Structure-Function Coupling Design in Intelligent Bionic Materials and Its Application in Robotics

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Abstract: The structure-function coupling design of intelligent bionic materials is the key to breaking through the limitations of traditional robot materials. Starting from the biological prototype, this paper analyzes the law of multi-scale structure and function in the principle of bionics. It elaborates on the analysis of biological prototypes, function-oriented mapping, and design methods for multi-scale optimization, as well as the response mechanisms of materials to external stimuli. On this basis, it summarizes three typical designs, including bionic multi-level structure, intelligent response structure, and multi-functional integrated structure. It discusses their use in robotic motion systems, perception-driven systems, and complex environments. The design has been validated to effectively enhance the flexibility, environmental adaptability, and functional integration of the robot. The research indicates that the structure-function coupling design offers a novel approach to upgrading robot technology, necessitating advancements in precision, high performance, and industrialization in the future.

1. Introduction

1.1 Research Background

Intelligent bionic material is a novel type of material designed to emulate the biological structure and functional characteristics of nature. In the contemporary era, marked by unrelenting advancements in science and technology, robotics has emerged as a pivotal element within various domains. These domains encompass industrial manufacturing, medical health, and the service industry, among others. Conventional robot materials are characterized by their inability to exhibit high levels of responsiveness, adaptability, and environmental resilience [1].

Intelligent bionic materials offer new opportunities for robot technology development by mimicking the superior properties of biological materials, including adaptability, environmental response, and multi-functional integration. These materials dynamically adjust their structures to adapt to diversified working environments and task requirements, thus significantly improving the performance and adaptability of robots. The research and development of the structure-function coupling design of intelligent bionic materials will not only foster technological innovation in robotics but also establish a strong foundation for a more intelligent and efficient robotic system.

1.2 Research Significance

The research on intelligent bionic materials is of great significance in the development of contemporary science and technology. Studying biological structures and functions in nature through bionics helps reveal the fundamental principles of complex behavior in natural systems, thereby advancing the exploration of materials science. These materials can simulate the self-repair, self-adaptation, and environmental perception of organisms, and provide a new way to realize highly complex and flexible artificial systems. In the application of robot technology, intelligent bionic materials significantly improve the performance and efficiency of robots, thus promoting the popularization and use of robots in many fields. It plays a crucial role in industrial automation and precision medical care, while also promising to enhance the quality of human life and address practical problems in the medium to long term.

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Furthermore, the innovative design and application of intelligent bionic materials will enhance interdisciplinary cooperation and bring new vitality to fields like material science, bionics, and bioengineering. By developing more portable, energy-efficient, and flexible robotic systems, these materials also contribute to environmental protection by reducing energy consumption and optimizing resource use. The research on intelligent bionic materials will promote the progress of science and technology, and also has a far-reaching impact on achieving the goal of sustainable development.

1.3 Research Purpose

The research on the structure-function coupling design of intelligent bionic materials and their application in robotics aims at achieving multiple goals. Through in-depth analysis of the complex structure and functional relationships in biological systems, we aim to uncover the fundamental principles underlying efficient adaptation mechanisms in nature. It will provide theoretical support and inspiration for developing new intelligent materials. Given the limitations of material performance in existing robot technology, we are committed to developing materials that can adapt to environmental changes, thus improving the flexibility and operability of robots. In this process, the method of optimized structure-function coupling design is explored with the objective of enhancing the efficiency and functionality of materials in specific applications [2].

This paper aims to promote the popularization of intelligent bionic materials in practical applications, particularly in the advanced development of robotic motion systems and sensory drive systems. Through material innovation, we can achieve more efficient task execution and environmental interaction. In addition, through the multi-functional integrated architecture design of materials, it is hoped to reduce the complexity of the system and improve the comprehensive performance of the equipment. The ultimate goal is to establish a new approach for the integrated development of materials science, robotics, and bionics through interdisciplinary research and application integration, ultimately promoting scientific and technological progress as well as industrial innovation.

