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A Review of the Research Status and Development Trends of Dexterous Hand Technology

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ABSTRACT

Dexterous hands are pivotal for enabling advanced robotic manipulation. This review synthesizes recent advances in structural design, actuation, sensing, and control algorithms. Structurally, trends shift from serial/parallel mechanisms toward hybrid rigid-soft biomimetic designs. Actuation leverages electromagnetic, fluidic, and smart-material systems for improved precision and compliance. Multi-modal sensing—integrating force, position, tactile, and vision data—enhances environmental awareness. Control algorithms evolve from classical PID to intelligent strategies like neural networks and reinforcement learning for adaptive manipulation. Persistent challenges include flexibility-stability trade-offs, sensing latency, and high costs. Future directions emphasize AI integration, lightweight designs, and improved reliability for complex tasks in industrial and biomedical applications.

KEYWORDS

Dexterous Hand; Robotic Manipulation; Actuation and Sensing; Intelligent Control; Biomimetic Design.

1. INTRODUCTION

As a core end effector enabling robots to interact precisely with the physical environment, the importance of dexterous hands has become increasingly prominent with the rapid development of robot technology. Driven by emerging concepts such as "embodied intelligence," dexterous hands have become a key component in breaking through the application bottlenecks of robot technology and empowering a wide range of industries. Research on dexterous hands involves not only the mechanical structure design and optimization of drive methods but also key technical fields such as sensing technology and control algorithms. By simulating the movement characteristics and perception abilities of human hands, dexterous hands have shown broad application prospects in fields such as industrial manufacturing, medical assistance, and service robots[1].

This paper aims to systematically review the current research status of dexterous hand technology in key areas such as drive, perception, and control, to conduct an in-depth analysis of the challenges it faces, and to look forward to its future development trends. By summarizing and comparing domestic and international research results, this paper will provide a comprehensive reference framework for researchers and technology developers in this field to promote further innovation and development of dexterous hand technology. The development history of dexterous hand technology shows that from early simple prosthetic designs to modern highly bionic intelligent dexterous hands, its research has gone through multiple stages of evolution and is gradually moving towards the direction of having compliant operation functions and multimodal perception capabilities[1].

2. CURRENT RESEARCH STATUS OF DEXTEROUS HAND TECHNOLOGY

2.1. Structural Design

The structural design of dexterous hands forms the basis for their fine manipulation and profoundly affects their motion performance and potential for engineering applications. An excellent structural design not only needs to ensure high flexibility and multi-degree-of-freedom motion capabilities but also has to meet multiple requirements such as load capacity, precision, and environmental adaptability to cope with the challenges of diverse application scenarios like industrial assembly, service robots, and space operations.

In the development history of dexterous hands, the serial structure, as a traditional configuration, has been widely used in early research. This type of structure draws on the design concept of industrial manipulators and is favored for its simple configuration, clear kinematic model, and convenient control. Serial fingers are usually composed of multiple joints connected by links in sequence, forming an open-chain motion structure (as shown in Figure 1-for the Shadow Dexterous Hand). The joint modularization and drive arrangement of this structure are relatively straightforward, making it easy to achieve multi-degree-of-freedom motion. However, as an open-chain system, the serial mechanism has the drawback that the end-point error increases with the number of joints, limiting the positioning accuracy. Moreover, it has inherent shortcomings in rigidity and load capacity, making it difficult to meet the requirements of high-load or high-precision operations. Therefore, although serial structure dexterous hands still have applications in theoretical research and experimental verification, they face significant limitations in actual industrial environments[2].

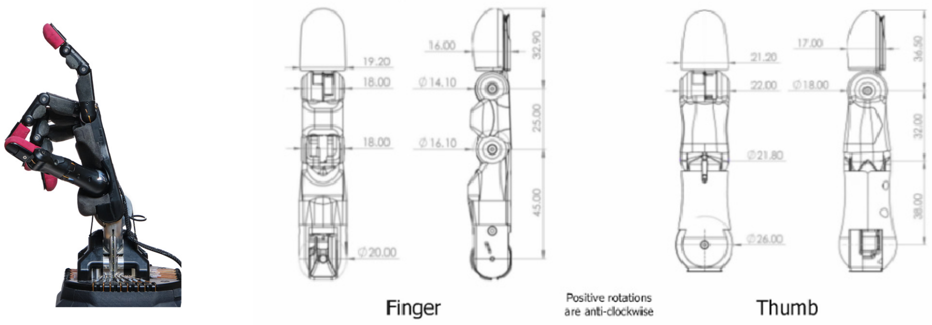

Figure 1. Shadow Hand with Serial Architecture

To compensate for the shortcomings of serial structures, parallel structure dexterous hands have gradually become a research focus. Parallel mechanisms, with their closed-chain characteristics, offer high stiffness, high precision, and superior load-bearing capabilities, making them particularly suitable for precision operations and strong, stable grasping. These mechanisms typically consist of a moving platform connected to a fixed platform through multiple independent branches, forming a closed motion loop, which effectively suppresses error accumulation and enhances overall load stiffness. The ILDA hand, which adopts a parallel structure, is illustrated in Figure 2. Scholars such as Fang Yuefa have proposed a finger unit based on a three-degree-of-freedom parallel mechanism. Through systematic optimization of its kinematic performance using configuration synthesis methods and the design of a matching palm structure, the operational dexterity and task space coverage of the entire hand have been significantly enhanced[3]. Gong Junshan et al. further optimized the load-bearing characteristics of this type of finger and verified the continuity of its workspace and grasping adaptability based on the ADAMS simulation platform, demonstrating the potential of parallel configurations in high-end industrial applications[4].

