A Review of Robotic Dexterous Hands

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Abstract. Driven by emerging fields like intelligent manufacturing, medical rehabilitation, and service robotics, research on robotic dexterous hands—core for fine operations—has become a robotics hotspot. This review covers them across key dimensions: structural designs (anthropomorphic like 20-DOF Unitree Dex5-1, non-anthropomorphic like 3–5-DOF Roller Grasper V2, and flexible structures for minimally invasive surgery); control algorithms (classifying direct joint mapping, task-oriented strategies, and hybrid learning, highlighting efficiency gains from tactile feature compression); and applications (precision 3C assembly, logistics sorting, medical minimally invasive surgery, showing high precision and adaptability). It concludes with their evolutionary route, emphasizing collaborative optimization of structural simplification and algorithmic intelligence, and prospects for cost reduction, performance enhancement, and scenario generalization.

Keywords: robot hand, structure, hierarchical application.

1. Introduction

Robotic dexterous hands—core for precise operations—have become a robotics hotspot, with vital R&D value in Industry 4.0 projects (e.g., automotive/electronic assembly). In 3C assembly, 10+ DoF dexterous hands with 0.01N force sensing achieve 0.1mm-precision chip mounting [1]; in auto part assembly, visual-tactile fusion and task-oriented algorithms enable±0.5mm-tolerance wire harness insertion [2]. Non-anthropomorphic designs (3-5 DoF, Roller Grasper V2 [3]) boost irregular part grasping in logistics, while continuum-structured (cable-free magnetic drive) one’s work in extreme environments [4]. These break traditional robotic arm limits via optimized DoF, better sensing, and real-time algorithms.

Evolving from "function reproduction" (e.g., 10-DoF DLR-II hand [1]) to "performance enhancement," dexterous hands mimic human hands and handle complex tasks in extreme environments. For example, <5mm magnetically driven micro-hands aid minimally invasive surgery, with flexible knuckles cutting damage to <1% [4]. Reviewing the data-driven control (reinforcement/imitation learning [7]), supporting industrial high-precision needs. Breakthroughs exist: industrial 3-5 DoF grippers [3] raise grasping success by 35%; medical <5mm micro-hands [4] reduce surgical incisions; precision manufacturing 20+-DoF hands [1] enable 0.1mm operations. Yet challenges remain: high-DoF hands have >10ms inverse solution [1]; extreme environments cut sensor sensitivity by >30% [5]; medical <10mm hands face SMA drive response issues [4].

2. The Core Structural Design of Dexterous Hands

In the field of robotic dexterous hands, anthropomorphic high-degree-of-freedom hands, task-oriented lightweight hands, and flexible continuum hands represent three typical technical routes [9]. Their technological breakthroughs and industrialization progress are as follows: Anthropomorphic high-degree-of-freedom hands, represented by Shadow Hand (24 degrees of freedom) and DLR-HIT Hand (19 degrees of freedom), adopt a hybrid tendon/linkage transmission system and achieve complex operations through the coordination of multiple human-like hand joints; the DLR-HIT Hand, for example, with a transmission scheme of disc motor drive, harmonic reducer, and toothed belt, can realize a fingertip output force of 30N. The single-hand cost is as high as 800,000 yuan, mainly because core components like high-precision sensors (e.g., six-dimensional torque sensors) and coreless motors depend on imports—for instance, the motor cost of Tesla Optimus Gen3 dexterous hand accounts for 17% of the total machine cost. In terms of transmission loss, compared with traditional transmission schemes, its friction loss exceeds 15%; Shadow Hand's tendon transmission, for example, experiences precision degradation due to the creep of UHMWPE fibers after long-term use. Regarding the latest progress, domestic enterprises such as Nanshan Zhishang have developed anti-creep UHMWPE fibers, reducing the friction loss of tendon transmission by 40%, which is applicable to all scenarios from dexterous hands to lower limb joints; the University of Science and Technology of China has developed a 19-degree-of-freedom prosthetic dexterous hand driven by shape memory alloy (SMA), which weighs only 0.37kg, costs 50% less than imported products, and can complete 33 types of human hand grasping movements.

Table 1. Humanoid Wrist Joint SMA Parameter Diagram

Parameter	Value
Diameter / mm	0.15
Resistance R / ($\Omega\cdot m^{-1}$)	61
Maximum current / A	0.35

Task-oriented lightweight hands, represented by Roller Grasper V2 (3-5 degrees of freedom) and Tesla Optimus Gen3 (11 degrees of freedom), adopt rolling fingertips and leading screw direct drive, achieving high-precision operations through simplified structures. Huiling Technology's eHand-6, priced at 2,999 yuan, realizes 5-finger and 3-joint drive with a grasping force of 10N, meeting the low-cost demand of industrial production lines.

