

Exploration of the Mechanisms and Applications of Bionic Grippers

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Abstract: Based on the research literature on new mechanical claws from 2020 to 2025, this paper analyzes and finds that bionic technology has become a key direction for technological breakthroughs. By summarizing the bionic fields such as motion mechanisms, structural topologies, and material properties, this paper systematically evaluates the performance of bionic mechanical claws from five dimensions: grasping success rate, driving energy consumption, response speed, load capacity, and scene adaptability, providing theoretical basis and practical guidance for future research and development. Moreover, referring to the current evaluation standards for gripper performance, a new comprehensive scoring formula with certain weights that better meets the current requirements for mechanical grippers is proposed, which better quantifies the performance.

Keywords: Bionic Mechanical Claw, Performance Evaluation, Comprehensive Scoring Formula

1. Introduction

As a core component of the robot end effector, the mechanical gripper is an intelligent device that achieves object grasping, manipulation, and release through a driving mechanism. Its essential function is to simulate the functional characteristics of biological grasping organs, break through the rigidity constraints of traditional fixtures, and achieve multi-modal and adaptive efficient operations in complex dynamic environments, playing an irreplaceable role in multiple fields[1][2].

Based on the global market statistics, In Figure 1, we obtain the following data.

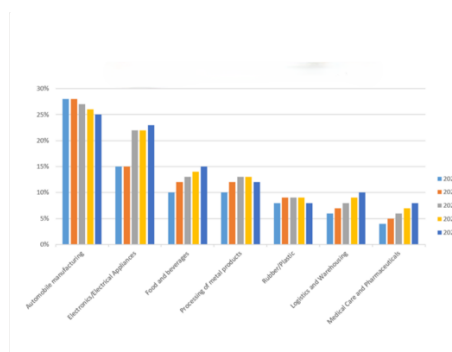


Figure 1: The proportion of mechanical claw applications

As a key technical carrier in the fields of industrial automation, medical surgery and special robots, mechanical grippers mainly undertake three responsibilities: first, to promote the upgrade of production processes towards flexibility and intelligence; second, to solve the problem of precise operation in high-risk environments; third, to endow robot systems with life-like environmental interaction capabilities.

Early mechanical grippers were centered on rigid connecting rods and gear transmission. Although they could achieve basic grasping functions, they were limited by preset trajectories and a single structure, making it difficult to meet the flexible operation requirements of complex objects. Bionic mechanical claws have effectively broken through the limitations of traditional rigid structures through multi-dimensional innovations inspired by biology: by drawing on the moral-material-motion synergy mechanism of biological systems, they have, to varying degrees, solved the three core pain points of traditional mechanical claws: lack of flexibility, single function and decoupling from the environment.

However, most of the existing studies are limited to isolated analyses of single performance parameters such as maximum load and movement speed, lacking specialized evaluations of the essence of bionic characteristics: biological similarity has not been quantified, and environmental interaction capabilities have been ignored, such as: The grasping stability under dynamic disturbance, multi-material adaptability, and comprehensive indicators such as the Bionic Efficiency Index have not been constructed. The absence of this standard system leads to three major problems: the lack of data support for the selection of technical routes, the difficulty in horizontally comparing bionic innovation achievements, and the lack of a unified language framework for interdisciplinary collaboration. Therefore, five evaluation dimensions were established, including success rate, adaptability to scene applications, maximum load ratio, driving energy consumption efficiency and response speed. Provide an objective scale for the performance comparison of different technical routes to avoid misjudgment caused by the fragmentation of evaluation dimensions; Guide the R&D direction to focus on core contradictions such as rigid-flexibility balance and energy efficiency load coordination, and accelerate technological iteration; And establish a mapping relationship with the scene requirements to shorten the adaptation period from laboratory prototypes to industrial applications.

