Research on Structure Design and Assembly Performance Optimization of Robotic Arm Based on Modular Architecture

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Abstract: This study investigates the synergistic optimization of modular structural design and assembly performance in robotic arms. By systematically elucidating the fundamental principles, classification framework, and interface standardization methodologies of modular design, we establish a comprehensive methodology spanning structural design to assembly integration. The research analyzes optimization strategies for critical processes including precision control, sequence planning, and quality stability during assembly, while proposing a corresponding integrated evaluation system. The study reveals the intrinsic influence mechanism between design parameters and assembly processes, establishing a structure-process collaborative design framework to achieve comprehensive balance among multiple objectives such as module independence, system integrity, lightweight design, and assembly efficiency. Results demonstrate that through lifecycle-wide collaborative optimization, modular robotic arms can significantly enhance reconfigurability, assembly efficiency, and maintenance convenience while maintaining functional and precision requirements. This provides theoretical basis and practical pathways for developing high-performance robotic arm systems tailored to flexible manufacturing demands.

Keywords: Modular Structural Design; Assembly Performance Optimization; Collaborative Optimization Mechanism; Lightweight Design; Precision Control

1. Introduction

With the rapid advancement of intelligent manufacturing and flexible production systems, robotic arms as core execution units have seen their design flexibility, reconfigurability, and assembly efficiency become key performance indicators. Traditional monolithic robotic arm structures face challenges such as lengthy design cycles, maintenance difficulties, and limited adaptability, making them inadequate for modern industrial demands of rapid response and customized production. The introduction of modular design concepts has provided crucial direction for structural innovation in robotic arms. By decomposing complex systems into independent functional modules, this approach not only significantly enhances design scalability and maintainability but also creates new research opportunities for optimizing assembly performance. This paper systematically explores design principles and methodologies for modular robotic arm structures, while conducting in-depth analysis of assembly performance optimization pathways. These findings aim to provide theoretical foundations and practical references for developing efficient, reliable, and easily deployable robotic arm systems.

2. Methodology for Modular Structure Design of Robotic Arms

2.1 Basic Principles and Classification System of Modular Design

The core philosophy of modular design lies in managing system complexity through decoupling and recombination, with its fundamental principles rooted in functional independence and structural separability. Specifically, this approach treats traditional integrated robotic arm structures as systems composed of multiple subunits with clearly defined functional boundaries. These subunits, referred to as modules, are defined and encapsulated based on their core functions, such as drive modules, transmission modules, actuation modules, and control modules. Functional independence means that internal implementations and modifications of individual modules should minimize interference with other modules, thereby establishing the foundation for system maintainability and upgrade potential. Based on different classification criteria, the modular taxonomy exhibits multi-dimensional characteristics. From a functional perspective, it can be divided into power modules, motion modules, and perception modules; from a structural hierarchy perspective, it can be categorized into joint-level modules, link-level modules, and even end-effector-level modules. Additionally, according to the degree of replaceability and reusability, modules can be further distinguished into standard universal modules and specialized custom modules. This multi-level, multi-standard classification system is not isolated from one another but collectively serves a common goal: providing designers with a clear architectural blueprint that enables flexible selection, combination, and replacement of modules while ensuring system functional integrity, thus efficiently constructing robotic arm configurations tailored to various task requirements. The granularity of classification directly impacts the sophistication and flexibility of subsequent designs, serving as the logical starting point for the entire methodology [1].

