Research on robot structure design and motion characteristics based on the bionic principle

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Abstract. With the development of science and technology, robot technology has been widely used in many fields, but traditional robots have limitations in terms of structure and motion performance. Based on the principle of bionics, this paper studies the structural design and motion characteristics of robots. The application principle of bionics in robot design is described, including the imitation of morphological structure, motion mechanism, perception, and control. The development course of the bionic robot is reviewed, which is divided into the embryo exploration stage, the technology development stage, and the rapid breakthrough stage. The working principle and typical cases of each stage are analysed. By comparing the structure design, control technology, application field, and effect of different development stages, the development trend of bionic robots is revealed. The research shows that although the bionic robot has made remarkable progress, it still faces challenges such as high cost and insufficient reliability. In the future, it is necessary to further optimize the structural design, improve the control algorithm, and reduce the cost to promote the wider application of bionic robots. The research results provide theoretical reference and practical guidance for the development of bionic robots.

Keywords: Bionic Robot, Structural Design, Motion Control.

1. Introduction

At present, with the rapid development of science and technology, robot technology has become an important force in promoting the progress of modern society and has been widely and deeply integrated into industrial production, medical health, logistics and transportation, aerospace, and many other fields. With the increasing complexity and diversification of application scenarios, the limitations of traditional robot design in terms of structure and motion performance are gradually highlighted. Traditional robots often have too much structural rigidity but not enough flexibility, and their adaptability, flexibility, and energy efficiency are not satisfactory in the face of complex and changeable natural environments or fine operation tasks. For example, in rescue operations in rough terrain, traditional wheeled or tracked robots are prone to getting into trouble, and it is difficult to reach the rescue site quickly. When carrying out fine work such as precision assembly, their motion accuracy and flexibility cannot meet the requirements.

In industrial production lines, robots greatly improve production efficiency and product quality by highly accurate and tireless operation and reduce labour costs [1]. In the medical field, surgical robots can assist doctors in completing extremely delicate operations, improve the success rate of surgery, and reduce the pain of patients [2]. In the logistics industry, automated robots achieve efficient sorting and handling of goods, speeding up the speed of logistics operations [3]. In recent years, the installed capacity of global industrial robots has shown a significant growth trend. The International Federation of Robotics (IFR) notes that its annual growth rate has remained steadily above double digits [4]. This strong growth trend is a strong testament to the growing importance of robotics and its broad application prospects on a global scale.

Traditional robot design's structure and motion performance limitations in operational environments. In stark contrast, creatures in nature have evolved over billions of years to develop an extraordinary array of structures and efficient modes of movement to adapt to their unique environments. These magical phenomena in nature provide a rich source of inspiration for robot design [5]. Bionics, as an interdisciplinary subject connecting biology and engineering technology, emerged at a historic moment and became a key path to breaking through the bottleneck of robot design and promoting robot technology to a higher level.

This research focuses on the design of a robot structure based on bionic principles and makes an in-depth study of its motion characteristics. This study stops at the simple morphological imitation, and in-depth analysis of the internal relationship between the bionic structure and the robot's motion characteristics, and comprehensive consideration of key performance indicators such as motion speed, stability, flexibility, and energy consumption.

2. Principle

In the design of robots, the principle of bionics is mainly to imitate the form, structure, movement mechanism, perception, and control mode of living things.

2.1. Morphological structure

From the perspective of morphological structure, for example, the design of a robot shell imitating the structure of an insect exoskeleton can reduce weight while ensuring strength. Mimicking the streamlined body of a fish can optimize the shape of the robot and reduce movement resistance [6].

2.2. Motion mechanism

In terms of the motion mechanism, the leg movement patterns of mammals are highly adaptive and efficient. Take humans, cheetahs, and so on, for example, their leg muscles and bones cooperate through the orderly flexion and extension of the hip joint, knee joint, and ankle joint. This can achieve a stable, flexible, and diverse mode of movement, whether it is walking, running, jumping, or climbing, it is not a problem. According to these mechanical principles, the multi-joint walking mechanism is designed for the robot so that the walking action of the robot is closer to that of a real mammal [7].

