Proceedings of CONF-MLA 2025 Symposium: Intelligent Systems and Automation: AI Models, IoT, and Robotic Algorithms
DOI: 10.54254/2755-2721/2025.LD28092

Bionic Robot Overview and Future Prospects

Jufeng Wang

School of Aeronautics and Astronautics, Sun Yat-sen University, Shenzhen, China
518107Wangjf76@mail2.sysu.edu.cn

Abstract. Bionic robots, an advanced technology mimics biological structures and functions, have a broad application prospects in industrial, medical, military and other fields, and this paper will provide a series of introductions to bionic robots: first, it review the concept and development history of bionic robots; second, it analizes the core technologies of bionic robots, such as kinematic bionics, perceptual bionics, and material bionics; third, it discuss the practical applications of bionic robots in different application fields, such as disaster rescue, medical rehabilitation, and agricultural production; and finally, it looks forward to the future development trends of bionic robots, such as multidisciplinary integration, and ethical issues, etc. The purpose of this paper is to give a clear picture of bionic robots, and to provide an overview of their future development, offering valuable references for researchers and engineers in the field of bionic robotics.

Keywords: bionic robotics, bionics, motion control, application scenarios, ethics

1. Introduction

Bionic robot is a cutting-edge technology field that integrates multidisciplinary knowledge of biology, mechanical engineering, material science, control engineering and artificial intelligence, etc. It is a combination of robotics and bionics principles, and its core concept is to mimic the structural, functional, and behavioural characteristics of nature's living creatures in order to design and develop robotic systems with biologically similar characteristics, which are different from traditional rigid robots in pursuit of structural morphology, locomotion mode, , perception capabilities, and environmental adaptability to biological organisms in order to obtain more efficient and flexible working capability [1].

The design concept of bionic robots originates from the in-depth investigation of biological systems, and the principles and methods of engineering are extracted after deconstructing the movement mechanism, perception means and adaptation strategies of living organisms. This "learning from nature" design philosophy endows bionic robots with unique advantages in complex, variable, and unstructured environments.Currently, bionic robotics has formed a variety of technical routes, such as humanoid robot "forerunner", bionic quadruped robot, bionic aircraft, bionic underwater robots, such as robotic fish, frog-type bionic jumping robots, etc., and each of these technology routes has its own characteristics to build up a rich ecology of bionic robotics research [1].

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2025.LD28092

The earliest bionic robot can can be traced back to the mechanical devices invented by Zhuge Liang in the Three Kingdoms period of China, in the initial stage of human imitation is relatively elementary, and the invented models can only be launched by human power.

From the 1950s onward,, with the continuous development of human science and technology, humans gained a deeper understanding, began to use the power system to drive the new invention of bionic robots, which also marks the development of human bionic robots to enter the second stage: the shape of the imitation plus the bionic motion control.

In the 21st century, as computer technology and the mechanical engineering industry became more sophisticated, scientists began to systematically analyse and create bionic robots. Examples include "BigDog" (developed by Boston Dynamics for the U.S. military) and SoFi (an underwater robotic fish developed by the Massachusetts Institute of Technology, MIT). The current development stage focuses on "life-like systems" that integrate structural and biological properties, i.e., the new bionic robots have the ability to sense and react to the outside world. It is foreseeable that bionic robots are becoming more and more realistic and the capabilities they possess are more refined [2].

This paper explores the development history, core technologies, and practical applications of bionic robots, synthesizing key content in this field. Specifically, it first conducts an in-depth analysis of the core technologies of bionic robots; afterwards, it discusses the practical applications of bionic robots in different application fields such as disaster rescue, medical rehabilitation, and agricultural yield improvement; and finally, it looks ahead to the future development trends of bionic robots. This paper provides a systematic introductory review for researchers and engineers in the field of bionic robots and offers valuable insights.

2. Typical biological models and bionic design

Bionic robots mainly use the principle of bionics, the technology involved includes mechanism bionics, perception bionics, control bionics, intelligent bionics and material bionics, etc. [2].