2.2 Interface Standardization and Compatibility Design of Key Functional Modules

After establishing the division and classification of modules, ensuring their effective integration into a coordinated operational system relies on precise and standardized interface design. Interfaces serve as boundaries and channels for material, energy, and information exchange between modules, with standardization acting as the critical bridge that bridges theoretical modular design to practical engineering implementation. Interface standardization does not pursue a single physical form but aims to establish unified constraints and protocols across mechanical connections, power transmission, electrical communication, and data interaction. For instance, at the mechanical interface level, specifications must define the geometric shape of connection surfaces, fit tolerances, fastening methods, and load transfer paths to ensure precision, rigidity, and reliability in module assembly. At the information interface level, unified data formats, communication protocols, and instruction sets must be defined to ensure seamless flow of control commands and status feedback. Compatibility design extends and complements standardization by emphasizing interoperability between modules with different origins, versions, or performance characteristics within established standards. This requires designers to focus not only on uniform interface forms but also on ensuring functional semantic consistency behind the interfaces. Well-designed compatibility solutions can significantly expand the range of available modules, reduce system dependence on specific suppliers, and enable users to optimize and combine modules from broader libraries based on cost, performance, or usability considerations, thereby fully unleashing the flexibility and economic benefits of modular architecture [2].

2.3 Structural Coupling and Lightweight Synergistic Optimization of Modules

Modular design introduces inherent challenges through structural coupling between modules while offering flexibility. Coupling describes the degree of mutual dependence and influence between modules. Excessive structural coupling erodes module independence, making modifications or replacements of any module prone to unpredictable chain reactions that contradict the original intent of modularity. Therefore, designers must carefully manage and optimize these coupling relationships. The goal of optimization isn't to completely eliminate coupling, but to restrict it to clearly defined, controllable, and minimized interfaces while ensuring overall system performance (e.g., stiffness, precision, dynamic characteristics). This typically involves meticulous structural design at module boundaries, such as using localized reinforcements or flexible hinges to isolate or absorb partial mutual influences. Meanwhile, lightweighting-a universal pursuit in modern equipment design-poses unique collaborative optimization demands in modular contexts. Lightweighting cannot be isolated within individual modules, as this may lead to excessive weakening of local stiffness, thereby affecting joint performance and even the stability of the entire structure. Lightweighting must be balanced at the system level, analyzing how changes in mass distribution impact joint loads, system dynamics, and vibration characteristics. The ideal design approach seeks a balance: By employing material selection, topology optimization, and biomimetic structures, it reduces weight while meeting each module's functional and strength requirements. Simultaneously, optimizing inter-module connections and mass distribution ensures the integrated system achieves optimal trade-offs between dynamic performance and structural coupling, thereby realizing a win-win scenario for both module independence and overall system performance [3].

3. Optimization Strategy and Evaluation System of Assembly Performance

3.1 Analysis of Module Connection and Positioning Accuracy Based on Assembly Process

The foundation of assembly performance lies in the feasibility and precision of inter-module connections, which constitutes the primary technical link in transforming design blueprints into physical entities. The connection process is not merely a simple physical assembly, but a complex system behavior involving multiple precision transmissions and error control. Positioning accuracy analysis requires penetrating surface-level observations to investigate the root causes and transmission paths of errors. These errors may originate from geometric deviations during module manufacturing, microscopic displacements at connection interfaces due to fit tolerances, or additional stresses introduced during assembly caused by clamping forces, temperature variations, or operational sequence. These error elements do not exist independently-they propagate, accumulate, and amplify progressively through the assembly chain, ultimately profoundly affecting the absolute pose accuracy of end-effectors and system repeatability. Therefore, analysis must cover everything from individual module manufacturing tolerances, through the fit characteristics of connection pairs, to the spatial error model of the entire serial mechanism. The core optimization strategy involves predicting and allocating these errors during the design phase, adopting error-compensating structures at critical interfaces (e.g., self-centering pins or flexible adaptive washers), and establishing strict assembly process specifications to constrain operational variables. The goal is to ensure, within economically viable manufacturing costs, that the static and dynamic precision of the modularized robotic arm meets predetermined performance thresholds through systematic precision control, enabling the integration of decentralized manufacturing modules into a high-precision unified system [4].