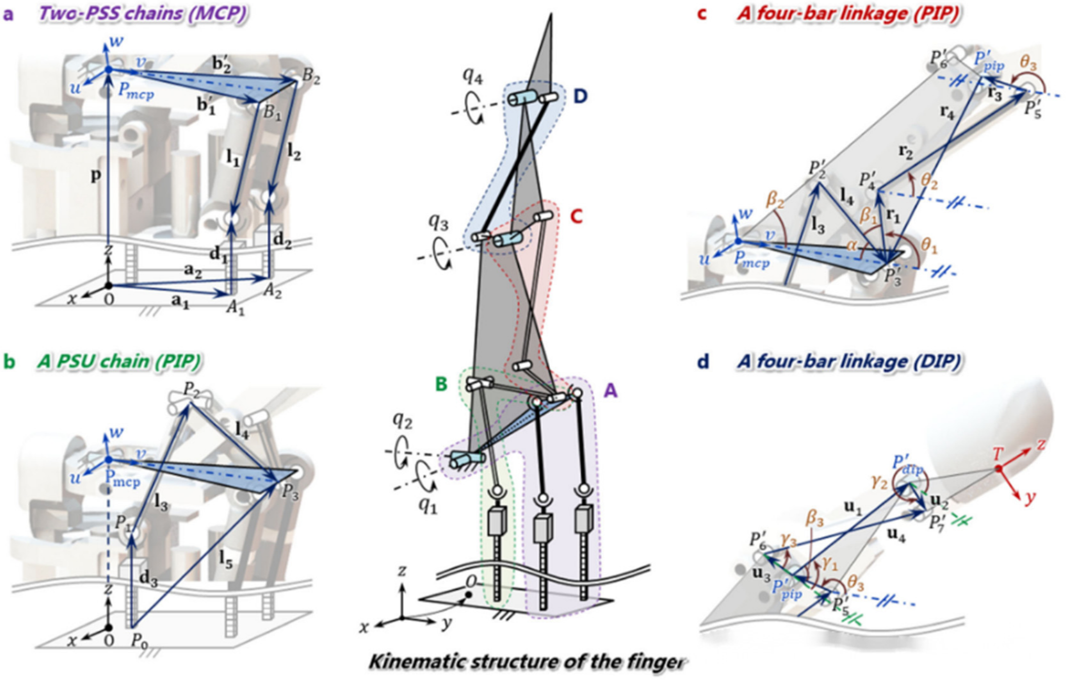

Figure 2. ILDA Hand with Parallel Architecture

In recent years, research frontiers in dexterous hands have focused on novel hybrid and biomimetic structures. These designs move beyond traditional purely rigid or fully soft paradigms by integrating multiple actuation methods, materials, and mechanical architectures, aiming to synergistically enhance adaptability, energy efficiency, safety, and manipulation capabilities. The core idea is to mimic the rigid-soft synergy found in biological systems—such as the human hand—where flexible tissues are attached to rigid skeletal structures, enabling both precise force transmission and safe physical interaction. A representative example of this concept is the Harvard-MIT "Programmable Rigid-Soft Hybrid Dexterous Hand"[5], As shown in Fig. 3. It employs a hybrid actuation system combining shape memory alloys (SMA) and micro-motors: SMA mimics muscle contraction to provide compliant motion, while micro-motors adjust and maintain joint stiffness. This design effectively resolves the conflict between the low load capacity of fully soft hands and the insufficient safety of purely rigid manipulators.

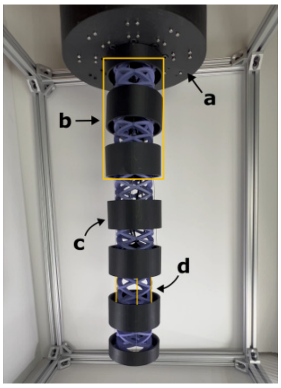

Figure 3. Harvard-MIT Hybrid Rigid-Soft Hand

To systematically summarize the characteristics of different structural types, Figure 4 provides a visual overview and classification of the current research status in dexterous hand structural design across three dimensions: structural categories, performance attributes, and typical applications.