2.1. Motion bionics

In the research of bionic robotics, kinematic bionics is one of the most core directions, and its basic concept is to deconstruct and simulate locomotion mechanisms of living organisms, thereby designing robotic systems with similar movement ability, and the research in this field is not only focusing on the surface movement form of living organisms, but also probing into the principles of biomechanics, the efficiency of energy conversion, and the mechanism of neural control.

Motion bionics is characterised by adaptability and efficiency. In response to the social phenomenon that the number of elderly patients with cerebrovascular disease is increasing year by year, Xu Hongwei from Jilin University used motion bionics to develop a rehabilitation robot to assist patients in rehabilitation training. By analysing the kinematics and dynamics of the human gait walking process, he conducted innovative design and 3-dimensional modelling of the mechanism of the whole lower limb rehabilitation training equipment, and calculates tthe key parameters of the transmission system, and applies simulation analysis software to carry out mechanical validation and lightweight design of the main load-bearing mechanism in the mechanical structure [3]. This study shows that kinematic bionics is developing from pure morphological imitation towards deep-level biological mechanism recreation.

DOI: 10.54254/2755-2721/2025.LD28092

2.2. Perceptual bionics

Perceptual bionics develops sensor systems and information processing methods that mimic biological perceptual abilities through the study of the working principles of organisms' perceptual systems, which are different from traditional sensing technologies and place more emphasis on the overall architecture of the perceptual system, multimodal fusion, and adaptive processing capabilities. Harvard University and NeuroTactile jointly developed an e-skin is a typical achievement of perceptual bionics, which mimics the multilayered structure of human skin and the distribution of mechanoreceptors, and integrates pressure, temperature, humidity, vibration, and other sensing functions. 2021 NatureElectronics study shows that this bionic electronic skin can recognize over 100 different types of stimuli. In June 2024, Chinese scientists achieved breakthrough progress in the field of electronic skin and successfully developed the world's first electronic skin system with a bionic three-dimensional structure, which is on par with that of real human skin [4].

Perceptual bionics has three main features, namely, multimodal integration, low-power processing, and adaptive learning. For example, the bionic tentacle system developed by the University of Tokyo integrates mechanoreception and chemosensory functions so that robots can simultaneously perceive the shape of an object and material properties. The TrueNorth neuromorphic chip from IBM Research mimics the cortical processing of the human brain, and its energy consumption when doing visual recognition tasks is only 1% of that of traditional GPUs, which is a good demonstration of the energy efficiency advantages of bionic perception systems. The Darwin Mouse, developed by Zhejiang University, can build a brain-inspired computing system with a scale of ten million-level neurons and accomplish various recognition tasks [5]. These cases fully illustrate that perceptual bionics has an outstanding advantage in complex environment adaptation.

2.3. Material bionics

Material bionics refers to the study of the structural, material, and organizational properties of living organisms to develop artificial materials and structural systems. This field not only pays attention to the static performance of materials, but also pays more attention to the dynamic response characteristics and self-healing capabilities. Material biomimicry is mainly embodied in the aspect of structure-function integration. In recent years, inspired by the body structure and movement characteristics of mollusks, researchers have designed and manufactured a variety of flexible robots. For example, a seal-like crawling robot with a thin-film oscillator as a power source has been designed, which can move rapidly and autonomously between electrode plates and can carry a weight of about 5.2 times its own weight forward. On this basis, PE/MXene optical actuators were assembled on both forelimbs of the robot as rudders to control the robot's steering, and the optical actuator film was externally irradiated with an infrared laser to bend and deform the film to steer the moving robot. Under the dual control of voltage and laser, the crawling robot was able to complete the complex task of avoiding obstacles over a distance of about 180 mm in 104 s. . Unlike traditional rigid robots, this robot uses a new type of flexible actuator material, making it more flexible and enhancing its adaptability to the environment [6]. The development of material bionic technology has evolved from single-function materials towards multifunctional integration, self-adaptation and even self-organisaion, which plays a key supporting role for bionic robots to break through traditional limitations.

