Available Online: 3 November 2026 DOI: 10.54254/3029-0880/2026.38426

Overview and development directions of bionic robot research

Jiayu Qian

No. 26 Middle School, Wuhan, Wuhan, China

18971583601@163.com

Abstract. Bionic robots integrate life science, mechanical engineering, intelligent control and other multidisciplinary theories, and have important application value in military and civilian scenarios such as agricultural and forestry operations, post-disaster search and rescue, deep-sea exploration, and national defense counter-terrorism. This article divides the development of bionic robots into four stages: primitive exploration, macro-imitation and sports bionics, partial integration of electromechanical systems and biological performance, and integrated research and development for life systems, and sorts out the technical characteristics and representative prototypes of each stage. According to the operating environment, bionic robots are divided into ground, underwater, and aerial categories. The technical characteristics and application scenarios of typical prototypes, including bipedal, multi-legged, limbless, fish-like, and bird-like robots, are analyzed. The study points out that at present, bionic robots still face real bottlenecks such as insufficient analysis of biological movement mechanism, high cost of mass production of new flexible materials, low energy conversion efficiency and limited endurance, and weak environmental perception and autonomous control ability. On this basis, future research should further explore the intrinsic mechanisms of living organisms, promote the integrated design of structure, materials, actuation, and control, improve the environmental adaptability and intelligence of robots, and advance the practical application and industrialization of bionic robots.

Keywords: bionic robot, bionics, structure-driven integration, artificial intelligence

1. Introduction

Under the screening mechanism of natural superiority and inferiority, organisms have developed unique life forms through a series of adaptation and evolution. Their biological structures and body parts have been optimized through evolution, offering superior structural performance, flexible movement, and strong adaptability. The colorful natural organisms have inspired human exploration and innovation. In the early 1960s, an emerging interdisciplinary discipline was born - bionics, which improves existing or creates new machines, instruments, etc. by learning, imitating, copying and reproducing the structure, function, working principle and control mechanism of biological systems [1].

With the progress of intelligent robot technology, bionic robots combine bionics with the application needs of the robot field, imitate the structure, movement characteristics, biological mechanism and other superior

Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

mechanical and electrical designs of organisms, enabling robots to learn from nature such qualities as adaptability, robustness, movement diversity, and flexibility, so as to cope with various real-world situations.

2. Four stages of research and development

Bionic robots have gradually realized the broad application prospect of agricultural and forestry plant protection, deep-sea operation and maintenance, post-disaster search and rescue, medical diseases and other civilian fields, and military fields such as anti-terrorism and riot prevention, deep space exploration and other military fields. In terms of development history, bionic robots have gone through four major stages: primitive exploration, macro-imitation and sports bionics, partial integration of electromechanical systems and biological performance, and integrated research and development for life systems. Relying on the rapid development of the three major technologies of bionics, intelligent control and advanced manufacturing, the life-like system of rigid and flexible hybrid structure, integrated design of bionic structure, material and drive, precision neural control, and high conversion rate energy supply continues to iterate. At present, bionic robots have developed to the stage of life system integrating structure and biological characteristics [2].

2.1. Primitive exploration phase

The early exploration of bionic robots can be traced back to ancient times. The ancients relied on pure mechanical structures to reproduce birds, beasts and human body shapes to design. For example, craftsmen in the Western Zhou Dynasty made highly bionic wooden dolls for King Mu of Zhou, Luban made wooden kites in the Spring and Autumn Period, and Zhu geLiang of the Three Kingdoms invented wooden cows and horses, in the West, early examples include Archytas' wooden pigeon in 350 BC, Al-Jazari's mechanical peacock in the 12th century, da Vinci's flying machine, and Lewis A. Rygg's mechanical horse in 1893 [3], all of which further accelerated human exploration of bionic robots.

2.2. Macro profiling phase

At this stage, the industrial revolution promoted the maturity of precision mechanical technology such as gears and clockwork, which can achieve movement reproduction. The machinery can stably reproduce bird fanning and four-leged steps, but the research is limited to the surface of the body, so that "the movement is like a living thing" cannot adapt to environmental changes. For example, in 1893, Lewis A. The mechanical horse designed by Rygg became the template for all kinds of mechanical beasts in the 20th century, in 1960, Italy's Maratori Golden Horse appeared, in September 1960, the First World Bionics Congress was held at the Air Force Base in Ohio, the United States. Bionic machines have been further promoted in the world. In the following decades, countries around the world have competed to carry out bionic technology research. Bionic theory and technology have developed rapidly, and new bionic principles and bionic equipment have continued to emerge.