2. The Design Principle of Structure-Function Coupling of Intelligent Bionic Materials

2.1 Principles of Bionics and Biological Prototypes

The principle of bionics involves extracting rules from biological phenomena to inform the design of artificial systems. Its essence is to draw lessons from the logic of collaborative optimization of structure and function in biological evolution. The high efficiency of biological systems stems from the precise matching of multi-scale structure and functional requirements. Each structural level, ranging from micro to macro, possesses distinct functions and collaborates to generate overall effectiveness.

For example, the composite structure of nacre and the prismatic layer of shells is a typical case of mechanical function coupling. At the micro level, calcium carbonate flakes and an organic matrix are arranged alternately. This arrangement allows stress to be dispersed through interface sliding, resulting in a toughness that is more than ten times greater than that of pure calcium carbonate. At the macro level, the curved shell enhances impact resilience and demonstrates the simultaneous existence of lightness and substantial strength. The principle of collaborative damage resistance of this hierarchical structure inspires the design of robot protective materials.

Another typical prototype is the movement mechanism of plant tendrils. Its cell layer consists of cellulose fibers arranged vertically and lignin distributed horizontally. When the environmental humidity changes, the fiber layer produces asymmetric stress due to the difference in water absorption expansion rate, which drives the tendrils to bend. The principle behind the anisotropy of this structure dictates the direction of motion. It illustrates that adaptive deformation can occur without needing a complex driving device; in other words, the structure itself functions as both a sensor and a driver.

These biological prototypes jointly reveal the underlying logic of bionic design. The functioning of the system is not reliant on external complex factors. Instead, it is achieved through multi-scale regulation of the structure, ranging from molecular composition and micro-configuration to macro-morphology. This approach provides a biological basis for the structural design of intelligent bionic materials [3-4].

2.2 Design Method of Material Structure-Function Coupling

The design of intelligent bionic materials should systematically follow several methods: analyzing biological prototypes, extracting structural parameters, mapping functional targets, and integrating across multiple scales. The key is to convert the functional requirements found in biology into quantifiable structural parameters.

The first step is the cross-scale analysis of the biological prototype. Through microscopic imaging and mechanical testing, the structural hierarchy of biological systems is dismantled, from nano-molecular arrangement to centimeter-level overall morphology, and its key functions are identified. For instance, when analyzing gecko soles, it is imperative to meticulously delineate parameters such as the length of bristles, which ranges from 30 to 130 microns, the diameter, which is approximately 5 microns, and the terminal bifurcation structure, which is about 100 nanometers. Additionally, it is crucial to ascertain the correlation law between these parameters and adhesion.

The second step is function-oriented structural mapping. According to the specific requirements of the robot, such as driving speed and sensing accuracy, the required structural characteristics are deduced in reverse [5]. If we need to design high-sensitivity tactile materials, we can learn from the dermis and epidermis structure of human skin. Micro-bumps on the epidermis increase the contact area, enhancing perception, while elastic fibers in the dermis cushion pressure to prevent overload damage. By adjusting bump density and fiber elastic modulus, we can realize the functional coupling of sensitive perception and anti-damage.

The third step is multi-scale integrated optimization. We use computer simulation, such as finite element analysis, to verify the synergistic effect of different-scale structures. For instance, in the design of flexible materials that emulate octopus tentacles, it is imperative to simulate the effect of the arrangement angle of microscopic muscle fibers—alternating between 30 and 60 degrees—on the overall bending curvature. Furthermore, it is imperative to ensure a precise alignment of fiber shrinkage, global deformation, and grasping force through iterative optimization. This approach is instrumental in averting functional imbalances that can arise when design is concentrated on a solitary scale [6]. By breaking away from the traditional separation of structure and function, this method allows materials to shift from being passive bearers to active responders.

2.3 Performance Regulation and Response Mechanism

The performance regulation of intelligent bionic materials depends on the dynamic coupling of structural parameters, external stimuli, and functional output. The key is to design the materials to produce predictable functional responses to specific stimuli.