2. Bionic movement mechanism

In the bionic design of mechanical grippers, the inspiration for the motion mechanism comes from the functional characteristics of the grasping organs of organisms in nature. This design concept is based on the core assumption of bionics: the motion patterns formed through biological evolution often possess functional optimality, and the coordinated mechanisms of their structure, materials, and movements provide an efficient paradigm for solving engineering problems. Similar to the grasping organs of organisms in nature, the bionic design of mechanical grippers is not a mechanical replication of a single motion unit, but rather achieves a balance between dynamic adaptability and energy efficiency at the functional level through the integration of multi-degree-of-freedom joints, flexible materials, and intelligent control systems. The functional requirements of modern mechanical grippers have evolved from basic grasping to complex operations, needing to adapt to irregular objects, dynamic loads, and human-machine collaborative scenarios. Bionic motion mechanisms provide an innovative path for this, such as dynamically reconfiguring the grasping strategy of mechanical grippers by simulating the combined actions of rotation, extension, and bending of biological organs.

2.1. Bionic entanglement of octopus tentacles

The tentacles of octopuses achieve efficient and flexible grasping capabilities through a unique biomechanical mechanism. They not only have high degrees of freedom and continuous deformation ability, allowing for 360° bending, twisting, and stretching in any direction, but also possess extremely strong dynamic adaptability. The tentacles can dynamically adjust the contact surface according to the shape of the object, wrapping complex geometries such as concave-convex surfaces or small objects, avoiding the "point contact" limitation of traditional rigid grippers. Additionally, the base of the octopus tentacles is thick and the tip is slender, allowing for the adjustment of flexibility and strength balance through the taper angle. These characteristics have to some extent inspired research on bionic mechanical claws. Most of them [3-6] take the octopus's movement mechanics as the bionic object, proposing solutions to the pain points of traditional mechanical claws and achieving technological breakthroughs.

A typical example of the application of the bionic octopus tentacle wrapping is [7]: This paper mainly studies a conical soft actuator inspired by the octopus tentacle. By combining bending drive and vacuum suction cup design, the grasping performance is significantly improved. The inspiration comes from the fact that the octopus tentacle can grasp prey of various shapes by virtue of the conical structure, flexible bending ability and the coordinated action of the suction cups. The functional significance of the difference in the taper angle of the tentacle is explored, and a bionic soft actuator is designed based on this.

Traditional soft actuators are mostly cylindrical in shape, while the mechanism of the conical structure of octopus tentacles is still unclear. The research focus on the octopus-inspired claw is on the influence of the taper angle on the bending performance and grasping force of the actuator, as well as the collaborative effect after integrating the suction cups. They measured the taper angles of tentacles of 10 octopus species ($3^\circ - 13.5^\circ$), and based on this, designed soft actuators with different taper angles. The internal structure of the actuators is a single-chamber pneumatic structure, and the outer surface is covered with interlaced suction cups (material: silicone). The suction cups are vacuum-assisted to attach objects. In Figure 2, they found that the influence of different taper angles: the smaller the taper angle, the greater the bending curvature (for example, when $\alpha = 3^\circ$, the curvature is twice that of $\alpha = 13.5^\circ$), and spiral curling can be achieved. The larger the taper angle, the higher the stiffness of the actuator and the greater the applied force (for example, when $\alpha = 13.5^\circ$, the applied force is 16 times that of $\alpha = 3^\circ$). In practical applications, flexibility and force are inversely related, and an appropriate taper angle needs to be selected according to different scene requirements.