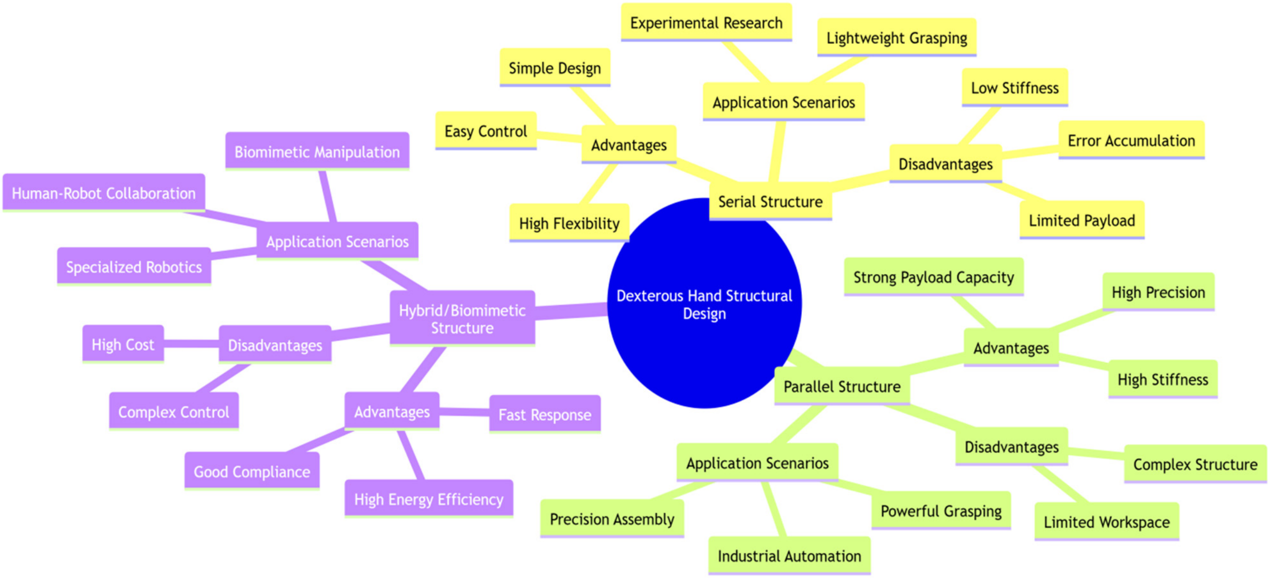

Figure 4. Structural Performance of the Dexterous Hand

2.2. Transmission Methods

The transmission mechanism, serving as a critical link between the actuator and the end-effector, directly influences the power transmission efficiency, motion accuracy, and overall structural layout of dexterous hands. Common transmission methods primarily include gear transmission, belt transmission, cable (tendon) transmission, and linkage mechanisms.The advantages and disadvantages of each transmission method are shown in Fig. 5.

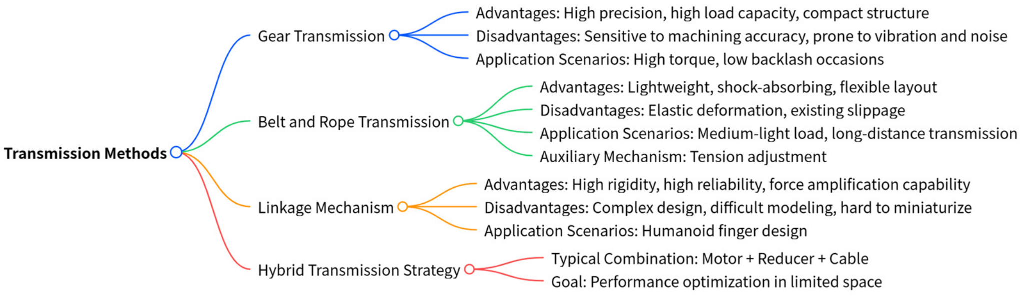

Figure 5. Mind Map of Dexterous Hand Drive Mechanism Comparison

Gear transmission is widely used in various high-precision dexterous hands due to its notable advantages such as high transmission accuracy, strong load capacity, and compact structure. It is particularly suitable for applications requiring high torque output and low backlash. For instance, the PASA-GB Hand[6], developed by Tsinghua University, employs a hybrid gear-belt transmission mechanism that integrates gear and belt drives to enhance parallel adaptive grasping performance, as illustrated in Figure 6. The meshing of gear pairs ensures stable and reliable power transmission but also imposes extremely high requirements on part machining and assembly precision. Under high-speed operating conditions, variations in meshing stiffness and tooth surface impact can easily induce vibration and noise, adversely affecting the system's dynamic performance. Therefore, in high-performance dexterous hand designs, gear transmission often must be combined with high-precision manufacturing processes, lubrication control, and vibration damping measures to fully realize its advantages.

