Modern Robot Bionic Design Directions and Application Prospects

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Abstract. This paper focuses on bionic robots in the age of intelligence and discusses their research directions and application prospects. Traditional robots often encounter challenges such as poor flexibility and limited sensory and decision-making abilities, which restrict their adaptability to complex and dynamic environments. Bionic robots, inspired by the structures and behaviours of living organisms, offer solutions by enhancing flexibility, perception, and environmental adaptability. Modern bionic principles encompass behavioural patterns, structural bionics, functional bionics, control systems, and new materials. Advanced research fields include bionic sensing systems, such as bionic skin capable of multi-sensory feedback, bionic drive technologies, like flexible drive robots, and the application of new smart materials. These technologies have found applications across a range of sectors, including healthcare, industrial operations, special environment exploration, and national defence, demonstrating significant potential for real-world impact. However, the development of bionic robots still faces challenges, particularly related to high production costs and insufficient adaptability for diverse environments. In the future, research is expected to move toward smarter, more versatile functionalities, with improvements in cost efficiency and system reliability. These advancements are anticipated to drive transformation across multiple industries and contribute to significant breakthroughs in robotic technology. This study provides a theoretical foundation and practical guidance for the ongoing research and future development of bionic robots.

Keywords: Research Direction; Biomimetic robots; Application Prospects.

1. Introduction

In today's rapid development of science and technology, robots have been widely used in various fields, but traditional robots face many problems. On the one hand, its rigid mechanical structure and movement mode are relatively fixed, with poor flexibility and difficulty in adapting to a complex and changing environment, such as low efficiency in rugged terrain or narrow space operation. On the other hand, traditional robots have limited perception and decision-making capabilities, a lack of rapid response to environmental changes, and are difficult to complete refined and intelligent tasks, which greatly limits their application scope and effectiveness.

Bionic robotics provides a new way to solve these challenges. It gives robots greater flexibility, adaptability, and intelligence by mimicking the behavioural patterns, structures, functions, and materials of living creatures. For example, simulating the multi-legged structure of insects enables robots to walk stably in complex terrain; borrowing the echolocation function of bats enables robots to accurately perceive surrounding objects in dark environments. These advantages of bionic robots can expand the application scenarios of robots. And bionic robots can enhance their work quality and efficiency, which is crucial for promoting the development of robotics.

Bionic machinery originated in the 1960s, is the product of multidisciplinary cross-fertilization. In 1967, Japan's Waseda University developed the first humanoid robot WABOT-1, although subject to technical limitations, but opened the door to bionic robotics research. Since then, with the development of related technologies, more and more multi-functional and powerful bionic machines continue to emerge. Nowadays, in the era of big data and artificial intelligence, bionic robot research is moving towards a more practical and intelligent direction.

This paper is to integrate the research directions and technologies of bionic robots in the age of intelligence and explore their application prospects. The article first describes the principles of modern bionics, then introduces the advanced research directions, then analyses the actual cases in each application field, and finally summarizes the development of bionic robots, discusses the technological challenges, and looks forward to the future changes, providing a reference for the research and development of this field.

2. Modern Bionics in Robot Design

2.1. Modern principles of bionics

2.1.1 Behavioural patterns of organisms

For today's bionics, the behavioural pattern of an organism is already a very broad concept, which can refer to a certain behavioural action of an individual organism. It also encompasses the changes in linkages within and outside the organism's body when it performs a particular action (e.g., the unique body shape of marine organisms in conjunction with their unique locomotor postures), and the behaviour of organisms in groups (e.g., the synergistic cooperation of ants in lifting a heavy object). The functioning of systems necessary for biological activity, like perceptual and feedback systems, and the unique body structures that organisms have evolved to perform a particular behaviour, like the six legs of spiders. All of these biological behavioural patterns that are better in nature are important repositories of material for bionics or bionic robotics research and are core research directions for making bionic robot designs smarter [1].