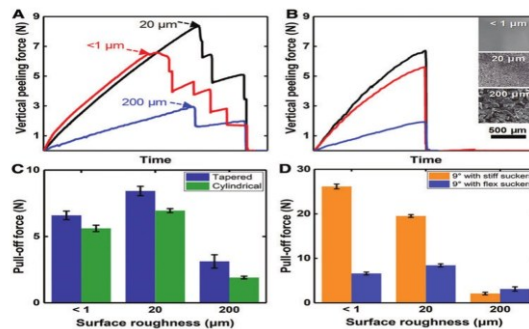


Figure 2: The relationship between taper angle and stiffness and curvature

The bionic mechanical gripper developed based on the octopus entanglement mechanism described in the original text demonstrates outstanding comprehensive performance: it has an extremely high grasping success rate and can stably handle flat thin sheets, curved objects (mugs), small-sized items (test tubes), and 27N heavy objects. It has good scene adaptability. The conical

structure supports passing through 4cm narrow holes, which has significant advantages in restricted environments such as medical care, industry and deep sea. Its innovation lies in the hybrid drive design that integrates pneumatic bending and vacuum adsorption, achieving multi-form grasping with a single actuator, breaking through the complexity of traditional multi-systems, and balancing flexibility and load capacity (maximum load 27N) through taper Angle optimization. Although there is still room for improvement in driving energy consumption and response speed, this design provides a key technical paradigm for the evolution of bionic machinery from "likeness in form" to "likeness in spirit".

2.2. The biomimetic of flower corolla opening and closing

The bionic design of the flower-shaped opening and closing of the mechanical gripper imitates the movement of plants, possessing advantages such as adaptive grasping, lightweight drive, and space optimization. It can efficiently handle irregular objects, evenly distribute the force, and adapt to narrow or sensitive environments. Its flexible structure enhances safety, and integrates the potential for multiple functions, applicable in fields such as medicine, agriculture, and logistics, representing the development direction of flexible and intelligent gripping technology.

This paper mainly studies a lightweight and resilient soft gripper designed based on bionic principles[8]. By combining the structure of plant stems with the flower-shaped opening and closing mechanism, it solves the problems of insufficient stiffness and poor dynamic grasping stability of traditional pneumatic soft grippers. The paper draws bionic inspiration from the opening and closing morphology of herbaceous plant stems and flower heads. The vascular bundle distribution structure of alfalfa stems provides a bionic basis for enhancing the stiffness of the gripper, and by embedding lightweight ribbons to simulate the supporting role of the thick-walled tissue; while the spiral closing movement mode of the pearl cherry flower head is transformed into the spiral winding action of the gripper, enabling the gripper to simultaneously generate axial bending and radial torsion when inflated, forming a composite motion trajectory, and enhancing the encapsulation ability of the object. The layout of the spiral chambers adopts a staggered array of pneumatic chambers (inclined angle 40°), driven by air pressure to achieve spiral deformation, providing radial clamping force and tangential friction force, effectively resisting the additional torques during dynamic operation of the robotic arm. Embedding polylactic acid (PLA) ribs in the pneumatic chambers, combined with the PVC sheet at the bottom, significantly enhances the stiffness of the gripper. In Figure, experiments show that after embedding ribs, the output force at the end of the gripper increases by approximately 28% (120 kPa pressure), while the hysteresis decreases by 83.8%, and the deformation angle still meets the enveloping requirements by 37%. This bionic gripper adopts a flower-shaped gripping configuration, with 5 grippers symmetrically distributed on a pentagonal base, simulating the spiral closing morphology of petals.



Figure 3: The mechanism of corolla opening and closing movement

This bionic mechanical gripper adopts a pneumatically driven synchronous retraction mechanism. It adaptively grasps spherical, thin and other irregular objects through spherical envelope or asymmetric winding. The maximum grasping mass reaches 890 grams (load self-weight ratio 4.06), and it can stably withstand a load of 930 grams under an air pressure of 130 kPa without significant

deformation. Its innovative rigid-flexible coupling design breaks through the performance bottleneck of traditional soft grippers: compared with the Harvard starstar-type gripper, its load capacity is increased by 9 times, the retractable size is reduced to 108mm×85mm, and it can stably grasp fragile/irregular objects such as light bulbs and metal parts during high-speed movement. Through bionic winding structure and material reinforcement technology, it achieves the coordinated optimization of lightweight (self-weight only 219 grams) and high rigidity, featuring both dynamic anti-interference performance and precise operation potential. It provides innovative solutions that balance smooth grasping and high load requirements for scenarios such as logistics sorting and precision assembly.