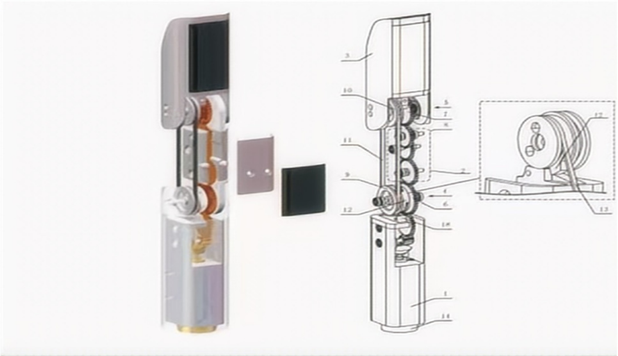

Figure 6. PASA-GB Hand with Gear Transmission

In comparison, belt and tendon transmissions offer unique value in dexterous hand applications due to their lightweight nature, simple structure, and inherent buffering and vibration-damping properties. A representative example is the BRL/Pisa/IIT SoftHand [7], a tendon-driven anthropomorphic hand powered by a single motor, which incorporates linkages and gear pairs to balance structural reliability and grasping performance through enhanced flexibility and adaptability, as shown in the accompanying figure.7. Such flexible transmission methods not only enable long-distance power transmission under light to moderate loads but also significantly reduce the rotational inertia of joint-moving components, thereby improving the system’s dynamic response and control sensitivity. However, belt and tendon transmissions are prone to elastic deformation and slippage during operation, which can diminish transmission accuracy and compromise the positioning performance of the end-effector. Consequently, tensioning mechanisms or pre-tightening strategies are often employed in engineering applications to ensure transmission stability and long-term reliability.

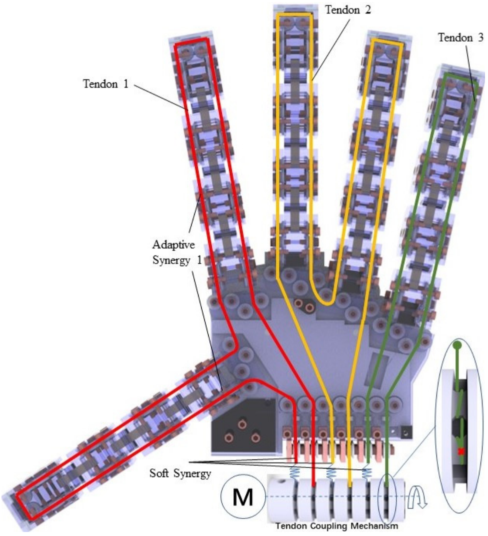

Figure 7. Tendon-Driven BRL/Pisa/IIT SoftHand

Furthermore, linkage mechanisms are widely used in the design of finger joints for humanoid dexterous hands due to their unique configuration capabilities, which enable complex motion trajectory generation and mechanical amplification effects. The MCR-Hand II [8], for instance, employs a hybrid system combining linkages and tendon (cable) drives. This compact design achieves high dexterity by integrating linkages and cables to simulate human hand movements, as illustrated in the figure.8. Such mechanisms not only offer high stiffness and reliability but also allow their kinematic characteristics to be optimized for adaptability across various working conditions through parameter tuning. However, linkage systems often involve complex structures, pose challenges in kinematic and dynamic modeling, and face spatial layout and integration difficulties in applications requiring miniaturization and high levels of integration.

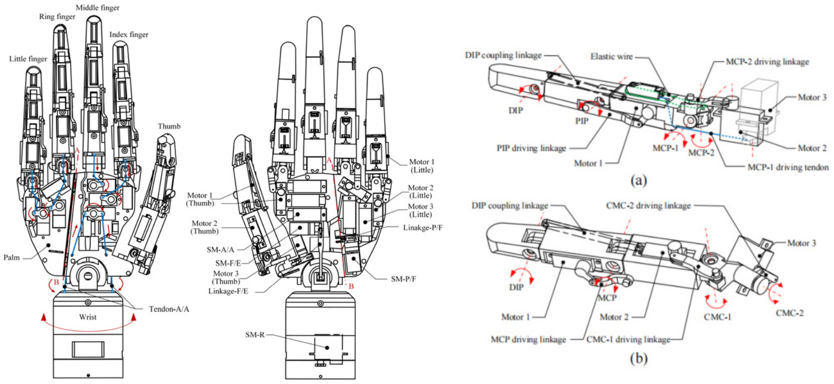

Figure 8. MCR-Hand II with Linkage Drive

To balance transmission efficiency, motion accuracy, and structural adaptability within limited space, contemporary dexterous hand systems widely adopt hybrid transmission strategies that integrate multiple drive methods. A typical solution is the composite “motor + reducer + cable” transmission mode, which maintains high torque output and a compact structure while leveraging flexible transmission to reduce joint inertia and enhance control performance. This approach achieves optimal power transfer and motion performance. The design concept of such multi-modal transmission systems has gradually become a critical direction in the development of new-generation high-performance dexterous hands.

2.3. Actuation Methods

The actuation system serves as the core executive unit of a dexterous hand, directly determining its operational accuracy, load capacity, and overall applicability. Mainstream actuation methods currently include traditional electromagnetic drives, fluid power systems (hydraulic/pneumatic), and emerging smart material-based technologies. Each strategy exhibits distinct performance characteristics and complementary advantages in practical applications; The specific performance is shown in Table 1.