2.1.2 Bionic type

In the bionic robot in-depth research direction, the general bionic type is divided into structure bionic, function bionic, control bionic, and material bionic. In terms of bionic robot design, structural bionics can optimize the mechanical properties of the robot so that the robot has a more flexible limb structure and more stable connections. Bionic materials provide more lightweight design possibilities for robots, more resilient connectivity materials, and biomaterials that are more compatible and interactive in biological environments. Functional biomimicry expands how robots can collect data and complete tasks. For example, an echo system that mimics a bat can replace visual sensors, allowing robots to accurately identify their surroundings in dark environments. Control biomimicry allows robots to mimic a more efficient biological nervous system to achieve precise robot movement, as well as to mimic the learning feedback mechanisms of organisms to the external environment to allow for better decision-making [2].

3. Advanced Research Directions for Modern Bionic Robotics

3.1. Advanced technology research

3.1.1 Bionic Sensing System - Bionic Skin

In nature, the ability to perceive changes in the outside world is very important for the survival of living creatures, and this is also true for robots that participate in human society. A strong perception system can capture a lot of information for robots to make them more accurate and efficient, so the bionic perception system has become a very important research direction.

One promising bionic sensing research is called bionic skin, which is a bionic sensing system that builds an environment with bionic soft materials and distributes multiple sensors (piezoelectric, magnetic, photoelectric, and other tactile sensors) inside for detecting the external environment [3]. Compared with the traditional robots loaded with specific sensors at specific locations, this bionic skin can monitor the shape, temperature, hardness, texture, and other characteristics of the external objects with the same covering of the skin's position, and the good plasticity also allows this smart skin to attach to any shape of the object to work [4]. At the same time, the bionic skin has good toughness, which can protect the sensors built into the skin.

In addition, this kind of bionic skin has great prospects in skin materials and sensor integration technology, and some researchers have conducted bionic skin construction based on conductive polymer gels. This material can be self-healing and adhesive by adjusting the design of molecules. And it is resistant to high and low temperatures. Some studies introduce an all-protein bionic skin, which is rigidly biocompatible and provides a skin material option for bionic robots with bionic skin to work in a biological environment.

3.1.2 Bionic Drive Technology - Flexible Drive Robot

Bionic drive research has flourished in this direction, mostly using structural bionics, such as hexapod drive robots modelled on spiders or robotic arms modelled on human arms. Today, the limitations of rigid bionic robots in complex environments have led to a focus on soft robots. Many researchers believe that such flexibly driven bionic robots can be adapted to more complex working environments.

Flexibly driven robots are designed to mimic soft creatures such as octopuses or soft robots that are given multiple joints, pneumatically driven robots that are driven by changes in air pressure, magnetically driven robots, and many other types of robots. Different robots have their advantages.

Harvard University has developed an octopus-simulating underwater soft-bodied robot, which mimics the octopus's ink-jet propulsion behaviour by using pneumatic actuation and a viscous soft-bodied gripper for grasping irregular objects. This robot has a good adaptability to the chaotic underwater environment because it is a mimic of a soft-bodied organism [5]. However, such soft-bodied robots often require many motors to control the bionic muscles, which increases the size of the robot and limits the feasibility of soft-bodied robots in many important applications.

Pneumatic soft robots, by definition, also suffer from the problem of motors increasing in size, but today's researchers have designed a pneumatic memory to solve this problem. It uses air (rather than electricity) to set and maintain the state of many soft robot actuators without the need for specialized electromechanical hardware. The researchers have designed a special set of pneumatic logic where gas replaces current through the pathway and air pressure is used to express the logic state of the switches [6]. With this approach, gas soft robots have a smaller size and their corresponding fast characteristics, with a wide range of applications.

Magnetic-driven robots are a relatively new design in modern times, where motion control is achieved by generating a drive or torque through the interaction of an external magnetic field (static, alternating, or gradient) with the magnetic material inside the robot. This design, which does not require a motor drive, allows magnetic robots to be miniaturized. Researchers have developed miniature magnetically driven robots by modelling bacterial flagella or fish swimming, which allows them to work inside living organisms due to their tiny size and flexible magnetic drive [7]. Magnetic actuation also offers the possibility of developing more functionality for soft robots. Some studies have proposed the use of reconfigurable multifunctional ferromagnetic fluid droplets as soft robots, along with the basic mechanism of controlling reconfigurable large deformations and coordinated motions of multiple ferromagnetic fluid droplets through spatio-temporal programming of the external magnetic field [8]. More miniature, more flexible, and more synergistic are the advantages of magnetically driven bionic robots.