From the perspective of the response trigger mechanism, external stimuli such as temperature, electric field, and humidity can realize functional transformation by changing the internal structural state of materials. Temperature-responsive materials like shape memory polymers rely on the crystallization and transformation of molecular chains between amorphous and crystalline states. When the temperature exceeds the critical value, the molecular chain changes from the ordered crystalline state to the disordered state, and the material returns to the preset shape, which can be controlled by adjusting the length of the molecular chain and the crosslinking density. Electric-field-responsive materials, such as electroactive polymers, align molecular chains in response to the electric field generated between electrodes. The degree of deformation is positively correlated with both the thickness of the material and the intensity of the electric field. The driving force can be enhanced by designing multilayer laminated structures.

The mapping relationship between structural deformation and functional expression is the key to regulation. Taking the tensile properties of bionic wrinkle structure as an example, when the micro-wrinkle spacing is 10 to 50 microns, the material can achieve 100% to 300% tensile rate, and the expansion and contraction of wrinkles are accompanied by resistance changes, which can simultaneously realize the driving and sensing functions; If the spacing of the wrinkles is reduced to

1 to 5 microns, the material will exhibit higher tensile strength, but its response speed will decrease. Structural parameters determine the principles of performance selection, providing a foundation for targeted regulation. By adjusting the geometric parameters of a microstructure, such as size, density, and arrangement, a balance between the sensitivity, strength, and response speed of materials can be achieved to meet the functional requirements of robots in various scenarios.

3. Typical Structure-Function Coupling Design Types of Intelligent Bionic Materials

3.1 Bionic Multi-Level Structure Design and Mechanical Function Coupling

The bionic multi-level structure design achieves cooperative coupling of different mechanical properties by replicating the multi-scale hierarchical characteristics of biological systems [7]. The fundamental principle underlying this design is to empower micro, meso, and macro structures to execute their respective functions and collaborate effectively.

The bionic skeleton structure focuses on the balance between light weight and high strength, and draws lessons from the "sandwich" configuration of insect exoskeleton-the outer layer is a dense mineralized layer with high hardness; a porous, loose layer is arranged in the middle to reduce the weight; the inner layer is an elastic fiber layer to absorb impact. This structure reduces the material density by more than 40%. Moreover, the bending strength has improved by more than two times, solving the problem of "the stronger the strength, the heavier the weight" in traditional robot structures.

The bionic flexible joint structure refers to the "boneless drive" mechanism of octopus tentacles, and realizes continuous deformation through the layered arrangement of muscle fibers: The outer annular muscle contracts to control diameter changes; the longitudinal muscles in the middle layer contract to regulate length changes, while the oblique muscles in the inner layer adjust the bending direction. In summary, the coordinated movement of a multi-layer muscle structure allows the material to maintain flexible bending ability while accurately controlling the deformation angle. This innovation overcomes the limitations of the motion range found in rigid joints.

Biomimetic surface structures focus on regulating the mechanical functions of interfaces, similar to the micro-nano bristle array found on a gecko's sole. Microscopically, the ends of these bristles diverge to form nano-scale contact points, enhancing intermolecular force. Macroscopically, the arrangement density of bristles changes dynamically with the contact angle, which realizes the rapid switching of "touching and sticking, pulling and releasing", enabling materials to maintain stable adhesion and flexible desorption on smooth and rough surfaces.

3.2 Design of Intelligent Responsive Structure-Function Coupling

Intelligent responsive design can effectively convert structural changes in materials into specific functional outputs by adapting to external stimuli. This process establishes a directional relationship between "stimulus, structure, and function."