DOI: 10.54254/2755-2721/2025.LD28092

3. Core technology analysis

3.1. Motion control: analyzing key motion control technologies and their implementation modes

In order to realize the biologically inspired movemen of bionic robots, the motion control system serves as the core technology. Key components of this system include biomechanical model construction, motion planning and trajectory generation, multi-dimensional perception feedback and adaptive control are the key technologies, and the biomechanical model construction technology provides a theoretical foundation for the control algorithms by accurately modelling the kinematics and dynamics of living organisms.

The traditional centralized control model is no longer the sole implementation path for motion control technology; instead, the field is shifting toward a distributed bio-neural control network that simulates an organism's neural reflex arcs and central pattern generator (CPG). This system enables tightly couple local sensing and control. Guo-Jun Chen, Yu Wang, Wei Chen and Zhi-Ming Wang jointly proposed a particle swarm optimisation algorithm-based CPG motion control method for generating motion control signals for an underwater bionic robotic fish. This method has high control efficiency and offering a new direction for future research on motion control methods for high mobility underwater bionic robots, and provides a research basis for subsequent underwater bionic robots for continued improvement and optimisation [7].

3.2. Driving methods: exploring the diversity of driving methods and optimisation paths of bionic robots

The drive technology of bionic robots is no longer limited to traditional motor-driven systems, but towards diversification and high integration development, which derives from electric drive, pneumatic/hydraulic drive, artificial muscle drive and hybrid drive and many other technological routes, of which the electric drive system relies on precision motors and specialized transmission mechanisms to achieve high-precision, high-responsiveness motion control, for example, the development of the MIT MiniCheetah quadrupedal robot. For example, the MiniCheetah quadruped robot developed by the Massachusetts Institute of Technology (MIT) is equipped with customised high-torque-density motors and a planetary gear reduction system, which enables each leg to be controlled at a frequency of 230Hz and allows the robot to jump with a load 12 times its own weight.

Technological routes align more closely with biological driving principles are represented by pneumatic/hydraulic drive and artificial muscle drive. Zhang Daohui et al. proposed a new equivalent spring model for pneumatic artificial muscles in 2018, achieving relatively independent control over joint position, force, and stiffness to accomplish complex movements such as bending and twisting [8]. This hybrid drive scheme has become the mainstream technology route for bionic quadrupedal robots and bionic prosthetics, reflecting the trend of technological evolution towards biologically inspired driving mechanisms.

3.3. Energy systems: studying the impact of energy systems on bionic robot performance

The practicality of bionic robots is determined by the key element of the energy system, the design of which needs to take into account the characteristics of energy density, power output and biological energy management mechanism. For example, Cai Wenjie from Harbin Institute of

DOI: 10.54254/2755-2721/2025.LD28092

Technology designed an energy control system based on the classical PID algorithm for quadruped robots, drawing on the theoretical model of conventional PID, which overcame the difficulties in algorithm design and hardware design, realised the algorithm design of the controllable energy system, and addressed the impact ofthe state change of quadruped robots in the process of movement on the engine speed. , which enhances the stability and reliability [9].

4. Application scenarios and future prospects

4.1. Current applications: practical case studies in disaster relief, medical care, agriculture, etc.

Bionic robots have unique value in the field of disaster relief. BigDog, a quadrupedal robot from Boston Dynamics in the US, is modelled after a dog and is capable of performing search and rescue tasks at a disaster site, including moving on uneven terrain and crossing obstacles in the disaster area. RoboSimian, a robot developed at Caltech and the University of California, Santa Barbara, is ape-inspired and can be used to respond to emergencies in disaster scenarios by performing a variety of ground and manoeuvring tasks such as driving vehicles, entering buildings, opening doors, turning valves, and picking up tools [10]. A hexapod robot built on the Robot Operating System (ROS) exhibits excellent intelligence, responsiveness, and stability, enabling it to perform various rescue activities more effectively [11] This shows that in complex environments, the adaptability and flexibility of bionic robots are unmatched by traditional machines.