3.2. Advanced Smart Materials

Nowadays, bionic robots are going farther and farther in the development of flexible and soft robots, and thus the development of related material science is also moving towards non-rigid materials. Nowadays, there are three directions for the development of advanced and popular intelligent materials for bionic robots: new structural materials, new sensing materials, and new drive materials.

3.2.1 New structural materials

Robots such as bionic soft-bodied organisms or bionic microorganisms require soft materials with a wealth of properties as a substrate for their structures. More common today is the use of shape-memory alloys, which can revert to a predefined shape in response to temperature changes or external stimuli. This property allows robots equipped with such structural materials to deform and adapt quickly in different temperature environments, while maintaining structural stability when working in regular environments [9]. Interestingly, memory alloys can be used both as joints in larger bionic robots and as the form of memory wires as the core skeleton of small bionic robots. It is a promising smart material.

3.2.2 New sensory materials

In the research of new sensing materials, nanomaterials, piezoelectric materials, and optoelectronic materials have broadened the way for bionic robots to pursue faster and more accurate information collection and feedback.

Nanomaterials have a unique quantum size effect, which means that nano sensors can sense even smaller changes in external pressure, temperature, and matter. And sensitive information collection often means that sophisticated operations are possible.

In addition, piezoelectric materials enhance a robot's ability to sense objects by taking advantage of their excellent properties in electric fields. Piezoelectric materials can deform in an electric field and can also convert this pressure signal into a highly sensitive electrical signal to the robot, a property that facilitates the robot's ability to perceive the hardness of an object, surface texture, and other information.

Putting aside the tactile sensing materials, photoelectric materials tend to realize the visual system of natural living creatures in visual sensing. Photoelectric materials perceive light signals through photosensitive materials, and at the same time, realize the mutual conversion of light signals and electrical signals, simulating the visual system of biological eyes receiving light sources and electrical signals transmitting to the brain. Today's optoelectronic materials tend to be more organic, to enhance the flexibility of optoelectronic materials, facilitating the addition of devices used for visual aids, and enhancing visual clarity [10].

3.2.3 New drive materials

The research of new drive materials corresponds to the direction of drive technology research described above, i.e., there is a corresponding development of new drive materials in conventional skeleton drive, electrical stimulation drive, and magnetic drive.

In order to adapt to the more promising soft-bodied robots, shape memory polymers have become the mainstream research direction for new skeletons. For example, in some bionic insect robots, memory polymers are used in the wings of insects, which are not only lighter but also can instantly change their shape according to the external conditions, such as temperature and humidity, and adapt to different flight requirements [11].

Driven by electrical stimulation, ion-conducting polymers use ionic movement to trigger deformation of the material. This ionic movement can correspond to environmental changes. Ionic movement can also be actively moved by autonomously changing the electrical signals, with a variety of morphologies, natural movements, and a lightweight mass.

In contrast, research on magnetohydrodynamic materials focuses on enhancing the rapid change of rheological properties (e.g., viscosity, fluidity) of the materials in changing magnetic fields. In the case of small bionic insects or microbial robots, the sensitivity and accuracy of magnetic actuation as the core actuation means are critical [12]. Today's researchers are trying to achieve the efficiency of magnetic actuation by blending the composition of the magnetic fluid and optimizing the control system of the magnetic field.

4. Application Areas and Case Studies

4.1. Healthcare

4.1.1 Surgical Robot

Human-robot combination of surgical robots is currently more widely used surgical robots, it can provide doctors with magnified high-definition vision, with relatively high flexibility of the mechanical arm, can accurately complete complex surgical operations, reduce surgical trauma, and patient recovery time. The disadvantages are the high cost of equipment, high maintenance costs, the need for professional training, and most importantly, the limited perceptual ability of the robotic arm, which is unable to provide the surgeon with more detailed and precise information, making it difficult for the surgeon to accurately perceive the texture of the tissue and the force applied to it [13].