3. Structural topology bionics

In the design of mechanical grippers, "structural topology bionics optimizes the mechanical properties and functional adaptability of the grippers by simulating the spatial configuration and material distribution patterns formed by organisms during evolution." Consistent with the structural logic of nature, such research simultaneously deconstructs the efficient topological logic of biological prototypes at the micro, mesoscopic and macro levels. This type of bionic structure emphasizes the survival wisdom of "achieving maximum performance with the least material". By deconstructing redundant masses and strengthening key force transmission paths, it significantly enhances the specific strength and energy utilization rate of the gripper. At present, the bionic topologies of mechanical grippers mainly include: lightweight truss structures, impact-resistant mesh structures, gradient composite material structures, and foldable and deployable structures. In the future, with the deep integration of biomechanical modeling and intelligent optimization algorithms, structural topology bionics will drive mechanical grippers to evolve towards more efficient "life-like" forms, providing innovative solutions for extreme environment operations and human-machine integration scenarios.

3.1. Bionic adsorption structure of geckos

The gecko adsorption bionic mechanical gripper achieves seamless and adaptive grasping through a bionic micro-nano bristle structure and van der Waals force, firmly adhering to smooth, rough or fragile surfaces without the need for vacuum or magnetic force. It is energy-saving, silent, suitable for both dry and wet environments and has strong durability. It is applicable to scenarios such as aerospace, medical care and wall-climbing robots, solving the adaptability problem of traditional adsorption methods in complex environments and demonstrating the advantages of high efficiency and low damage in grasping.

This paper [9] has achieved a significant breakthrough in bionic adhesion technology by imitating the layered structure and dynamic movement mechanism of geckos' toes. The climbing ability of geckos stems from the multi-level bristle structures on their toes. These structures provide strong adhesion through van der Waals forces and can actively regulate the contact state through specific configurations (such as the Y-shaped posture) during movement. The core innovation of this paper lies in combining the intelligent deformation characteristics of liquid crystal polymers (LCN) with bionic microstructures to develop a multi-leg gripper that can actively control adhesion and release, solving the limitation of passive adhesion of traditional bionic materials.

In Figure 4, the research team first started from the topological structure of geckos' toes and used soft lithography technology to prepare PDMS microcolumn arrays to simulate the bristles of geckos. The ends of the microcolumns are covered with elastic films (E-FT) or viscoelastic coatings (VE-FT) to enhance the contact area and van der Waals forces. Experiments show that the introduction of the viscoelastic coating significantly improves the adhesion energy (up to 1.49 J/m²), approaching the

adhesion performance of natural geckos. This structural design not only optimizes static adhesion, but also avoids cohesive failure during peeling through the elastic deformation of microcolumns.

The backscrolling motion of geckos when they detach from the surface is ingeniously transformed into the thermally induced deformation response of LCN. Researchers designed a hybrid arrangement of LCN cantilevers, whose upper and lower surfaces respectively have planar and vertical anchoring characteristics. When heated, LCN undergoes asymmetric expansion/contraction due to the transition from the nematic phase to the isotropic phase, causing the cantilever to bend in a specific direction. This bending simulates the curling movement of a gecko's toes, concentrating the peeling force through the leverage effect to achieve an effect similar to self-peeling. Experiments show that the LCN cantilever can output an energy density as high as 8.4 kJ/m^3 at 100°C , which is sufficient to drive the peeling of the $28\text{-}84 \text{ mm}^2$ adhesive pad.