2.3. Perception and control

In terms of perception and control, the robot is equipped with similar navigation and obstacle avoidance sensing modules based on the ultrasonic positioning system of bats. To simulate the neural control mechanism of the human brain, develop an intelligent control algorithm for the robot, so that it can make decisions independently and adjust the movement according to the change of environment [8].

3. The development of bionic robots

3.1. Embryonic exploration period (1960s - 1980s)

3.1.1. Working principle

In this period, the bionic robots were in the embryonic stage, mainly imitating the basic form and action mode of organisms. Taking the robot that mimics the movement of crabs as an example, its working principle is to achieve lateral movement like that of crabs through a simple connecting rod mechanism and motor drive. The legs of the robot are composed of several rigid connecting rods and joints, and the motor drives the joints to rotate through the gear drive, so that the legs can open and close and move. One of the advantages is that its structure is relatively simple. It is easy to manufacture and control, and low cost. The disadvantage is that the movement flexibility is poor; only simple and regular movements can be carried out. The adaptability to complex terrain and environmental changes is extremely weak. At the same time, the movement efficiency is low and the energy consumption is large [9,10].

3.1.2. application

In some simple industrial handling scenarios, the robot, which mimics the movement of crabs, has been tried and applied. It can carry some lightweight, regular-shaped items in a fixed route on a flat factory floor. However, once the ground is uneven and there are obstacles, the robot finds it difficult to work normally, and human intervention is required. And because of its low movement efficiency, the handling speed is far from meeting the needs of large-scale industrial production, which also limits its further promotion and application in the industrial field.

3.2. Technological Development Period (1990s - early 21st century)

3.2.1. Working principle

With the development of computer technology, material science, and control theory, the structure design and motion control of bionic robots in this period have been significantly improved. Take flapping-wing robots that mimic the flight of birds, which work by making wings out of lightweight, high-strength materials such as carbon fibre. Then, through a complex motor drive system and connecting rod mechanism, the flutter frequency, amplitude, and Angle of the wing are precisely controlled. The motor transmits power to the joints of the wings through a series of gears, belts, and other transmission devices to realize the up-and-down flutter and torsion of the wings. The advantage is that it has better manoeuvrability and hover ability than conventional fixed-wing or rotorcraft. This allows flexible flights in tight Spaces, closer to the flight characteristics of birds. The disadvantages are complex structure, high manufacturing and maintenance costs, and extremely high requirements for motor performance and control algorithms. The flight stability is greatly affected by the airflow, and the endurance is poor, which makes it difficult to fly for a long time [11].

3.2.2. application

In the field of urban environmental monitoring, this kind of flapping-wing robot is used for low-altitude, close monitoring. It can flexibly shuttle between buildings in the urban environment, and carry out real-time monitoring of air quality, noise pollution, and more. For example, during a large event held in a city, flapping wing robots are deployed for environmental monitoring around the event venue [12].

3.3. Rapid Breakthrough Period (early 21st century - present)

3.3.1. Working principle

At this stage, the deep integration of multiple disciplines has promoted the bionic robot to make breakthroughs, and the robot has developed in the direction of intelligence and multi-functionality. Taking the underwater bionic fish robot as an example, its performance has been improved with the help of new smart materials and advanced fluid dynamics design. In terms of structure, the robot adopts flexible adaptive intelligent materials such as shape memory alloy and intelligent hydrogel, which can automatically adjust its shape with the change of water flow, reduce resistance, and improve movement efficiency. In terms of motion control, artificial intelligence algorithms and sensor technology are integrated. The sensor collects information such as water flow speed and pressure, and adjusts the motion strategy in real time after algorithm analysis, so that the robot can realize autonomous decision-making and path planning. This kind of robot has high underwater movement efficiency and strong concealability, can work in a complex underwater environment for a long time, and can adapt to various tasks independently. However, it relies heavily on smart materials and algorithms, and material failure or algorithm failure can cause performance to plummet. In addition, the cost of smart materials is high, which limits large-scale applications, and issues of battery life and energy supply have yet to be solved.