Table 1. Summary of Dexterous Hand Actuation Performance

Actuation Method	Key Advantages	Main Limitations	Typical Applications
Motor Actuation	high control precision fast response easy integration	Low power/weight Overheats under load	Precision assembly laboratory bionic hands service robots
Fluid Power Actuation	high output force high power density good impact resistance	Complex system High sealing demand requires fluid source	Heavy-duty grasping large manipulators Special environments
Smart Material Actuation	lightweight quiet operation good biocompatibility	Low energy efficiency slow response complex control models	safe collaboration Rehabilitation devices biomimetic robots

Electromagnetic drives dominate dexterous hand design due to their high control precision, fast response, and ease of miniaturization and integration. Among these, DC servo motors are widely employed in high-precision position servo systems owing to their excellent speed regulation and torque control capabilities. Stepper motors, with their simple open-loop control and lower cost, are adopted in cost-sensitive applications. However, electromagnetic drives suffer from inherent drawbacks such as low power-to-weight ratios and significant heat generation under heavy loads, limiting their use in extreme power-density scenarios like space robotics and exoskeletons. To address these issues, ongoing research focuses on integrating miniature reducers, optimizing magnetic circuits, and improving thermal management strategies to enhance overall performance [9].

Fluid power systems excel in high power density and large force output, making them particularly suitable for medium-to-large dexterous hands and heavy-duty tasks. Hydraulic drives offer extremely high force output and rigidity, commonly applied in industrial heavy grasping and assembly operations. Pneumatic drives, characterized by clean operation, relatively simple system structures, and controllable costs, are frequently used in clean environments such as food and pharmaceutical industries. However, fluid power systems rely on auxiliary components including pumps, valves, and pipelines, resulting in overall system complexity and large volume. Challenges in maintaining motion accuracy and sealing reliability further limit their application in highly integrated and lightweight dexterous hands [10,11].

In recent years, smart material-based actuation technologies—such as shape memory alloys (SMA), piezoelectric ceramics, dielectric elastomer actuators (DEA), and pneumatic artificial muscles—have made remarkable progress, offering innovative pathways for dexterous hand actuation. These methods provide prominent advantages including compact structure, quiet operation, and inherent compliance, making them especially suitable for close human-robot interaction scenarios such as rehabilitation robots and collaborative manipulators. Nevertheless, smart material actuators still face challenges such as slow dynamic response, low energy efficiency, significant hysteresis nonlinearity, and complex control modeling. Most research remains at the laboratory stage, requiring further breakthroughs to enable engineering applications [12].

To comprehensively summarize and compare the characteristics of the above actuation technologies, this study presents a mind map in Table 1, systematically contrasting them across four dimensions: actuation type, key advantages, main limitations, and typical applications, thereby supporting subsequent research and engineering selection.

2.4. Sensing Technologies

Sensing technologies constitute a fundamental enabler for dexterous hands to achieve fine manipulation and intelligent perception, and their level of development directly determines the adaptability of the hand to dynamic environments as well as the efficiency of task execution. Among various sensing modalities, force/torque sensors play a pivotal role. By continuously monitoring the contact forces and torques between the fingers and the target object, they not only prevent damage caused by excessive gripping forces but also reduce the risk of slippage due to insufficient grasping, thereby ensuring operational stability and safety. Currently, strain gauge–based and capacitive sensors are the most widely employed types of force/torque sensors, whose accuracy, response speed, and long-term stability have been extensively validated in both industrial and research applications [13].

Position sensors are another essential component, primarily responsible for detecting the positions and motion states of finger joints, thereby providing critical data for kinematic modeling and control algorithms. Commonly used sensors such as encoders and potentiometers are recognized for their high resolution and reliability, which makes them widely adopted in the design of multi-joint dexterous hands [14].

In pursuit of multimodal perception that more closely approximates the human hand, researchers have increasingly integrated tactile and visual sensors in recent years[15-17]. Tactile sensors enable the detection of surface roughness, hardness, and slip tendencies of grasped objects, offering valuable feedback for adaptive grasping in dynamic environments. Visual sensors, on the other hand, leverage advanced image processing and three-dimensional reconstruction techniques to acquire information on the pose, geometry, and texture of objects, thereby substantially enhancing the hand's operational intelligence and environmental perception in complex tasks.

Despite these advancements, current sensing technologies still fall short when compared with the human hand. In particular, their ability to achieve comprehensive perception remains limited, as existing sensors cannot yet match the sensitivity and flexibility of the human skin–nervous system. This limitation constrains the potential of dexterous hands in high-precision assembly, surgical operations, and human–robot interaction [18]. Consequently, future research in sensing technologies should focus on multimodal data fusion, miniaturization of sensors, and intelligent signal processing, in order to drive dexterous hands toward higher levels of performance.

To provide a systematic overview and comparison of the aforementioned sensing modalities, a conceptual mind map is illustrated in Figure 9, which summarizes their respective characteristics and supports subsequent research and engineering design choices.