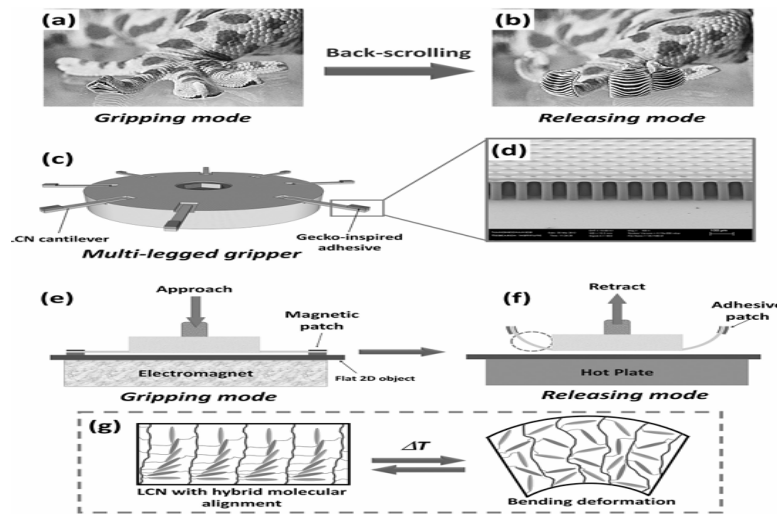


Figure 4: The adsorption structure of geckos' feet

This research focuses on enhancing the success rate of grasping and scene adaptability. Through the active deformation of the temperature-controlled liquid crystal network and the magnetic preload adhesion mechanism, it achieves high-precision and non-destructive grasping and placing of 9-gram silicon wafers. The eight-legged bionic structure combined with the self-cleaning function enhances the adaptability to complex environments such as dust and oil stains. The tile preload stress balancing strategy increases the load self-weight ratio to 4.06, breaking through the rigidity limitation of the traditional adhesion system. Although there is still room for optimization in thermal drive energy consumption and response speed, the optical/electrical trigger technology path has pointed out the direction for improving its energy efficiency. The core breakthrough lies in upgrading passive bionic adhesion to an intelligent active system. Through the collaborative design of materials and drives, it overcomes the contradiction between flexibility and load-bearing stiffness, providing innovative solutions that combine biological inspiration and engineering controllability for fields such as micro-operation robots and semiconductor manufacturing.

3.2. Bionic structure of finger joints

The mechanical gripper with bionic finger joints, through a multi-degree-of-freedom anthropomorphic design, integrates flexible drive and haptic feedback, achieving human-like fine operations (such as pinching and adaptive grasping), and can intelligently adjust the force to stably control irregular objects. Its high dexterity and high sensitivity make it particularly suitable for fields

with strict requirements for precision and safety, such as medical surgeries and collaborative robots, demonstrating the leading advantages of human-like mechanical grasping.

In this paper [10], a soft-rigid structure gripper SRSg inspired by the antagonistic mechanism of human fingers is proposed. Through variable stiffness design and sequential motion strategy, the balance problem among flexibility, load capacity and dynamic adaptability of traditional soft grippers is solved. Inspired by the synergistic effect of tendons in human fingers, the stiffness of each joint of the gripper is adjusted by the preload force of the spring. The antagonistic effect between the dorsal and ventral tendons in the fingers was simulated. In Figure 5, the gripper can achieve sequential bending motion (the proximal joint deforms before the distal joint) and active posture adjustment (such as single-joint bending to grasp large objects), significantly improving the adaptability to objects of different curvatures.