3.2 Assembly Sequence Planning and Efficiency Optimization with Process Constraints

Assembly sequence planning aims to identify the most efficient assembly path among multiple feasible module sequences under specific constraints. This is not a simple sequencing problem but a complex decision-making process influenced by multiple practical constraints. These constraints form the planning's action space: heavy or precision modules must be prioritized or installed last to avoid interference or risks; specific functional tests must be conducted immediately after completing a particular assembly phase; the availability of specialized tooling and fixtures limits parallel operations; operator accessibility and ergonomic considerations directly impact assembly fluidity and safety. Efficiency optimization involves balancing time, cost, and resources within this constrained space. While the objective function typically aims to reduce total assembly time, its implementation requires multi-faceted approaches: minimizing unnecessary component flipping, redirection, or temporary fixation through optimized sequences; reducing main-line assembly procedures via pre-assembly of modules; and preventing difficult-to-manage transitional states by analyzing process stability and balance. Effective sequence planning is essentially predictive design, requiring the integration of assembly process perspectives into structural design phases. This ensures that module division and interface design inherently incorporate assembly-friendly features, thereby establishing foundations for improving assembly fluidity, reducing reliance on highly skilled workers, and enabling large-scale efficient production from the outset [5].

3.3 Comprehensive Evaluation Index of Assembly Quality Stability and Maintainability

A comprehensive evaluation of assembly performance must extend beyond the transient state of initial assembly to encompass quality stability throughout the entire lifecycle and the convenience of subsequent maintenance. This requires an integrated evaluation framework. Assembly quality stability focuses on the ability of assemblies to maintain critical performance parameters such as connection stiffness, positioning accuracy, and vibration characteristics after enduring transportation vibrations, load variations, environmental fluctuations, and long-term use. Evaluation metrics should reflect the anti-relaxation properties of connection points, the effectiveness of anti-micro-motion wear designs, and the robustness of overall structural resistance to degradation. Maintainability evaluation centers on the user-friendliness of assembly structures during system maintenance, troubleshooting, or upgrades. This involves quantifiable dimensions such as the ease of diagnosing and isolating faulty modules, the average time and specialized tools required for module disassembly, the probability of damage to adjacent intact modules during disassembly, and the complexity of recalibration and functional restoration after module replacement. A well-designed evaluation system should organically integrate the "static quality" and "dynamic durability" of assemblies with the "convenience" of usage and the "economy" of maintenance. It guides designers not only to pursue efficiency and precision in assembly processes but also to embed long-term reliability and easy maintenance into modular architectures, thereby maximizing the comprehensive benefits of products throughout their entire lifecycle.

4. Synergistic Optimization Mechanism of Modular Design and Assembly Performance

4.1 Mechanism Analysis of Design Parameters on Assembly Process

In modular design, selecting any specific parameter is never merely about functional implementation of individual modules. The deeper significance lies in how these parameters essentially predefine boundary conditions and operational paths for subsequent assembly processes, creating a profound causal relationship between them. Take tolerance design for module interfaces as an example: while overly tight tolerances may enhance static precision after connection, they inevitably impose stringent requirements on individual module manufacturing. This could lead to higher alignment skills, increased press force, or additional adjustment shims during assembly, resulting in a sluggish and uncertain process. Conversely, excessively loose tolerances, though reducing manufacturing difficulty, might shift precision control entirely to the assembly stage, forcing the adoption of expensive online measurement and active compensation technologies-thus increasing process complexity and costs. Similar mechanisms are ubiquitous: the geometric shape and center of gravity of module housings determine their stable posture and clamping schemes on assembly line pallets; composite material joints used for lightweighting may require unconventional fastening methods; even screw hole orientations and operational space dimensions directly affect the accessibility of automated assembly tools and manual assembly efficiency. These impacts aren't unidirectionally linear but form a complex network. A design decision aimed at optimizing a single performance metric may trigger a chain reaction across the assembly chain, sometimes even causing unpredictable process obstacles in other stages. Therefore, a thorough understanding of how design parameters permeate and shape every detail of assembly processes through physical geometry, mechanical properties, and user-friendliness is the cognitive prerequisite for achieving higher-level collaborative optimization.