A temperature-responsive structure is created using shape memory polymers. Its functionality is achieved through a collaborative design that considers both the crosslinking density of molecular chains and the macro-scale morphology. At the molecular level, the distribution of crosslinking points is adjusted to control the memory temperature threshold. At the macro level, the material is preset to fold or bend into a specific shape. When the temperature reaches a critical point, the molecular chains revert to an ordered arrangement, causing the macro-structure to reset. This design allows the material to perform both "temporary deformation storage" and "high-temperature-driven reset" functions. The accuracy of the reset can be adjusted based on the length of the molecular chain.

Based on the principle of "asymmetric expansion" of plant tendrils, the humidity-responsive structure adopts a double-layer fiber composite structure: one side is a hydrophilic fiber (high expansion rate after water absorption), and the other side is a hydrophobic fiber (low expansion rate). When the humidity changes, the volume difference between the fibers on both sides produces a bending moment, which drives the material to deform directionally. By adjusting the fiber density and the strength of the bonding between layers, we can accurately control both the bending angle and the response speed, enabling a transition from slow curling to rapid turning.

The electromagnetic response structure emphasizes efficient driving functions, mimicking the mechanism of biological muscles. In this design, polar molecules are arranged directionally within a polymer matrix, with a flexible electrode layer on the surface. When an electric field is applied, these molecules align with the field, resulting in the contraction of the entire material. Suppose magnetically sensitive particles are incorporated, and a specific chain distribution structure is created. In that case, these particles will align along the magnetic field lines, allowing the material to be stretched or twisted. By optimizing the molecular orientation and the arrangement of electrodes or magnetic fields, the driving efficiency can exceed three times that of a traditional motor.

3.3 Design of Multifunctional Integrated Structure

Multifunctional integrated design is a method of material fabrication that enables a material to possess two or more core functions concurrently. This is achieved through the integrated planning of the material's structure, thereby circumventing the structural redundancy that results from the straightforward superposition of functional modules.

The sensing-driving integrated structure integrates the functions of signal sensing and mechanical deformation into the same structure: for example, a multi-layer composite structure imitating human skin, in which the surface micro-bumps sense pressure through the change of contact area (sensing function), the middle elastic conductive network changes resistance with deformation (signal transmission), and the bottom driving layer contracts under the action of electric field (driving function). The three-layer structure operates in unison, allowing the material to not only detect the force when it makes contact with an object but also to adjust the contact position simultaneously. As a result, the response delay is reduced by over 50% compared to the traditional "sensor + driver" setup.

Environment-adaptive composite structures emphasize the functional coordination of complex scenes, such as the integrated design of "light adjustment and thermal protection" to mimic chameleon skin. Its outer layer is a micron-scale concave-convex structure, which adjusts light absorption through reflectivity change and is used for temperature control. The middle layer is a porous thermal insulation layer for heat insulation. The inner layer is a hydrophilic gel, which is helpful for humidity adjustment. This structure helps the material to keep the internal temperature stable in the environment of -20℃ to 60℃. It can adapt to the light intensity through color change without additional temperature control equipment.

For the self-repairing and function-maintaining structure, it realizes the performance recovery after damage through the intrinsic structure design. Take the "microcapsule-matrix" composite structure imitating biological tissue as an example: microcapsules containing repair agents are distributed in the matrix material. When cracks form in the structure, the microcapsules break and release the repair agent, which creates new chemical bonds within the cracks. At the same time, the reticular fiber structure of the matrix limits crack propagation through elastic deformation, allowing the material to maintain more than 70% of its original strength during the repair process. It solves the problem of functional interruption that occurs when traditional materials are repaired.

4. Application of Intelligent Bionic Materials in the Field of Robotics

4.1 Application of Bionic Structure Design in Robot Motion System

The bionic multi-level structure design provides an efficient solution for the robot motion system, and improves the motion performance by reproducing the biomechanical coupling law. The biped robot utilizes a multi-level skeleton structure inspired by an insect-like exoskeleton. The outer layer is dense and abrasion-resistant, while the inner layer is porous and lightweight. As a result, the robot's load-bearing capacity is increased by 30%, and its weight is reduced by 25%, making it suitable for navigating complex terrain. Additionally, the flexible joint structure of octopus-like tentacles is utilized in continuous robots. Multi-layer muscle fibers simulate biological driving modes, enabling 360-degree bending and precise steering without rigid joints. This capability enables robots to navigate through narrow spaces with a diameter of only 1.5 times their diameter. The micro-nano surface structure of the gecko's foot allows the climbing robot to maintain stable adhesion and quick detachment on various surfaces, such as glass and concrete, by adjusting the contact area of the bristle array. Moreover, the climbing speed is increased to twice that of the traditional adsorption robot.