2.3. The phase where the electromechanical system and biological performance partially merge

In the 1960s, with the official establishment of bionics and the gradual popularization of motors, sensors, single-chip computers, and pneumatic and hydraulic components, the research and development of bionic robots entered a new stage of electromechanical integration. This P series humanoid robot can be controlled by electric motors on all fours. Early examples include electronically controlled bionic robotic fish that could simulate fish swimming and autonomous speed regulation, as well as pneumatic muscle-driven bionic wall-climbing robots. Most of the bionic robots at this stage were rigid structures. The electrical control logic and

the biological original body function are still separated. They could only reproduce some biological performance sporadically. It was difficult to take into account biological flexible deformation, adaptive design, high-efficiency consumption and other collaborative bionics.

2.4. The integrated R&D phase of the life system

Entering the 21st century, with flexible materials, high-precision servo drives, distributed neural control and precision processing technologies, bionic robots have jumped out of the limitations of fragmented electromechanical integration and entered the stage of life-like development of integration of structure and biological characteristics. At this stage, they no longer merely reproduce the external movements of organisms but also draw deeply on the principles of skeletal and muscular layout, neural perception, and energy metabolism in animals and plants. The rigid and flexible coupling fuselage is generally adopted to realize the integrated design of bionic structure, functional materials and drive unit. With neuronal closed-loop control and bionic energy storage structure,these robots greatly improve environmental adaptability and energy efficiency.

A large number of representative prototypes were born in the world: Atlas Festo in Boston, the United States, reproduces the balance logic of human movement by relying on the rigid and flexible structure of the hydraulic tendon, the German Festo bionic kangaroo uses the elastic structure to restore the kangaroo bouncing energy storage mechanism, the underwater bionic robot of Tsinghua, China, realizes deep-sea self-sugment with the help of rigid and flexible coupling. On the whole, at this stage, bionics has been upgraded from "shape imitation, function assembly" to full-dimensional reproduction of biological mechanism. Robots have flexible movement close to natural organisms, environmental adaptability and high-efficiency consumption characteristics.

3. Categories of bionic robots

Bionic robots use the principle of bionics. The technology involves institutional bionics, perception bionics, control bionics, intelligent bionics and material bionics, etc., and cross-integrates life science, information science, brain and cognitive science, engineering technology, mathematics and mechanics, systems science and other disciplines. Therefore, the classification of bionic robots is relatively complicated. According to the working environment, they can be divided into ground, underwater, and aerial categories. According to movement mode, they include bipedal, multi-legged, limbless, and other bionic robots. This article combines the attributes and characteristics of bionic robots to complete the classification.

3.1. Ground bionic robot

In nature, there are a large number of terrestrial organisms, and their organizational structures and movements have their own characteristics. Combined with the unique physiological structure and movement mode of these terrestrial organisms, global researchers have designed a series of ground bionic robots from the perspective of bionics to replace humans in performing dangerous tasks such as ground reconnaissance, detection, counter-terrorism and biochemical nuclear discharge.

3.1.1. Bipedal robot imitation

After decades of development, bionic bipedal robots have progressed from simple imitation of human lower-limb gait to low-level intelligence capable of basic environmental perception, and now can complete multiple complex anthropomorphic tasks with high intelligence. They hold broad prospects in interstellar exploration, military reconnaissance, life rescue, and other fields.Bionic robots began in the late 1960s. In 1969,

Vukobratovich (Yugoslavia) put forward the core theory of Zero Moment Point (ZMP) [4, 5]. Waseda University in Japan took the lead in carrying out research on bipedal walking robots, and the WAP, WL, and WABOT series robots it developed could achieve basic walking functions. Subsequently, Japan, the United States, the European Union, South Korea, etc. carried out relevant research one after another and achieved staged breakthroughs. In 1986, Dr. Zheng Yuanfang, a Chinese-American, successfully developed the first bipedal walking robot SD-1 in the United States and its improved model SD-2, and improved the basic walking control scheme of the bipedal robot.

Entering the 21st century, sensor technology and intelligent control algorithms have been iterated rapidly, and the movement stability and fluency of humanoid robots have been significantly improved. In 2000, the Honda ASIMO2000 humanoid robot achieved smooth and continuous walking, in 2003, Sony QRIO broke through running technology.

3.1.2. Bionic multi-legged robot

Bionic multi-legged robots are modeled on dogs, spiders, crabs, and other animals with multiple limbs. They rely on structural bionic design. After decades of technological iteration, this kind of robot has grown from a simple imitation of walking to a high-performance mobile robot that integrates environmental perception and intelligent control technology, and its comprehensive performance is closer to the biological prototype.