4.2 Structure-Process Co-Design Framework for Assembly Efficiency

To break the traditionally sequential and fragmented relationship between design and assembly processes, it is essential to establish a collaborative design framework that deeply integrates both. The core concept of this framework is to systematically and proactively incorporate assembly considerations from traditional downstream manufacturing stages into upstream conceptual and detailed design phases, achieving parallel progression in time and interactive exchange in information. This framework can be viewed as an organic multi-stage, multi-loop iterative process. During the initial design phase, structural engineers and process engineers must jointly define assembly-oriented design principles based on product functionality and modular division schemes. These principles will be concretized into structured requirements such as module independence, interface symmetry, error-proof design, and prioritized use of standard components, guiding design evolution toward easier assembly from the source. In the detailed design phase, collaboration becomes more specific: virtual assembly simulations based on 3D digital models can preemptively expose potential physical interference, tool accessibility issues, or unreasonable operation sequences;

while early involvement in assembly sequence planning and time estimation provides quantifiable efficiency evaluation criteria for comparing different structural solutions. This collaboration is not a one-time check but a dynamic dialogue throughout the process. Process constraint feedback drives structural design adjustments, while innovative structural solutions may also give rise to more creative assembly methods. The effective operation of the framework depends on an integrated platform that supports cross-domain data exchange and knowledge sharing. Its final output is not only a set of manufacturable structural drawings but also an executable, detailed assembly process plan closely tied to the design depth, thereby achieving the optimal solution for efficiency at its root.

4.3 Trade-off and Optimization Path of the Overall Performance of the Modular System

The ultimate optimization goal of modular systems is not to pursue the extreme of a single performance metric, but to achieve a sophisticated, holistic balance among multiple interconnected and even conflicting system attributes. This trade-off of overall performance essentially involves finding an acceptable Pareto optimal solution set in a high-dimensional space composed of multi-dimensional objectives. Key dimensions requiring trade-offs include: module independence versus system integrity, functional reconfigurability versus connection reliability, extreme lightweight design versus necessary structural rigidity, excellent assembly convenience versus outstanding operational precision, low manufacturing costs versus long-term maintainability, and so on. These objectives often exhibit competing relationships where one gains at the expense of another. For instance, overemphasizing module independence and rapid replacement may compromise the rigidity and dynamic performance of connection interfaces, while pursuing extreme motion accuracy through integrated design thinking could completely stifle modular flexibility. Therefore, the optimization path inevitably becomes an iterative optimization process under multi-objective and multi-constraint conditions. It typically begins with clearly defining the system's core mission and constraints, followed by establishing mathematical models or evaluation functions that quantitatively or qualitatively describe the performance of each dimension. Through parametric design, sensitivity analysis, and multi-objective optimization algorithms, designers can explore vast design spaces and observe how different design variable combinations affect the Pareto front of various performance metrics. This process is by no means an overnight achievement. It requires designers to leverage their professional expertise and engineering judgment to select the optimal solution from the numerous non-competitive alternatives generated by algorithms. The chosen solution must best align with the product positioning, lifecycle costs, and market demands, thereby guiding the modular system toward the direction of optimal comprehensive performance.

5. Conclusion

This study systematically investigates the modular structural design and assembly performance optimization of robotic arms, establishing a comprehensive methodology encompassing module segmentation, interface design, and collaborative assembly optimization. The research demonstrates that modular architecture not only enhances the flexibility and adaptability of robotic arm design but also provides a critical foundation for achieving efficient and precise assembly processes. By deeply integrating structural design with assembly techniques, the system can maintain rigidity and precision while significantly reducing assembly complexity and time costs, thereby improving the reliability and cost-effectiveness of robotic arms in practical applications. Future research may further explore the application of intelligent algorithms in self-adaptive module reconfiguration and real-time assembly optimization, driving robotic arm systems toward higher levels of autonomy and intelligence.

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