engineering experience and designers' intuition, making them difficult to directly apply to actual robot thermal design [9]. Traditional static analysis methods, when applied to structures with complex motion conditions, ignore the effects of acceleration, resulting in structural constraints that do not align with real-world conditions, which can lead to inaccurate topology optimization results [5]. During actual bipedal robot walking, the driving torque and angular velocity of the ankle joint differ significantly, resulting in dynamic imbalance characteristics of the ankle joint during bipedal robot gait walking [10]. Additionally, there is a disconnect between design and manufacturing. Some structures obtained through topology optimization contain complex topological shapes, making them difficult to process using traditional manufacturing processes [3].

3. Topology-optimized lightweight design of robot joint modules

3.1. The advantages of topological optimization in robot joint design

The application advantages of topology optimization technology in robot joint design are primarily reflected in two aspects: weight reduction and performance enhancement, and it demonstrates targeted value in different scenarios.

In terms of weight reduction, topology optimization can remove redundant materials based on the application scenario of the joint. For the thigh of a biomimetic humanoid robot, topology optimization achieved a 20% weight reduction, which directly reduced the limb inertia during robot walking, thereby improving gait stability and endurance [5]. In the design of industrial robotic arm joint flanges, a 8.95% weight reduction alleviates the rotational load on the joint, accelerating the robotic arm's motion response speed to meet high-speed production requirements [6]. Hydraulic robotic valve blocks optimized via topological optimization achieved a 60% weight reduction, not only lowering the overall structural weight but also creating space for optimizing internal flow channel layout [9].

In terms of performance enhancement, topology optimization can simultaneously strengthen the core performance of joints while reducing weight. For example, when applied to knee joint assistive

devices, its force transmission efficiency is effectively improved, enhancing the assistive effect on human movement [1]. For soft robot joints, topology optimization significantly enhances their interference resistance stiffness, improving operational stability while maintaining flexible movement [8].

3.2. Design process for topological optimization of joint modules



Figure 1. Topological optimization process flow chart for joint modules

Figure 1 shows the design process is primarily divided into three stages, with the first being modeling and parameter definition. A three-dimensional model of the joint module must first be established, upon which the design domain range is defined, i.e., the spatial regions where materials can be distributed. Additionally, suitable materials such as aluminum alloy or carbon fiber must be selected to align with the joint's load-bearing requirements and lightweighting objectives [2,4]. Furthermore, the load conditions of the joint during actual operation must be analyzed and defined, including static forces, forces during multi-finger grasping, and dynamic torques [5,7,10]. And optimization constraints must be clearly defined, such as the upper limit of material volume fraction and the maximum structural displacement limit [3,9], to provide boundary conditions for subsequent optimization.

Next is the optimization solution. After completing modeling and parameter definition, an appropriate optimization method and algorithm must be selected, such as the variable density method (SIMP) and the moving asymptote algorithm (MMA). Subsequently, key parameters are set based on joint characteristics, including penalty factors and iteration counts, and the optimal material distribution topology is solved through numerical calculations [2,6,9], forming an initial optimization structure scheme.

Finally, post-processing and verification are conducted. For the topology obtained from the optimization solution, process adaptability adjustments are made, such as rounding sharp edges [8,9], to meet manufacturing process requirements. After adjustments are completed, finite element analysis is used to verify the structure's strength, stiffness, and other performance metrics [3,6], ensuring that the optimized joint module meets the mechanical requirements of actual applications.

3.3. Key technologies for joint module topology optimization

Multi-condition and multi-physics coupling is a key technology that must be comprehensively considered in topology optimization. It requires incorporating factors such as the loads on robot joints under different motion states [5,10], thermal-structural coupling, for example, heat dissipation requirements during hydraulic valve block operation [9], synergistic effects between rigid and flexible components, and inertial unloading into the optimization model [5]. Its key feature lies in overcoming the limitations of single operating conditions or physical fields, ensuring that optimization results better align with real-world application scenarios. This avoids structural redundancies or strength deficiencies caused by insufficient consideration of local factors, thereby ensuring that the optimized joints operate stably in complex environments.

Manufacturing process constraint integration refers to incorporating process limitations such as the minimum feature size for 3D printing and the feasibility of CNC machining into the topology

optimization process [2,3,8], ensuring that the optimized structure not only meets performance requirements but can also be actually manufactured. Its key feature is the realization of design-manufacturing synergy, breaking the traditional optimization dilemma of “designable but not manufacturable.” This approach preemptively avoids performance losses caused by structural modifications due to manufacturing issues later in the process, ensuring the full realization of topological optimization potential.