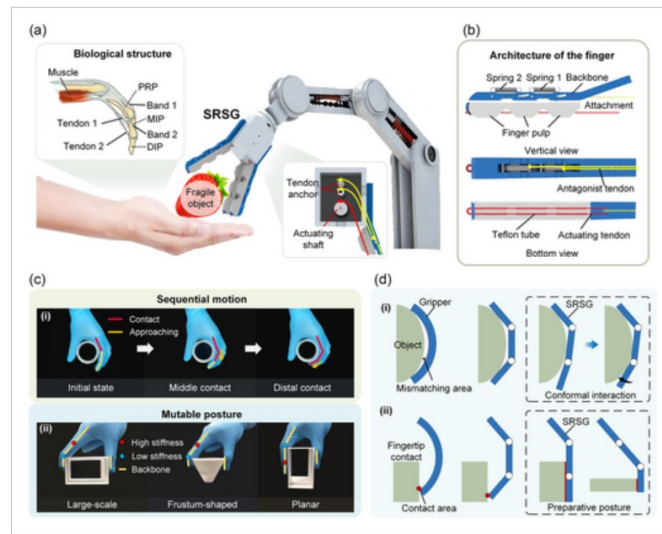


Figure 5: Biomimetic structure of finger grasping movement

Experiments show that by applying a preload force, the stiffness of the finger can be increased to a spring-free state. In the envelope mode, the gripper can stably grasp a 1kg load, with a horizontal load capacity of 9.7N, which is superior to the traditional uniform stiffness gripper. By adjusting the stiffness gradient, SRSg can grasp cylindrical, cuboid and triangular objects with diameters ranging from 35 to 75mm. Its sequential motion mode reduces the mismatch in the contact area and increases the friction force. The grasping experiments on fragile objects (such as paper cups and plasticine cylinders) show that by reducing the joint stiffness, the gripper can provide gentle contact, avoiding deformation or damage, demonstrating an interactive safety similar to that of soft fingertips. In high-speed reciprocating motion, the SRSg resists inertial forces through stiffness enhancement and successfully and stably grasps

4. Bionic movement mechanism

Bionics of the material properties of mechanical grippers is to design a grasping device with self-adaptation, high sensitivity and strong toughness by simulating the structural and functional characteristics of biological materials. This type of gripper is made of bionic materials such as flexible composite materials and smart polymers, endowing it with characteristics like variable stiffness, self-healing or pressure sensing. This enables it to precisely adapt to objects of different shapes and materials, achieving stable grasping in complex environments without damaging the target objects. This bionic design breaks through the limitations of traditional rigid grippers, significantly enhancing the robot's operational capabilities in unstructured scenarios. It is of great significance for industrial

automation, medical robots such as minimally invasive surgical instruments, and service fields such as human-machine collaboration and safe interaction. At the same time, it provides a practical example for the integrated innovation of intelligent materials and bionic robot technology, promoting the human-machine integration to move towards higher intelligence.

Traditional surgical forceps achieve mechanical interlocking through sharp toothed structures, but they are prone to cause tissue damage (such as a 25% rate of gallbladder perforation and a 20% mortality rate of intestinal perforation). Existing solutions, such as pressure sensors and vacuum suction cups, are difficult to balance the requirements of low damage and anti-slip. The strong wet friction characteristics of the PAWS of tree frogs provide inspiration for bionic design. Their closely arranged hexagonal prism structure can achieve high friction through liquid film regulation in a humid environment without the need for additional pressure.

The surface of the foot of the tree frog is composed of closely arranged hexagonal prismatic epithelial cells, accounting for 55%. The glands secrete mucus and distribute it evenly through grooves to form a liquid film. When the liquid film gradually thins from the continuous state to the boundary state, the surface tension dominates the frictional force, which can increase by more than 10 times [28]. The closely arranged hexagonal prism structure evenly splits the liquid film into micro-liquid Bridges, prolonging the boundary friction time (15 times longer than that of a smooth surface). The directionality of frictional force stems from the arrangement of prisms, while hexagonal prisms exhibit more balance due to their symmetry.

In the paper [11], a bionic surgical clamp was fabricated based on the material characteristics of tree frog feet. It was replicated using photolithography technology and PDMS, with a closely arranged hexagonal prism surface designed. The uniformity of the liquid film was enhanced through hydrophilic modification. In Figure 6,7,8, the frictional force of the hexagonal prism surface on the pig liver tissue was 20% higher than that of the traditional toothed clamp, and the directional adaptability was better. In the damage control test, the tissue deformation of the bionic clamp under a clamping force of 10 N was only 30 μm , which was 1/10 of that of the traditional clamp.

