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Structural Design and Performance Analysis of Lightweight Manipulator Based on Multi-objective Optimization

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Abstract: To address the multi-performance conflict in lightweight robotic arm design, this study establishes a systematic design framework integrating multi-objective optimization. By combining topology optimization with parametric modeling to develop lightweight structural solutions, and applying advanced optimization algorithms to resolve multi-objective coordination issues involving mass, stiffness, and dynamic characteristics, the framework generates a Pareto solution set that characterizes performance trade-offs. A comprehensive performance evaluation system is further developed to assess the synergy between static-dynamic characteristics and energy efficiency precision, validating the optimization outcomes. The research demonstrates that this framework effectively guides designers in achieving optimal balance between structural lightweighting and overall performance under multiple constraints, providing a methodological basis for high-performance robotic arm development that combines theoretical rigor with engineering applicability.

1. Introduction

As modern manufacturing and robotics advance toward greater flexibility and efficiency, lightweight design of robotic arms has become a critical approach to enhance motion performance and reduce energy consumption. Traditional design methods often focus on single performance metrics, failing to strike a balance among multiple constraints such as structural mass, stiffness, and dynamic characteristics. This limitation restricts the application potential of robotic arms in high-precision and high-speed operational scenarios. To address this, this paper introduces multi-objective optimization theory to systematically study structural design methods and comprehensive performance evaluation systems for lightweight robotic arms. The research aims to explore feasible pathways for lightweight design and multi-performance synergy through establishing an optimization model that encompasses statics, dynamics, and material properties, thereby providing theoretical foundations and methodological support for high-performance robotic arm development. The following sections will sequentially elaborate on core components including lightweight design theory, integration of multi-objective optimization algorithms, and performance analysis frameworks.

2. Design Theory and Method of Lightweight Robotic Arm

2.1 Principles and Guidelines for Lightweight Structural Design

The core of lightweight structural design lies in systematically reducing the overall mass of robotic arms while ensuring critical performance metrics such as stiffness, strength, and dynamic stability remain intact. This process involves rational structural reconstruction based on mechanical principles and engineering standards, rather than simple material reduction. The design philosophy is rooted in the principle of minimization, aiming for optimal mass distribution while meeting functional and safety requirements. For instance, load path analysis guides designers to identify and reinforce primary force-transmitting areas, while critical components may adopt hollow or thin-walled designs to reduce redundant mass. Additionally, stiffness-to-weight ratio optimization becomes crucial, requiring structures to maintain sufficient deformation resistance during lightweighting to avoid positioning errors or vibration issues caused by excessive flexibility. In terms of design principles, lightweight solutions must adhere to multi-objective coordination criteria, meaning individual performance metrics cannot be isolated. Designers must balance static load-bearing capacity with dynamic response characteristics—for example, reducing inertial forces during high-speed motion enhances acceleration and energy efficiency, but excessive lightweighting may weaken structural damping and increase resonance risks [1]. Therefore, the criteria emphasize integrated evaluation, examining lightweighting within the robotic arm's overall operational cycle and combining kinematic and dynamic models to predict cascading effects of mass changes on end-effector precision, energy consumption, and lifespan. The lightweight principle also extends to manufacturing and assembly, where process feasibility must be considered. Additive manufacturing technologies enable complex topological structures, while modular principles support standardized and rapid component replacement, further reducing lifecycle costs. In summary, the principles and guidelines of lightweight structural design form a multidimensional framework that advocates a systems approach to balance quality reduction and performance retention, providing theoretical foundations and directional guidance for subsequent optimization. This framework not only focuses on immediate design outcomes but also incorporates forward-looking considerations of material behavior, environmental loads, and long-term reliability, transforming lightweight design from a purely quantitative approach to an intelligent enhancement of performance [2].