3.1.3. Bionic legless robot

The snake-shaped robot has a slender body, flexible movement and strong environmental adaptability. It can enter areas that are difficult for humans to reach, and has a broad prospect in the fields of scientific examination, exploration, disaster relief, search and rescue. After decades of development, these robots have progressed from basic imitation of snake crawling to multiple movement modes, including winding, stretching, tumbling, climbing, and amphibious swimming, with basic environmental perception and obstacle avoidance capabilities.Foreign research started earlier. In 1972, Tokyo Institute of Technology in Japan developed the first classic prototypes such as the first snake-like robot ACM-R5 and Slim Slime robot. The models developed by American universities have greatly improved the obstacle-climbing and climbing performance of robots. Shanghai Jiao Tong University, Shenyang Institute of Automation Chinese Academy of Sciences， and other institutions have successively developed prototypes that achieve multi-mode motion and amphibious operation. At present, bionic crawling robots still have problems such as slow marching speed and insufficient autonomous operation ability in complex environments. In the future, it is necessary to focus on improving autonomous control and environmental adaptability.

3.2. Underwater bionic robot

As integrated platforms of underwater high-tech instruments and equipment, underwater bionic robots have broad application prospects and great potential value in military, civil, scientific research and other fields. Underwater bionic robots began by imitating fish swimming. They have evolved from the initial use of motor-driven mechanical systems that imitate the swing of fish tails for propulsion to the current use of new bionic materials and actuation methods.

3.2.1. MantaDroid

In November 2017, inspired by manta rays that can swim quickly in water, researchers at the National University of Singapore developed an underwater bionic robot fish called "MantaDroid". The bionic machine is 14 in (about 355 cm) long, 25in (about 635 cm) wide, and 15 lb (about 06 kg) in weight . MantaDroid's "fish fin" is made of flexible PVC sheet. Each "fish fin" has an electric motor to drive it to swim flexibly in the water, with a speed of up to 0.7 m/s, and a battery life of up to 10 h per charge. A series of sensors or other

payloads can be installed on the abdomen of the robot for underwater reconnaissance, marine resource exploration, marine mapping and other tasks.

3.2.2. RoboTuna

In 1994, the Massachusetts Institute of Technology in the United States created the robot fish "RoboTuna" (Figure 1) by imitating the structure of tuna, which opened the way for the development of underwater bionic robots [6]. The style imitates the appearance of the blue-fin tuna, adopts a multi-joint articulated body structure, and relies on the coordinated swing of the trunk and tail fin to achieve swimming, which pioneers the research direction of bionic machine fish hydrodynamics.

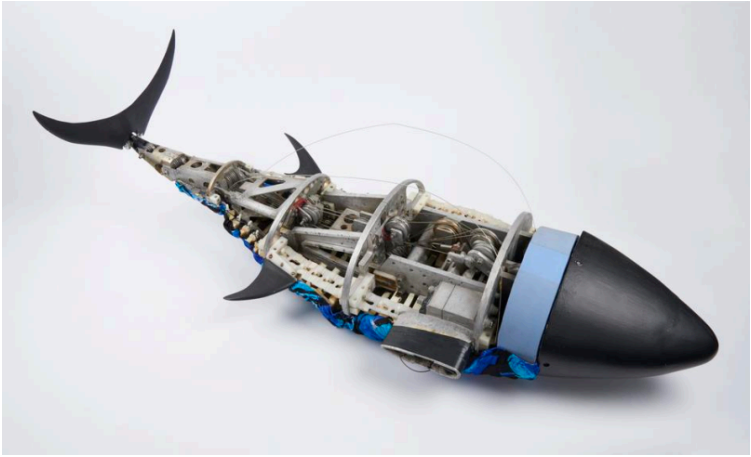


Figure 1. MIT RoboTuna robotic fish

3.3. Aerial bionic robot

Compared with ground and underwater bionic robots, aerial bionic robots have the advantages of small size and flexible movement. They have a wide range of mobile airspace and are not bound by terrain conditions [7]. They have shown outstanding application potential in military and civilian applications such as military reconnaissance, disaster disposal and counter-terrorism, and have therefore attracted wide attention from researchers worldwide.

FESTO, a German company, conducted research on the biostructural characteristics of fox bat wings and developed the BionicFlyingFox bionic fox bat drone. The whole mass of the prototype is 580 g, the number of welding points of the whole machine reaches 45,000, the wingspan is 228 cm, and the body length is 87 cm, the high-elastic spandex fabric wing membrane woven with a honeycomb structure is combined with a carbon fiber skeleton. The overall structure is lightweight, which can reproduce the movement characteristics of high-altitude flying and suspension of most flying animals.

The SmartBird bionic robot bird, also developed by FESTO, made a public appearance at the 2012 Asia PTC exhibition. The prototype is 196 cm long, with a weight of 450 g and a wingspan of 106 cm. It takes into account the lightweight design and power output performance, and follows the principle of aerodynamic design to achieve high movement flexibility [8].