Multi-objective optimization strategies balance multiple mutually constraining objectives such as lightweighting, strength, and stiffness in topology optimization. Objective weights are set based on joint application scenarios to seek the optimal balance. Its key feature is overcoming the limitations of single-objective optimization, achieving comprehensive performance improvements, and avoiding performance degradation caused by overemphasizing a single objective. This ensures that the optimized joint meets core requirements while also addressing other critical performance metrics.

3.4. Application examples of topology optimization

Xu et al. reduced the mass of the robotic arm by 15% and increased its stiffness by 20% using the SIMP method [2]. This method allows for precise control of material density distribution, removing redundant material while concentrating material along high-stress transmission paths, thereby achieving “weight reduction without compromising stiffness.” The 15% weight reduction directly reduces the inertia of the robotic arm's motion. The 20% increase in stiffness enhances structural stability during high-speed operations and reduces positioning errors of the end-effector.

Liao et al. combined level set topology optimization with orthogonal analysis to achieve an 8.95% weight reduction in the joint flange [6]. This method avoids the “checkboard” defects of traditional topology optimization through smooth boundary evolution, making the flange structure easier to manufacture; orthogonal analysis specifically optimizes slot positions and dimensions, reducing weight while avoiding stress concentration risks.

Nie et al. adopted a “variable-thickness shell + variable-density lattice” structure for an innovative design of the robot's thigh structure. Through simulation, it was found that the design meets usage requirements, with a total weight reduction of 20% [4]. The variable-thickness shell ensures the overall load-bearing capacity of the thigh structure, while the variable-density lattice further reduces weight through its internal porous structure and utilizes the lattice's energy absorption properties to reduce impact loads during walking. The 20% weight reduction not only directly enhances the robot's endurance but also reduces the torque requirements for the hip joint drive.

Chen et al. proposed soft joint multi-objective topology optimization to achieve anisotropic stiffness [8]. Their research broke through the traditional limitation of soft joints, where “flexibility and stability are difficult to balance,” by using multi-objective optimization algorithms to balance motion flexibility and interference resistance. The anisotropic design enables soft joints to conform to human motion while resisting external interference forces in human-machine interaction scenarios.

Li et al. developed a node-based thermal topology optimization method to enhance the heat dissipation performance of hydraulic robot valve blocks [9]. Their research utilized node-level topology control to align the internal flow channels of the valve block with heat distribution patterns, resolving the contradiction in traditional designs where “heat dissipation was prioritized at the expense of lightweight design.”

4. Additive manufacturing of robot joint modules based on topology optimization

4.1. Manufacturing processes adapted to topologically optimized structures

3D printing technology breaks through geometric limitations by layering materials, making it the preferred process for complex topological structures, such as 3D printing of finger exoskeletons and multi-material printing of soft robot joints [3,8]. Its advantages lie in the ability to disregard tool accessibility or mold opening/closing constraints, enabling the precise reproduction of complex features such as lattices and variable-thickness surfaces from topological optimization, ensuring material distribution aligns closely with the optimized model and avoiding performance losses caused by manufacturing compromises. For thin-walled, hollow structures in topological optimization designs, 3D printing can precisely control material usage, avoiding weight redundancy caused by “safety margins” in traditional processes, making weight reduction effects closer to theoretical optimal values.

Other processes, such as CNC machining, although limited in manufacturing extremely complex structures, remain irreplaceable in critical areas of topological optimization joints. Its advantage lies in the ability to control mating surface tolerances to the micron level using precision tools and CNC systems, meeting the high-precision requirements for bearing installation and sealing surfaces in joint modules, and avoiding performance degradation caused by assembly gaps.

Casting and forging must be adapted to simplified topological structures, but their mold forming is suitable for mass production, with unit costs significantly lower than 3D printing.

4.2. Quality control and inspection in the manufacturing process

To ensure the manufacturing quality of robot joint modules based on topology optimization, it is necessary to strengthen quality control and inspection during the manufacturing process. In terms of process parameter optimization, for 3D printing processes, parameters such as layer thickness, laser power, and scanning speed need to be reasonably adjusted to ensure the accuracy and mechanical properties of the topological structure [3,8]. For CNC machining, cutting parameters need to be optimized to reduce processing stress and deformation and avoid stress concentration [2,9].