4.2 Application of Intelligent Response Material in Robot Perception-Drive System

The intelligent responsive structure promotes the robot's perception-driven system to be integrated and realizes the direct correlation between environmental stimuli and actions. Temperature-responsive materials are used in adaptive grasping robots. The clamper is composed of a shape memory polymer, which possesses the capability to deform and conform to the contours of the object at low temperatures. Following the application of heat, the polymer recovers its original shape, thereby clamping the object. This mechanism is designed to prevent damage to fragile objects caused by rigid clamping techniques. Humidity-responsive materials are applied to pipeline inspection robots, which can sense the change of environmental humidity through the double-layer fiber structure, automatically bend and adjust the direction of travel, and adapt to the path switching in wet pipelines. Electromagnetic response materials are integrated into the micro-robots. The cordless drive design eliminates cable constraints, allowing for millimeter-level precision in displacement. By adjusting the electric field and utilizing an assisted magnetic field, it can achieve complex trajectory movements. This technology is particularly suitable for delicate applications, such as minimally invasive surgery.

4.3 Application of Multifunctional Integrated Materials in Robot System

The integration of multifunctional materials into robotic systems has the potential to streamline the system's structural design, facilitating collaborative functionality through the utilization of a singular material. The construction of a flexible robotic skin is predicated on materials with integrated sensing and driving capabilities. The surface microstructure senses the contact pressure, and the bottom driving layer synchronously adjusts the contact force. When employed in the context of robotic operations, the system demonstrates an ability to accurately identify both soft and hard objects, while exhibiting a capacity to adapt to the grasping force exerted by the robotic apparatus. The utilization of environment-adaptive composite materials in the construction of polar exploration robots represents a significant advancement in the field. The outer structure adjusts the light absorption and controls the temperature, and the inner moisturizing structure keeps the internal components stable. Its continuous working time at -40°C is extended to three times that of the traditional robot. Additionally, self-repairing materials enhance the reliability of disaster rescue robots. The microcapsule structure releases a repairing agent upon shell damage, restoring 80% of mechanical properties within 2 hours and reducing the failure probability in extreme environments.

5. Conclusion and Prospect

5.1 Primary Research Conclusions

The structure-function coupling design of intelligent bionic materials is the key to breaking through the performance bottleneck of robots. Research findings indicate that the multiscale structure coordination law of biological prototypes constitutes the fundamental basis for design. The design of bionic multi-level structure, intelligent response structure, and multifunctional integrated structure can realize the optimization of material mechanical properties and the efficient coupling of environmental response and functional integration. These design methods successfully address the issues associated with traditional robots, such as limited material flexibility and a singular focus on function. They demonstrate significant advantages in lightweight motion systems, integrating perception and drive, and adapting to complex environments. This verifies the feasibility and effectiveness of structure-function coupling design in enhancing the environmental adaptability and functional integration of robots.

5.2 Future Development Trend

Future research will focus on three aspects. The first is the precision of cross-scale design, which integrates AI and multi-physical field simulation to achieve parametric regulation from the molecular level to the macro-structure level. The second breakthrough is in material performance, which focuses on enhancing response speed, durability, and biocompatibility, thereby expanding its applications in medical treatment and deep space exploration. The third aspect is industrialization: developing cost-effective preparation technology, facilitating the transformation of laboratory results into practical robot components, and ultimately achieving a technological breakthrough for a new generation of robots featuring self-driving materials and adaptive systems.

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