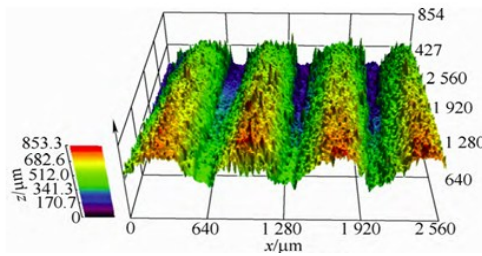


Figure 6: 1mm toothed clamp surface

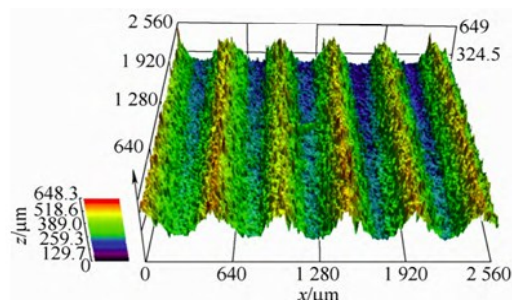


Figure 7: 0.5mm toothed clamp surface

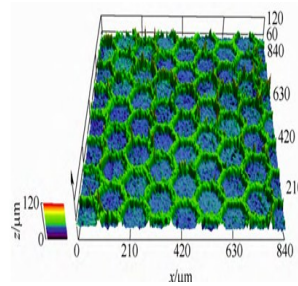


Figure 8: Bionic surgical pliers

The bionic clamp achieves "loose clamping without slipping" in a humid environment, significantly reducing the risk of tissue tearing, and is suitable for minimally invasive surgery and vascular clamping scenarios. In minimally invasive surgeries, small or irregular tissues such as blood vessels and mucous membranes can be precisely clamped. In complex fluid environments (such as laparoscopic surgery), its hydrophilic grooves can actively regulate the distribution of the fluid film and maintain stable frictional performance. In addition to conventional surgical operations, it can also be used in emerging fields such as endoscopic interventional therapy and robot-assisted surgery, providing a safe and reliable clamping solution for operations on highly difficult slippery tissues.

The rapid development of bionic mechanical grippers is promoting the leapfrog evolution of traditional mechanical grippers towards intelligence, flexibility and multi-functionality. Bionic mechanical grippers will break through the rigid logic of traditional machinery and become a bridge connecting the physical world and biological intelligence. Its development will not only reshape the operational paradigms in fields such as manufacturing, healthcare, and services, but also drive the evolution of robot technology towards greater flexibility, intelligence, and a closer alignment with the essence of life, ultimately achieving the ultimate goal of "machines adapting like life".

5. Summary

Bionic mechanical gripper technology, as a core research direction in the field of robotics, has opened up a breakthrough path for the innovation of traditional mechanical grippers by integrating the structural characteristics, motion mechanisms and functional principles of biological systems, and fusing the advantages of multiple disciplines such as materials science, control engineering and artificial intelligence. This paper systematically reviews its technological development context, combines the research progress of bionic kinematics, structural topology and material properties, constructs a multi-dimensional performance evaluation system, proposes a comprehensive scoring model and bionic efficiency index oriented to future demands, and promotes interdisciplinary collaboration and technological iterative upgrading. The essence of this technology lies in the engineering reconstruction of the wisdom of natural evolution, breaking the boundary between mechanical logic and biological logic. The proposed evaluation model and technical route not only systematically summarize some typical existing achievements, but also reveal the advanced path of bionic design from morphological simulation to functional reproduction. In the future, with the deep integration of materials, perception and intelligent technologies, bionic mechanical claws will develop into the core carrier of life-like operations, driving paradigm changes in fields such as industrial manufacturing, precision medicine and exploration of extreme environments, and ultimately achieving the ultimate goal of machines adapting like living beings.

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