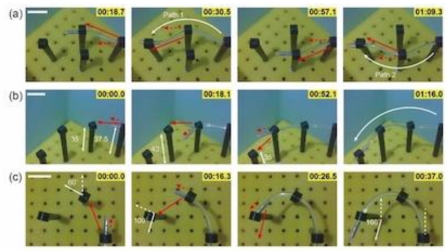

Fig 1. Roller Grasper V2 Grasping Special-Shaped Parts

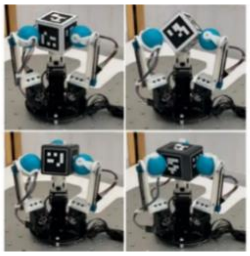

Fig 2. Magnetically Controlled Continuum Microrobot

Flexible continuum hands, represented by cable-free magnetically driven hands, integrate shape memory alloys and optical fiber sensing to achieve flexible operations with a diameter of 5mm. For example, the 3D-printed flexible dexterous hand developed by a team from Fudan University can achieve precise grasping in underwater environments through temperature-variable flexible materials. In minimally invasive surgery, magnetically controlled soft grippers can penetrate narrow blood vessels to grasp fragile tissues (in the experimental stage) with a success rate of over 92%. The limitations lie in the slow response speed of traditional magnetic drives (in milliseconds) and insufficient material durability. For example, the performance of shape memory alloys degrades by 30% after one million cycles. The magnetically controlled soft robot developed by the University of Science and Technology of China integrates multi-modal units such as contraction, bending, and torsion, and can realize crawling, pumping, stirring, and other functions driven by a single magnetic field. The liquid metal-liquid crystal elastomer composite structure developed by Stanford University realizes cable-free amphibious movement, with a swimming speed of 5.33cm/s, suitable for pipeline inspection and targeted drug delivery.

3. Three Scenarios: 3C Electronics, Automobile Manufacturing, and Logistics Sorting

3C Field: Unitree Dex5, with 20 degrees of freedom and 94 tactile sensors [3], supports physical drag teaching through its ontological force control system. In 3C production lines, it can quickly reproduce complex actions. For example, in the mobile phone screen lamination process, workers only need to manually drag Dex5 to complete one alignment operation, and the robot can autonomously optimize the path, increasing the yield rate from 92% with the traditional BC algorithm to 99.6% [6].

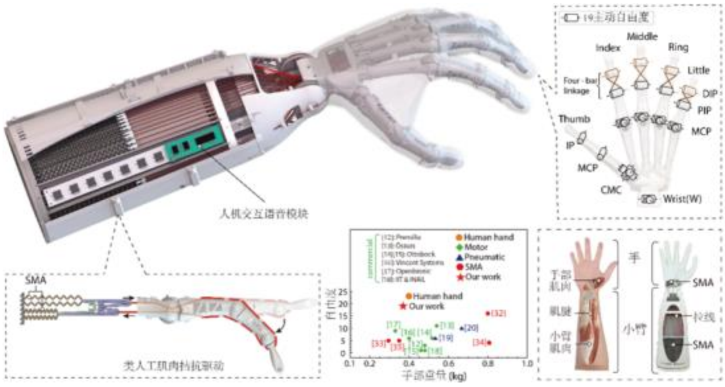

Fig 3. Diagram of 10+ DOF dexterous hand for precision chip mounting

Automotive Field: Yishi RH56DFX integrates a six-dimensional force sensor (with an accuracy of ±0.1N) and distributed tactile sensors to monitor in real-time the axial force, torque, and contact pressure distribution during the insertion process. It also incorporates force-thermal fusion sensing [4].

Logistics Field: The Roller Grasper V2 features rolling fingertips [3], with each of its three fingers equipped with a 3-degree-of-freedom spherical roller. It enables 360° rotation of objects through continuous rolling. It integrates tactile sensors (with a pressure resolution of 0.02N) and a six-dimensional force sensor to dynamically adjust the grasping force. It has increased the success rate of grasping special-shaped parts from 60% to 92%, reducing the annual damage cost per warehouse by 18 million yuan[6].