4. Problems with bionic robots

With the continuous expansion of application scenarios, the industry has put forward stricter requirements for the structure and functional performance of bionic robots. There are still many shortcomings in the existing

technical system, which has become an important factor restricting the industrialization and practical implementation of bionic robots.

First of all, the study of the internal mechanism of biological movement is not in-depth enough, resulting in the phenomenon of "likeness" in prototypes. Most of the existing studies focus on the reproduction of biological external limb structures, and the exploration of deep movement mechanisms such as muscle synergy, joint flexible linkage, and dynamic balance regulation is insufficient. Most prototypes can only reproduce basic movement forms, and their movement smoothness and environmental adaptation remain limited. Under complex terrain and dynamic conditions, it is easy to have problems such as rigid movement and poor coordination. It is difficult to fully reproduce the movement advantages of natural creatures, and the bionic adaptation effect needs to be improved.

Secondly, traditional rigid materials constrain flexible motion performance, while new bionic materials face high mass production costs. At present, most bionic robots use rigid substrates such as metal and hard plastic, making it difficult to achieve biological-level flexible deformation and restricting flexible movement and environmental adaptation. The preparation process of flexible bionic materials such as silicone, intelligent polymers and artificial muscles is complex, with low yield and high large-scale production costs. It is difficult to achieve large-scale popularization, forming a double constraint at the level of technology and cost.

At the same time, the low efficiency of energy conversion leads to a prominent short battery life. The energy loss of the bionic robot drive system is significant, and the energy utilization efficiency of the motor and transmission mechanism is far less than that of biological muscles, the high-energy density battery adapted to small and flexible equipment has not achieved a technological breakthrough, and the endurance performance of the whole machine is limited. Most prototypes can only carry out short-term and low-intensity operations, which is difficult to support outdoor detection, long period inspection and other practical tasks.

In addition, the simplicity of the control algorithm architecture also causes insufficient autonomous environmental perception ability. The existing robots mostly rely on preset programs to complete fixed actions. The detection accuracy of the perception system is limited. The ability to identify obstacles and predict the situation of complex environments is insufficient. It lacks the ability of independent decision-making, real-time obstacle avoidance and dynamic adjustment. It is prone to abnormal action in unknown and changing scenarios. The independent operation performance still needs to be further optimized.

5. Future development direction

After 3.5 billion years of natural evolution, organisms have developed body structures and movement mechanisms with excellent performance and strong adaptability, providing an important basis for the research and development of bionic robots. Relying on the cross-disciplinary integration of bionics, machinery manufacturing, information science and artificial intelligence, bionic robots have made breakthroughs in bionic structure design, intelligent perception, drive control and other fields. They can be applied to high-risk scenarios such as environmental detection, military reconnaissance, rescue, etc., and have become a research fever in the field of scientific research at home and abroad.

Despite the rapid development of bionic robot technology, there are still many shortcomings in the research and development system at this stage. Existing research mostly focuses on superficial imitation of appearance and basic movement, while the exploration of biological movement mechanisms, energy conversion mechanisms, and perception mechanisms remains insufficient At the same time, there are problems such as imperfect structural design, limited bionic material properties, insufficient control accuracy, and low energy

consumption efficiency, resulting in the dexterity, stability and environmental adaptability of robots that are far inferior to those of natural organisms, which seriously restricts the actual application.

In the future, bionic robots need to break through the traditional research and development ideas, deeply explore the internal movement mechanisms of living things, rely on multidisciplinary technology to optimize the structure, materials and control system, promote integrated bionic design, develop towards high adaptability and high intelligence, and broaden their application scenarios in rescue, national defense, deep space exploration and other fields.

References

[1] Sun, J., & Dai, Z. (2016). *Introduction to bionics*. Tsinghua University Press.

[2] Gao, F. (2005). Thoughts on the current situation and development trends of organization studies. *Journal of Mechanical Engineering, 41*(8), 3–17.

[3] Rygg, L. A. (1893). *Mechanical horse* (U.S. Patent No. 491927). U.S. Patent and Trademark Office.

[4] Wang, G. B., Chen, D. S., Chen, K. W., & Zhang, Z. Q. (2015). Research status and development trends of bionic robots. *Journal of Mechanical Engineering, 51*(13), 27–44.

[5] Wang, T., & Tao, Y. (2016). *Introduction to robotics*. Tsinghua University Press.

[6] Cui, X., Chang, C., & Miao, X. (2017). Research on the development and application of bionic robots. *Robot Technology and Applications*, (4), 33–36.

[7] Barrett, D. S. (1994). *The design of a flexible hull undersea vehicle propelled by an oscillating foil* [Master's thesis, Massachusetts Institute of Technology].

[8] Meng, T., Wu, X., Fu, Q., & He, W. (2025). Research progress on intelligent bionic flapping-wing robots. *SCIENTIA SINICA Informationis, 55*(12), 2991.