2.2 Material Selection and Topological Optimization Strategy

Material selection and topology optimization strategies are two closely coupled aspects in lightweight robotic arm design, jointly determining the physical properties and performance boundaries of the structure. Material selection involves comprehensive evaluation of various engineering materials, with key considerations including specific strength, specific stiffness, fatigue characteristics, and cost-effectiveness. Traditional metals such as aluminum alloys and titanium alloys are widely used due to their superior strength-to-weight ratio, while emerging composites like carbon fiber-reinforced polymers offer lower density and customizable anisotropy, making them suitable for components with clearly defined load-bearing directions [3]. Material decisions cannot be made in isolation; they must be coordinated with structural layout. For instance, materials with higher modulus should be selected in regions requiring high stiffness, while lightweight foams or honeycomb sandwich structures can be introduced in weight-reduction priority areas. Topology optimization, as a computation-driven design tool, employs mathematical algorithms to optimize material distribution within a given design space to achieve objectives such as minimum flexibility or lowest mass. Its strategy typically starts from continuum optimization, using variable density methods or level set methods to iteratively generate optimal force-transmitting paths, thereby eliminating materials in low-stress regions and forming naturally biomimetic bone-like or truss-type configurations. The successful application of topology optimization strategies relies on precise boundary conditions and load definitions, as well as reasonable manufacturing constraints such as minimum member size or ejection direction to ensure processability. Furthermore, material selection and topology optimization must be performed collaboratively to form an integrated strategy. For example, in multi-material design, optimization algorithms can simultaneously allocate different material types to specific regions to fully leverage their respective advantages [4]. This synergy extends to multi-scale optimization, where materials' microstructures are designed at the microscopic level after macroscopic topology is determined, further enhancing performance. The implementation challenges involve balancing computational complexity with physical realism, as well as the sensitivity of optimization results to input parameters. Consequently, advanced strategies often integrate response surface models or surrogate models to accelerate iterations, while incorporating robustness considerations to counter load uncertainties. Overall, material selection and topology optimization strategies form a dynamic interactive design layer. By rationally exploring the potential combinations of materials and morphologies, they open innovative possibilities for lightweight robotic arms, enabling structures that are not only lighter and stronger but also more adaptable and efficient [5].

2.3 Key Component Configuration Design and Parametric Modeling

The configuration design and parametric modeling of key components form the practical core of lightweight robotic arm design, transforming abstract principles into actionable engineering solutions. Critical components such as the arm, joint modules, and base directly determine the overall performance and mass distribution of the robotic arm. Configuration design focuses on precise adjustments to geometric shapes and internal structures. For instance, the arm may adopt variable cross-section designs or internal rib reinforcement layouts to optimize stress distribution under bending and torsional loads, while the joint section requires integration of actuators and transmission elements, necessitating compact configurations to reduce inertia and enhance stiffness. The design process emphasizes functional integration, such as embedding sensing units or wiring channels within the structure to avoid external additional mass. Parametric modeling plays a pivotal role here, defining component geometry through control parameters like length, thickness, and curvature radius, making design variables explicit and easily adjustable [6]. This modeling approach supports rapid iteration, allowing designers to generate new geometries by modifying parameter values without rebuilding models from scratch, significantly improving efficiency in exploring design space. Parametric models are typically implemented using CAD software or specialized scripts, coupled with finite element analysis tools to achieve a closed-loop design-analysis-optimization process. In lightweight contexts, parametric modeling enables multi-objective optimization—parameters can be linked to responses such as mass, stiffness, and dynamic frequencies, with optimization algorithms subsequently searching parameter combinations to balance these objectives. The integration of configuration design and parametric modeling is further demonstrated through incorporating manufacturing constraints. Parameters such as machining accuracy and assembly tolerances ensure designs are both performance-driven and practical. Moreover, parametric methods enable variant design, allowing customized component configurations for different task scenarios and enhancing robotic arm adaptability. Notably, configuration design often requires a combination of empirical intuition and computational assistance. Parametric models provide a flexible framework that allows designers to manually refine algorithmic suggestions, avoiding local optima or violating implicit constraints [7]. In summary, key component configuration design and parametric modeling jointly establish a systematic design implementation platform. Through controllable variables and predictable responses, they transform lightweight concepts into concrete structural innovations, laying the foundation for performance leaps in robotic arms. This process emphasizes both theoretical rigor and engineering applicability, enabling lightweight design to transition from concept to real-world application [8].