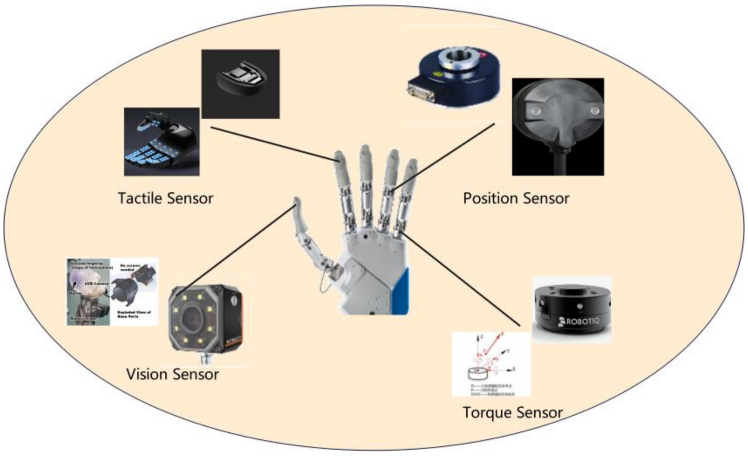

Figure 9. Classification of Sensors for Dexterous Hands

2.5. Control Algorithms

Control algorithms constitute the core technology underpinning the execution of complex manipulation tasks by dexterous hands. Their design and optimization directly determine the system's dynamic response, operational precision, and overall level of intelligence. Early studies predominantly adopted conventional methods such as proportional–integral–derivative (PID) control and fuzzy control. These approaches are characterized by simplicity of implementation, computational efficiency, and strong engineering applicability, enabling dexterous hands to achieve basic motion control and grasp stability to a certain extent. Nevertheless, due to their inherent structural limitations, such algorithms exhibit significant deficiencies in handling scenarios involving strong nonlinearity, high coupling, and environmental uncertainty, thereby restricting their capacity to achieve high performance and robustness [9].

To overcome the limitations of traditional methods, researchers have increasingly integrated intelligent control algorithms into dexterous hand control frameworks. For example, artificial neural networks, leveraging nonlinear mapping and self-learning capabilities, enhance modeling and prediction in unstructured environments; while genetic algorithms and other evolutionary optimization approaches, with their global search and parameter adaptation properties, improve convergence speed and system stability. These intelligent methods have demonstrated notable advantages in enhancing adaptability and task efficiency in complex environments. However, their high computational complexity and stringent requirements on hardware performance and energy consumption confine their application primarily to experimental validation and specialized scenarios [18].

Meanwhile, as dexterous hands evolve toward multi-fingered configurations and high degrees of freedom, research has increasingly focused on master–slave control and coordinated control strategies. The former enables natural and intuitive human–robot interaction by mapping human hand motions in real time to dexterous robotic hands, which is particularly suitable for high-precision and delicate manipulation tasks. The latter emphasizes inter-finger coordination, employing kinematic modeling and optimized task allocation algorithms to achieve efficient cooperation and flexible adaptation during grasping, manipulation, and assembly tasks [19]. Both strategies have yielded encouraging progress in academic research and have shown promising applications in industrial production, medical rehabilitation, and domestic service.

Overall, the control of dexterous hands is undergoing a clear paradigm shift—from conventional control to intelligent control, and from independent single-finger control to coordinated multi-finger control. Future research must balance algorithmic complexity against hardware resource constraints and further explore the deep integration of multimodal perception and control, thereby advancing the practical deployment of dexterous hands in broader and more challenging task environments.

3. CHALLENGES IN DEXTEROUS HAND TECHNOLOGY

3.1. Balance Between Flexibility and Stability

In the design of dexterous hands, achieving a balance between flexibility and stability remains a critical challenge. Enhancing flexibility often requires increasing the number of degrees of freedom (DOF), which inevitably leads to structural complexity and compromises stability. For instance, dexterous hands based on parallel-finger mechanisms provide high load capacity and precision. However, kinematic analysis and singularity studies reveal that as the DOF increases, the distribution of singular points within the workspace becomes more complex, thereby reducing operational reliability[3]. Conversely, serial-structure dexterous hands exhibit greater motion flexibility, but cumulative joint errors significantly degrade the positioning accuracy of the end-effector, making them less suitable for high-precision tasks [4]. Current solutions mainly involve optimizing mechanism design to mitigate the impact of singularities, and employing real-time control algorithms to compensate for structural deficiencies. Nevertheless, these methods face limitations in practice: optimization may raise manufacturing costs, while real-time algorithms demand considerable computational resources, which constrains their implementation in embedded systems.

3.2. Sensing Accuracy and Response Speed

The sensing accuracy and response speed of dexterous hands are essential to achieving fine manipulation, yet significant challenges remain. Force/torque sensors, as core sensing components, directly determine the reliability of grasping through their measurement accuracy and stability. However, due to constraints in material properties and fabrication techniques, existing sensors perform poorly in high-frequency dynamic force measurements and are prone to noise interference [20-22]. Position sensors provide relatively high accuracy in joint angle detection, but their response speed may fall short under high-speed motion scenarios, limiting their contribution to real-time control. The integration of tactile and vision sensors has further enhanced dexterous hand perception, but these technologies still fall short of replicating the comprehensive sensing ability of the human hand. For example, tactile sensors still face limitations in terms of resolution and sensitivity, while vision sensors may suffer from delays or misinterpretations when processing complex environmental information. Such limitations not only hinder dexterous hand performance but also restrict their applications in fields requiring high precision, such as fine assembly and surgical operations.