In terms of performance testing, multiple methods should be employed to inspect the manufactured joint modules. For example, dynamic performance testing can evaluate the response characteristics of the joint under different motion states [2]. Stress testing can be used to assess the strength performance of the joint module [6]. And thermal sensors can be used to test the heat dissipation performance of components such as hydraulic robots [9], ensuring that the joint module meets design requirements.

4.3. Collaboration between topology optimization and manufacturing technology

The integration of topology optimization and manufacturing technology is key to achieving efficient design and manufacturing of robotic joint modules. During the design phase, manufacturing process constraints should be fully considered and incorporated into the topology optimization model [2,3,8,9]. For example, based on the selected manufacturing process, corresponding process parameter constraints should be set to ensure that the optimization results not only perform well but are also easy to manufacture, thereby avoiding significant design modifications later due to manufacturing issues. During the manufacturing phase, appropriate manufacturing processes should be selected based on the results of topological optimization. For complex lattice-structured joint

modules, 3D printing technology is prioritized [4,8]. For mating surfaces with high precision requirements and strict surface quality standards, CNC machining technology is employed [2]. Additionally, manufacturing processes can be adjusted as needed during production to better realize the design intent of topological optimization, thereby enhancing the quality and performance of the joint modules.

5. Challenges and prospects of topology optimization in joint module applications

5.1. Key challenges

First, computational efficiency is a significant issue. Complex joint module models, especially those involving multiple operating conditions and multi-physics coupling, require a large number of iterations and significant computational resources during the topology optimization process, resulting in substantial computational time [5,11]. This limits the practical application efficiency of topology optimization in real-world engineering scenarios.

Second, manufacturability remains a major challenge. Although manufacturing process constraints are considered during the optimization process, the results of topology optimization may still include small features or sharp angles that exceed the capabilities of traditional manufacturing processes [2,3,9], requiring special manufacturing techniques or additional processing steps, thereby increasing manufacturing costs and complexity.

Finally, achieving a balance among multiple objectives is also challenging. The conflicts between lightweight design and objectives such as strength, stiffness, and dynamic performance are difficult to completely eliminate. How to find the optimal balance among these objectives to meet the needs of different application scenarios remains a topic requiring further research.

5.2. Future outlook

In the future, as technology continues to advance, the application of topology optimization in the field of robotic joint modules will present new opportunities. In terms of technological integration, combining artificial intelligence technology with topology optimization holds promise for achieving automation and intelligence in joint module design.

In terms of process innovation, developing more advanced manufacturing technologies, such as 4D printing technology, can enable topology-optimized structures to possess dynamic response capabilities, further enhancing the performance and functionality of joint modules. Additionally, improving existing additive manufacturing processes to enhance manufacturing precision and efficiency while reducing costs will facilitate the widespread adoption of topologically optimized structures.

Application areas will also continue to expand. Topological optimization technology will not only be applied more deeply in existing robotic joint modules but will also be extended to the design of robotic joints for special environments such as underwater robots and space robots. Furthermore, multi-scale and cross-scale topological optimization research will be further deepened to meet design requirements at different levels.

6. Conclusion

This paper reviews the current state of research on lightweight design and manufacturing of robotic joint modules based on topology optimization, clarifying the core value of topology optimization technology in addressing the “lightweighting versus performance balance” dilemma: domestic

research has achieved effective weight reduction and performance enhancement in industrial robotic arms and joint flanges through methods such as the SIMP method and level set optimization; Internationally, breakthroughs have been made in areas such as structural innovation in humanoid robots, stiffness control of soft robot joints, and thermal design of hydraulic valve blocks, all of which validate the irreplaceable role of topology optimization combined with additive manufacturing in robot joint design.

The significance of this research lies in providing a transformation path from “experience-based design” to “performance-driven design” for robot joint modules, promoting the technological integration of design-manufacturing collaborative optimization, and laying the theoretical and practical foundation for performance upgrades in joint modules across multiple scenarios such as industrial, medical, and humanoid robots.

In the future, topology optimization technology will drive breakthroughs in robot joint modules toward “scenario-based customization,” offering more cost-effective lightweight solutions in fields such as medical, industrial, and special operations, accelerating the transition of robots from “high-tech” to “mass adoption.” Additionally, its deep integration with green manufacturing concepts will help the robotics industry seize the initiative in the carbon reduction and emissions reduction trend, becoming a key pillar in the global upgrade of intelligent manufacturing.

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