3. Integration and Application of Multi-objective Optimization Algorithms

3.1 Modeling and Constraint Handling of Multi-objective Optimization Problems

Constructing an accurate multi-objective optimization model serves as the critical first step in translating engineering requirements into computable mathematical problems. The core challenge lies in formalizing competing performance metrics—such as structural mass, static stiffness, and natural frequencies—in lightweight designs into a unified optimization objective set. System-level modeling requires establishing physical relationships between design variables and performance responses, typically achieved through parametric models and finite element analysis-derived surrogate models or approximate mappings. Objective functions are not defined in isolation; they collectively define a multidimensional performance space where improvements in any objective may come at the expense of others. Constraints, equally crucial in modeling, ensure the optimization results are technically feasible. These constraints encompass both explicit boundaries (material strength, allowable stress, maximum deformation) and implicit limitations (manufacturing processes, assembly clearance, motion interference). Effective constraint strategies like penalty functions or constraint relaxation techniques guide optimization searches within the feasible design domain, avoiding mathematically superior but impractical solutions. Robust models must also account for uncertainties such as load variations or material property fluctuations, often addressed through robustness constraints or reliability optimization frameworks. Therefore, the whole modeling process is an art of seeking balance between ideal performance and hard reality, which lays a precise and pragmatic mathematical foundation for the subsequent algorithmic solution.

3.2 Adaptability of Advanced Optimization Algorithms in Structural Design

Traditional optimization methods often prove inadequate when tackling high-dimensional, nonlinear, and potentially non-convex lightweight design optimization problems, while advanced optimization algorithms provide powerful solutions. The adaptability of these algorithms lies in their ability to efficiently handle multi-objective and multi-constraint scenarios, overcoming the common computational challenges in structural optimization. Evolutionary algorithms like genetic algorithms and particle swarm optimization (PSO), based on population search mechanisms, can explore different regions of the solution space in parallel, easily obtaining approximate distributions of the global Pareto front. This makes them particularly suitable for complex design spaces with objectives lacking explicit analytical expressions. However, their widespread drawback is the need for massive performance evaluations, resulting in high computational costs. To address this, combining global search algorithms with gradient-based methods that excel at local optimization, or adopting agent-assisted optimization strategies, has become a crucial approach to enhance adaptability. Agent models such as Kriging or radial basis function networks can construct approximate models of objectives and constraints using limited sample points, significantly reducing the need for time-consuming finite element analysis and enabling efficient optimization cycles. Furthermore, modern algorithms must adapt to handling mixed variables (both continuous and discrete) and variables with complex geometric relationships. Algorithm selection and tuning should not be rigid; they require targeted configurations based on the problem's scale, nonlinearity, and computational resource constraints. A good algorithm should not only have strong search ability, but also have the ability to deal with all kinds of "imperfect" conditions in engineering practice, such as the tolerance to noise and the reasonable punishment mechanism for violating constraints.

3.3 Evaluation of Pareto Solution Sets and Selection of Design Schemes

The direct output of multi-objective optimization algorithms typically presents a set of Pareto-optimal solutions, where each solution outperforms others in at least one objective without being inferior to all others simultaneously. This solution set constitutes a "optimal trade-off surface" rather than a single definitive answer. Therefore, systematically evaluating the Pareto solution set and selecting the final design is a critical decision-making process. The primary task involves analyzing the quality of the solution set, with common metrics including solution distribution uniformity, breadth, and frontier convergence. An ideal solution set should uniformly and extensively cover the entire Pareto frontier, providing decision-makers with a comprehensive performance trade-off map. Subsequently, the selection process must transition from pure mathematical optimization to a decision-making phase incorporating engineering judgment. This requires introducing higher-level decision preference information. Simple techniques like inflection point methods can help identify regions with the greatest marginal benefits for performance improvement, while multi-criteria decision analysis methods such as Analytic Hierarchy Process (AHP) or TOPSIS allow decision-makers to assign different subjective weights or priorities to various performance objectives based on practical application scenarios, thereby locating the most comprehensive solution on the compromise surface. Sometimes, specific application requirements (e.g., a certain natural frequency must exceed a specific threshold) can serve as post-screening conditions to directly filter out unsatisfactory solutions. The final selection of the optimal solution often combines quantitative calculations with qualitative judgments, respecting the objective physical laws revealed by the optimization process while integrating the designer's experience and deep understanding of the task requirements. This process signifies the evolution of multi-objective optimization from a computational tool to a complete closed-loop system supporting engineering decision-making.