3.3. Manufacturing Cost

The high manufacturing cost of dexterous hands mainly stems from their complex mechanical structures, high-precision sensors, and advanced actuation systems. First, the design often relies on high-performance materials to meet the requirements of strength, stiffness, and lightweight construction, which substantially increases raw material costs. Second, the manufacturing process involves multi-DOF mechanism assembly, precision machining, and sensor calibration, all of which impose stringent requirements on process capabilities, driving production costs higher[23,24]. In addition, the choice of actuation system significantly affects cost. While electric motor actuation is technologically mature and easy to control, high-performance miniature motors remain expensive. Hydraulic and pneumatic actuations are suitable for heavy-load tasks, yet their inherent system complexity further escalates manufacturing costs. To mitigate these expenses, researchers are exploring alternatives such as the development of low-cost, high-performance materials, simplified mechanical designs, and modularized manufacturing techniques. However, the practical effectiveness of these approaches requires validation through large-scale production, and they may compromise certain aspects of performance.

4. DEVELOPMENT TRENDS OF DEXTEROUS HAND TECHNOLOGY

4.1. Integration with Emerging Technologies

With the rapid advancement of artificial intelligence (AI), cutting-edge algorithms such as deep learning and reinforcement learning have provided innovative solutions for enhancing the autonomous operation capabilities of dexterous hands. Deep learning, by constructing deep neural network models, enables the extraction of complex features from large datasets, significantly improving the intelligent level of environmental perception and task execution for dexterous hands [25,26]. For instance, deep learning-based visual recognition algorithms can accurately locate the position and posture of target objects, offering high-precision guidance for grasping operations. Furthermore, reinforcement learning, as an optimization method centered on a trial-and-error mechanism, allows continuous adjustment of control strategies in dynamic environments, empowering dexterous hands with stronger adaptive capabilities in the face of uncertainties. Research has demonstrated that reinforcement learning algorithms have exhibited excellent performance in stable grasping tasks with humanoid dexterous hands, particularly excelling in real-time decision-making within complex scenarios[27]. However, the application of AI in dexterous hands still faces numerous challenges, such as the high computational costs required for model training, difficulties in data acquisition, and insufficient algorithmic generalization, all of which urgently need to be addressed.

The introduction of big data technology has provided critical support for optimizing control strategies and enabling adaptive learning in dexterous hands. By collecting and analyzing vast amounts of operational data, dexterous hands can continuously refine their motion planning and grasping strategies, thereby enhancing overall performance. For example, in industrial production, dexterous hands can record the success rate and efficiency of each grasping operation to build a historical database of task execution. Data analysis techniques can then be employed to uncover patterns within this database, leading to improvements in control algorithms[18]. Additionally, big data technology facilitates knowledge transfer across tasks, enabling dexterous hands to quickly adapt to new operational requirements in diverse application scenarios. However, the application of big data also encounters challenges such as inconsistent data quality and privacy concerns, which must be addressed in future research.

4.2. Functional Expansion

Multimodal perception is a key technology for dexterous hands to achieve refined operations. Its core lies in integrating information from various sensors, such as vision, touch, and force sensing, to enhance the comprehensive environmental perception capabilities of dexterous hands. Visual sensors provide spatial position and shape information of target objects, while tactile sensors detect pressure distribution and surface characteristics at contact points. Force sensors monitor real-time changes in force during grasping operations [28,29]. Through multimodal sensor fusion, dexterous hands can more accurately assess the state of objects in complex environments and adjust their operational strategies accordingly. For example, in precision assembly tasks, dexterous hands can use visual sensors to locate parts and combine feedback from tactile and force sensors to ensure appropriate grasping force and operational accuracy. Although multimodal perception technology has made significant progress, achieving efficient data fusion algorithms and improving the robustness of perception systems remain key focus areas for future research.

Dexterous hands are expected to perform increasingly complex tasks in the future, such as precision assembly and minimally invasive surgery, which place higher demands on their design and control. In the field of precision assembly, dexterous hands must exhibit extremely high positioning accuracy and motion flexibility to handle the assembly of miniature components. For instance, multi-fingered biomimetic dexterous hands, by mimicking human hand movements, can perform complex assembly tasks on automated production lines, greatly improving efficiency and reducing labor costs[30]. The potential applications of dexterous hands in the medical field are equally noteworthy. In minimally invasive surgery, dexterous hands, through miniaturized design and precise control, can perform delicate operations on internal human tissues, thereby reducing surgical trauma and improving success rates. However, the execution of complex tasks relies not only on hardware performance improvements but also requires breakthroughs in control algorithms and sensing technologies to address challenges posed by task diversity and environmental uncertainties.