3.3.2. application

This kind of underwater bionic robot plays an important role in Marine scientific research. In a deep-sea hydrothermal exploration mission, it completed the accurate mapping of seabed topography and the collection of biological samples under the complex environment of high temperature, high pressure, and strong currents. Through the adaptive deformation of the smart material, it can maintain a stable motion posture in different flow rates and use artificial intelligence algorithms to plan the optimal path to avoid obstacles on the seabed [6].

4. Comparative analysis

4.1. Comparison of structural design

In the embryonic stage of exploration, the structural design of the bionic robot is simple and rough. It mainly mimics the basic shape of organisms, and the joint and transmission mechanisms are simple in design, lacking a deep understanding and application of biological structures. In the period of technological development, with the progress of material science, lightweight high-strength materials began to be used. The design of the structure is also more elaborate, while focusing on the simulation of the biological motor joints and the musculoskeletal system. But the overall structure is still relatively rigid; flexibility and adaptability need to be improved. In the rapid breakthrough period, the introduction of new smart materials, structural design pays more attention to flexibility and adaptability, and can adjust its structure in real time according to environmental changes to achieve more complex and efficient movement [13].

4.2. Comparison of control technologies

The control technology of the early bionic robot is simple. It mainly adopts open-loop control and controls the robot's action through a preset program, which lacks the ability of real-time response to environmental changes. With the development of technology, closed-loop control and model-based control methods are gradually being introduced, which can adjust robot motion according to sensor feedback information. However, the control algorithm is relatively complex and its real-time and robustness need to be strengthened [14].

At present, artificial intelligence algorithms such as deep learning and reinforcement learning are widely used in bionic robot control, enabling robots to realize autonomous learning and decision-making, and have stronger environmental adaptability and task execution ability, but the complexity of algorithms and computing resource requirements also bring new challenges [15].

4.3. Application field and effect comparison

Due to the performance limitation, the application field of the bionic robot in the embryonic exploration stage is very limited. Mainly in some simple and specific scenes, and the practical application effect is not good. In the period of technological development, bionic robots began to be applied in industry, monitoring, and other fields, and can complete some relatively complex tasks. But in the face of complex environments and diverse needs, it is still powerless. With its superior performance, bionic robots in the rapid breakthrough stage have shown great application potential in many key fields such as Marine scientific research, medical surgery, disaster rescue, and military reconnaissance. However, in the process of large-scale promotion and application, they still face problems in cost, reliability, and other aspects [14].

5. Conclusion

This paper focuses on the research of robot structure design and motion characteristics based on the bionic principle. In the principal part, the application of bionics in robot design is described from three aspects: morphological structure, motion mechanism, perception, and control. By imitating the unique structure and function of organisms, ideas are provided for the improvement of robot performance. The development of bionic robots has gone through the embryonic exploration period, the technological development period and the rapid breakthrough period, each stage has different performance in technical principles and practical applications, from the early simple imitation to the current combination of intelligent materials and artificial intelligence algorithms, continuous breakthrough and innovation, playing an important role in Marine scientific research and other fields.

However, the development of bionic robots still faces many challenges. High material costs limit large-scale applications. At the same time, the complexity of the algorithm leads to a large demand for computing resources, and once the algorithm and materials fail, the robot's performance will be greatly reduced. The future work of bionic robots can focus on developing smart materials with lower cost and better performance. Optimizing AI algorithms to reduce computing resource requirements and improving algorithm stability and reliability. It is also necessary to further expand the application scenarios of bionic robots in various fields, at the same time, promote the sustainable development of bionic robot technology, and make it better serve human society.

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