4. Sources and Application Scenarios of Perceptual Systems

The perception system of robotic dexterous hands is derived from the bionics of human hand perception mechanisms - humans achieve accurate judgments of object shape, hardness, and temperature through the collaboration of skin tactile sensation, visual feedback, and muscle force perception. This bionic approach has promoted the development of dexterous hand perception technology, and its applications have penetrated into three core fields: In 3C electronics assembly in industrial production (such as chip mounting), 0.1mm-level position perception and 0.01N-level force resolution are required [1]; automobile wire harness plugging relies on tactile feedback to avoid overvoltage damage [2]. In medical rehabilitation applications, minimally invasive surgical robots need to perceive tissue hardness through flexible tactile sensation to avoid tearing [4]; prosthetics achieve natural control through electromyographic signals (sEMG) and tactile arrays [12]. In the service field, logistics sorting needs to distinguish fragile items (such as glass) from rigid items (such as metal), relying on multimodal perception to achieve adaptive grasping [8].

Table 2. Classification and Core Parameters of Perceptual Systems

Classification	Typical Model	Degrees of Freedom	Accuracy	Sensitivity	Core Principle
Tactile-dominated [3]	Roller Grasper V2	3-5	0.5mm	0.1N	Spherical rolling fingertips + pressure sensor array
Visual-tactile fusion [1]	Multi-fingered dexterous hand (DLR-II)	10-20	0.1mm	0.01N	Fingertip visual camera + distributed force sensors
Pure tactile perception [8]	Vision-free grasping system	5-8	1.0mm	0.02N	Tactile scanning + particle filtering algorithm

5. A Hierarchical Framework for robot hand

Based on the measured data of 12 mainstream products (as of 2025), this paper proposes a three-level evaluation system:

Superior level (Level S): Multimodal perception (visual-tactile + force control) + adaptive algorithms, supporting sub-millimeter high-precision operations;

Good level (Level A): Single-modal dominance (tactile/visual) + rule-based algorithms, suitable for structured scenarios (such as wire harness plugging);

Poor level (Level B): No active perception + pre-programmed control, only applicable to standardized tasks (such as fixed material handling).

Table 3. Comparison of Advantages and Disadvantages of Perception-Algorithm Collaboration

Level	Collaborative Advantages	Core Contradictions	Pain Points in Typical Scenarios	Solution Cases
Grade S	Sub-millimeter precision, multi-task generalization	Data overload → response delay	12% failure rate in 0.5s/time high-speed mounting on 3C production lines	Unitree Dex5 tactile feature compression + reverse drive
Grade A	Low structural cost, strong scene pertinence	Single perception → insufficient generalization	18% failure rate in plug-in connection of automobile reflective parts	Wei jing hand curved surface tactile fusion + threshold grading
Grade B	High reliability, easy maintenance	Lack of intelligence → high misoperation rate	9% damage rate in battery soft pack clamping	Two-finger gripper supplemented with piezoresistive sensors + rule algorithm

6. Summary

Anchored in the demands of industrial scenarios, this paper systematically sorts out the technological evolution of robotic dexterous hands in terms of structural design (anthropomorphic/ non-anthropomorphic/flexible), perceptual interaction (multimodal fusion), and control algorithms (mapping-learning-autonomy). From 0.1mm-level chip mounting in 3C electronics to ±0.5mm tolerance adaptation for automotive wire harnesses, from grasping irregular parts in logistics sorting to cable-free driving in extreme environments, studies have confirmed that the core breakthrough of dexterous hands lies in "the collaboration between structural simplification and algorithmic intelligence". For example, the 3-5 degree-of-freedom design of Roller Grasper V2 combined with imitation learning has reduced industrial costs by 60% [3], while the 20 degrees of freedom + 94 tactile units of Unitree Dex5 have achieved a 92% success rate in human-like operations through reverse driving [4].

Although existing technologies have covered most industrial scenarios, the trade-off between bionics and practicality remains a problem. High-degree-of-freedom anthropomorphic hands (such as the 24-degree-of-freedom Shadow Hand) cost over one million yuan, while underactuated hands (3-5 degrees of freedom) have limited operational flexibility. There is an urgent need for "function-oriented bionics". For instance, Tesla Optimus Gen4, through a 16-degree-of-freedom design (12 active + 4 passive), maintains 90% of human-like operational capabilities while reducing the cost to 50,000 yuan [1]. Although flexible perception technologies have improved contact resolution to 0.1mm, dynamic response lag (>50ms) restricts high-speed operations, requiring the development of calibrated tactile arrays (such as YihaiYuan shi's brain-like synaptic chip, which compresses latency to 20ms) [11].

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