4. Framework for Comprehensive Performance Analysis of Robotic Arms

4.1 Evaluation of Static Stiffness and Strength Properties

In the comprehensive performance analysis of lightweight robotic arms, static mechanical properties form the fundamental basis for their operational reliability. Evaluating stiffness and strength requires more than simply comparing yield limits from material manuals—it involves a systematic assessment of a structure's inherent resistance to deformation and failure under typical and extreme loads. Stiffness evaluation focuses on structural flexibility, specifically the elastic deformation caused by external forces, which directly impacts the positioning accuracy of the robotic arm's end effector. Beyond monitoring static pose deviations under maximum loads, we must also examine the uniformity of stiffness distribution across the workspace, as excessive local flexibility may become a weak link in the precision chain. Strength evaluation delves into material-level analysis, identifying potential failure risks through detailed stress analysis. This process must fully account for multi-axis stress states and possible stress concentration effects, with safety margins assessed using appropriate failure criteria (e.g., von Mises criterion). However, lightweight designs featuring thin walls and hollow structures may face structural instability challenges earlier, necessitating the integration of stability analysis—particularly local buckling analysis—into the strength evaluation framework. Ultimately, a complete static evaluation system aims to verify whether lightweight structures can provide a sufficiently robust geometric platform for precise motion while ensuring safety.

4.2 Dynamic Characteristics and Vibration Response Analysis

The dynamic characteristics of robotic arms are fundamental to achieving high-speed and high-precision motion. Lightweight design fundamentally alters the system's mass distribution and stiffness properties, exerting complex influences on its dynamic behavior. The primary objective of dynamic analysis is to identify the system's inherent characteristics—specifically, obtaining natural frequencies and corresponding vibration modes through modal analysis. The key lies in ensuring the lowest natural frequency remains far from the robotic arm's primary operational frequency range, thereby preventing resonance-induced amplitude amplification that could lead to precision loss or structural damage. However, simply avoiding resonance points is insufficient. Vibration response analysis further examines the structural behavior under time-varying loads or motion excitation. For instance, acceleration shocks generated during joint activation/deactivation or trajectory inflection points may trigger transient responses, and analyzing this decay process is critical for evaluating settling time. Moreover, lightweight structures often exhibit weaker damping characteristics, resulting in slower decay of free vibrations, which can significantly impact the precision of continuous path motion. Therefore, a comprehensive dynamic analysis framework must integrate modal parameters, forced responses, and energy decay characteristics—not only to predict potential issues but also to provide direct evidence for subsequent structural modifications or active control strategies to suppress harmful vibrations.

4.3 Synergistic Evaluation System for Energy Efficiency and Motion Accuracy

The ultimate value of lightweight design must be demonstrated through the overall efficiency of robotic arms performing specific tasks, which has led to the development of a synergistic evaluation system for energy efficiency and motion accuracy. This system transcends isolated assessments of individual metrics, focusing instead on the dynamic interactions and trade-offs between the two during execution. Energy efficiency is typically measured by the total energy or average power consumed to complete a specific task trajectory. Lightweight design reduces the mass of moving components, directly decreasing the inertial forces required for acceleration, thereby theoretically establishing a foundation for improving energy efficiency. However, maintaining precision poses challenges: potential reductions in structural stiffness may trigger greater elastic deformation, and to compensate for such deformation or suppress resulting vibrations, control systems may need to apply additional, sometimes energy-consuming, corrective torques. Therefore, the core of synergistic evaluation lies in creating a unified assessment scenario—for example, having robotic arms replicate the same precision trajectory at different speeds while observing changes in energy consumption, or testing optimal repeat positioning accuracy and trajectory tracking precision under constrained energy consumption. Such evaluations reveal the true benefits of lightweight design at the system level, compelling designers to think holistically—whether weight reduction genuinely translates to higher performance or lower operational costs. Only through this synergistic perspective can we determine whether lightweight optimization merely creates a lighter component or truly shapes a superior mechatronic system.

5. Conclusion

This study systematically addresses the structural design and performance optimization of lightweight robotic arms, presenting a comprehensive framework for multi-objective optimization. By integrating structural modeling, multi-objective optimization algorithms, and comprehensive performance analysis, we establish a design approach that effectively balances multiple objectives including mass, stiffness, and dynamic response. This provides a solution for robotic arm lightweighting that combines theoretical rigor with practical engineering applicability. The research not only deepens our understanding of multi-performance conflicts and synergistic mechanisms in lightweight design, but also lays a methodological foundation for future structural innovations tailored to complex operational scenarios. Future work should further consider the impact of uncertainties and nonlinear factors to drive the development of lightweight robotic arms toward higher performance and enhanced adaptability.

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