With the development of bionic technology in the intelligent era, in the future, using bionic skin technology to cover the bionic skin for the robotic arm of the surgical robot will be a direction, the bionic robotic arm equipped with bionic skin can sense the hardness of the tissue, temperature and other information in real time, to enhance the accuracy of surgical operations; in addition, the bionic skin combined with new intelligent materials (all-protein bionic skin) will allow the robotic arm to gently touch the patient's body, to reduce unnecessary medical risks.

4.1.2 Rehabilitation Exoskeletons and Bionic Prosthetics

Some rehabilitation exoskeletons can assist patients to carry out limb rehabilitation training and help patients to restore motor function; for patients who have lost limbs, there are bionic prostheses that can replace part of the function of the missing limbs to a certain extent, and there are some myoelectric-controlled bionic hands that can sense the subtle movements of the patient's amputated limbs and complete simple grasping movements through the development of a feedback system. However, this technology has not been realised on a large scale because the existing rehabilitation exoskeletons and bionic prostheses need to be improved in terms of adaptability, flexibility, and intelligence, lack of biomechanical coordination with the human body, and poor wearing comfort [14].

Subsequent bionic prostheses may use flexible drive technology to develop rehabilitation exoskeletons and bionic prostheses that fit better and are more comfortable. For example, the use of magnetic actuation technology will enable bionic prostheses to achieve finer movements, while using bionic skin to achieve more realistic haptic feedback.

4.2. Industrial and special environments

4.2.1 Quadrupedal Robot Inspection

Boston Dynamics' quadruped robot, Spot is used for inspection in industrial scenarios. It can move in complex terrains and can carry all kinds of testing equipment to inspect factory equipment, power facilities. However, the range of the electromechanical drive used is insufficient, requiring frequent charging when working for long periods of time; in extremely harsh environments, its mechanical structure may be damaged, and its stability needs to be strengthened.

New structural materials are used to improve the durability of the quadruped robot, and pneumatic drive technology combined with pneumatic memory is used to optimize the robot's power system and improve endurance so that it can work continuously and stably in more complex industrial and special environments.

4.2.2 Bionic drones and underwater robots

Bionic drones mimic the flight patterns of birds or insects and have applications in areas such as filming and mapping; underwater robots mimic fish or other aquatic organisms and are used for underwater detection and salvage operations. These kinds of various bionic robots are already involved in human society. In future development, these robots may tend to be more feature rich. Pneumatic actuation may make underwater robots more silent and facilitate biological observation. Flexible robots retrofitted with nano receptors and more flexible bodies could go to more narrow places for search and detection.

4.3. Defiance

Bionic drones have proven to be of great military utility, with their smaller size and unique flight patterns that are less likely to be detected, and advanced optoelectronic materials that provide accurate enemy information as well as the ability to identify and lock onto them. In addition, bionic skins and a variety of non-electromechanically driven bionic robots can be camouflaged into a variety of forms without being easily detected and are less susceptible to enemy signal interference, allowing them to fulfil several military tasks.

5. Conclusion

Bionic robotics is an effective way to solve the dilemma of traditional robots, integrating multidisciplinary results. It is based on biological behavioural patterns and carries out research from biological types such as structure, function, control, and materials. In advanced technology research, bionic skin can sense the outside world in all directions, flexible drive robots can adapt to complex environments, and new intelligent materials provide support for robot development. It is widely used in multiple fields, such as surgical robots to enhance precision, quadruped robots to inspect and optimize the power system, and bionic drones to carry out military missions.

However, the development of bionic robots faces many challenges, such as the high cost of surgical robots, poor adaptability of rehabilitation equipment, and insufficient range of industrial robots. In the future, efforts should be made to reduce costs and improve adaptability, intelligence, and range. We will continue to research and develop advanced technologies, explore more biomimetic inspiration, promote the deep integration of bionic robots with artificial intelligence and big data, expand application scenarios, help industrial change, lead robotics technology to a new height, and create greater value for human life and social development.

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