4.3. Performance Enhancement

Lightweight and miniaturization are important trends in the development of dexterous hand technology. Research in this area primarily focuses on material selection and structural design. In terms of materials, the application of new lightweight materials such as carbon fiber composites and aluminum alloys can significantly reduce the overall weight of dexterous hands while maintaining high strength and stiffness[31,32]. In structural design, innovative mechanisms such as cable-driven transmission can effectively reduce the volume and weight of driving components, thereby achieving the goal of lightweight dexterous hands. For example, a five-fingered dexterous hand design based on cable-driven transmission relocates the driving source to the rear, not only reducing the weight of the finger section but also improving the system’s compactness and flexibility[19]. Additionally, the development of lightweight and miniaturized dexterous hands must consider energy supply and thermal management to ensure stability and reliability during prolonged operation.

Improving the reliability and lifespan of dexterous hands is a critical factor in promoting their practical application. Currently, dexterous hands often face issues such as drive system fatigue and declining sensor accuracy during long-term use, which severely impact their performance. To address these challenges, researchers have conducted extensive explorations in optimizing drive and control systems. For example, improvements in motor drive design can reduce heat generation caused by stall conditions, thereby extending the lifespan of the drive system[23]. Additionally, developing highly sensitive, low-cost sensors is another important approach to enhancing the reliability of dexterous hands. Studies have shown that the application of underactuation principles can simplify finger structures to some extent while enhancing their self-locking characteristics, thereby improving the overall system’s stability and durability[33,34]. In the future, further optimization of material selection and manufacturing processes will be necessary to comprehensively enhance the reliability and lifespan of dexterous hands.

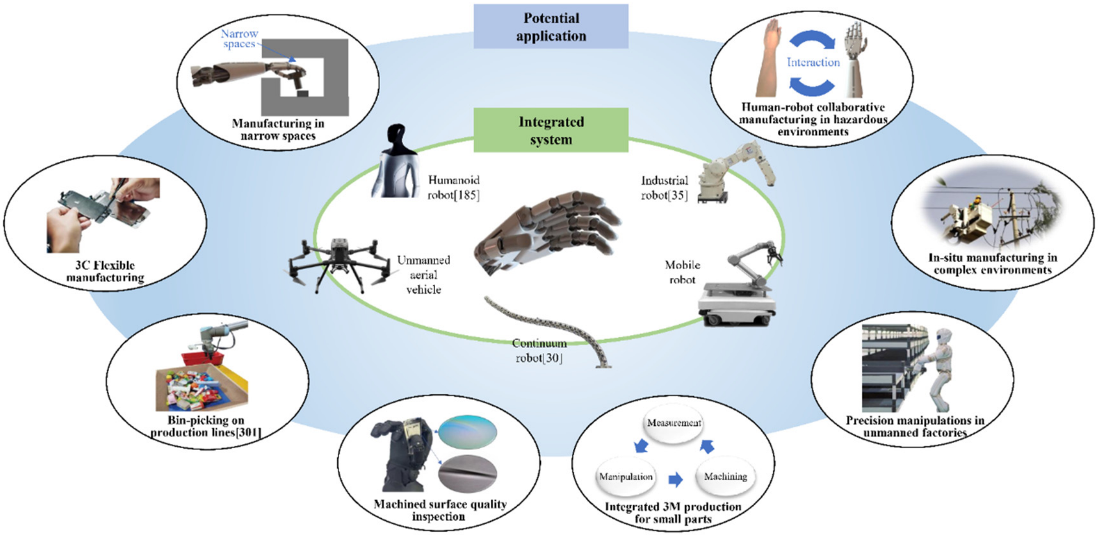

Figure 10. Future Development Trends of Dexterous Hands

5. CONCLUSION

(1) As a pivotal research domain in robotics, dexterous hand technology has witnessed remarkable advancements in structural design, actuation methods, sensing technologies, and control algorithms in recent years. In terms of mechanical architecture, both serial and parallel configurations offer distinct advantages, while novel biomimetic structures continue to demonstrate unique potential. Actuation methodologies have diversified from conventional electrical motors to hydraulic, pneumatic, and smart material-based systems. Sensing capabilities have progressively evolved to provide multi-modal perception encompassing force/torque, position, tactile, and visual feedback. Concurrently, control paradigms have shifted from traditional approaches toward intelligent algorithms and cooperative control strategies. Nevertheless, several challenges persist, including the inherent trade-off between flexibility and stability, limitations in sensing accuracy and response speed, as well as high manufacturing costs. Furthermore, the lack of co-design integration between intelligence and mechatronic subsystems continues to constrain overall performance enhancement. Despite these challenges, the accumulated research outcomes have established a solid foundation for future technological developments.

(2) Given the broad application prospects of dexterous hands in industrial automation, domestic services, and medical interventions, sustained research and innovation remain imperative. Future investigations should prioritize overcoming existing technical bottlenecks—for instance, enhancing durability and reducing production costs through advanced materials and manufacturing processes—while strengthening the co-design of "hand-brain-eye" systems to achieve higher levels of operational intelligence Moreover, convergence with emerging technologies such as artificial intelligence and big data analytics will unlock new opportunities, particularly in the domains of multimodal perception and complex task execution. Lightweight, compact, and high-reliability designs will also constitute critical research directions, thereby accelerating the adoption of dexterous hand technology in a wider range of real-world applications.

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