The applications in medical and agricultural fields are also notable. Take medical treatment as an example, Harvard University Wyss Institute's soft bionic cardiac assist device has been used in clinical trials since 2020, and so far more than 200 patients with heart failure have been assisted with treatment and the incidence of complications has been reduced by 42 per cent compared with traditional mechanical devices, and in agriculture, first of all, the soft robotic system minimises the risk of mechanical damage, which is the same as conventional mechanical devices. Firstly, the soft robotic system minimises the risk of mechanical damage, which is a common problem with traditional mechanical harvesters and manual picking. Mitigating mechanical damage has real benefits for farmers, as post-harvest losses can negatively impact profitability. Secondly, swarm robotics systems can enhance pollination by supplementing critically endangered natural bees. Alternatively, swarm robots could perform other important farm functions, including spraying pesticides and monitoring crop growth [12] This suggests strong application prospects and commercial value.

4.2. Future prospects: multidisciplinary integration trends and ethical considerations

The future development of bionic robots will clearly exhibit a trend of multidisciplinary integration. The boundaries between disciplines such as biology, materials science, artificial intelligence, and control engineering have gradually become blurred, and cross-disciplinary collaboration will be the next core driver for promoting innovation in bionic robots. The future development of bionic robots cannot proceed without ethical considerations, today's bionic robots are still in the development stage, without exposing obvious ethical conflicts between humans and robots. As bionic robots are slowly integrated into society, the technical and ethical issues become increasingly prominent, so there must be clear norms on the boundaries of human-robot interaction, privacy protection, and decision-making transparency. In today's era when bionic robots themselves are driving the global

DOI: 10.54254/2755-2721/2025.LD28092

economy, it is crucial to prioritize the well-being of individuals and society to ensure their steady development [13].

5. Conclusion

This paper focuses on the development bottlenecks and application value of bionic robots, with emphasis on analyzing three core issues currently facing them: motion control, driving modes, and energy consumption. Despite these challenges, with the iteration of bionic robot technology, its application scenarios and practical value continue to expand, and its potential in fields such as earthquake rescue and disaster relief, medical rehabilitation, and agricultural production is gradually being realized. Looking ahead, with breakthroughs in core technologies, bionic robots will further address the current bottlenecks and continuously unlock their technological value.

Limited by the quantity and scope of the literature cited in this paper, there are limitations in the comprehensiveness and depth of the elaboration of some contents. For subsequent research on bionic robots, efforts will be made to further expand the breadth and depth of literature retrieval, striving to provide more abundant theoretical support and more credible empirical evidence for the elaboration of relevant contents. In this way, the development status and trends in the field of bionic robots can be presented in a more comprehensive and objective manner.

References

[1] Jian Xun. Review of bionic robot research and development direction [J]. Robotics Technology and Application, 2022, (03): 17-20.
[2] MEN Bao, FAN Xuekun, CHEN Yongxin. Research on the development status and trend of bionic robot [J]. Robotics technology and application, 2019, (05): 15-19.
[3] Xu Hongwei. Structure design and optimisation of walking motion bionic robot [D]. Supervised by Kun Liu. Jilin University, 2020.
[4] Bionic Three-Dimensional Electronic Skin Unlocks New Experiences in Future Intelligent Perception [J]. Keji Chuangxin yu Pinpai (Journal of Technological Innovation and Brand), 2025, (01): 74.
[5] Zhu Saike & Zhao Yi. Towards Synaptic Devices and Chips for Neuromorphic Systems: A Review and Outlook [J]. Journal of Functional Materials and Devices, 2024, 30(06): 287-299. DOI: 10.20027/j.gncq.2024.0043.
[6] Qiu Changwen. Research on bionic intelligent actuators based on MXene flexible composite material and its performance [D]. Supervisor: Ying Hu. Hefei University of Technology, 2023.
[7] CHEN Guojun, WANG Yu, CHEN Wei, WANG Zhiming. Research on motion control of underwater bionic robot based on improved PSO [J]. Computer Simulation, 2025, 42 (01): 405-409+434.
[8] Zhang Daohui, Zhao Xingang, Han Jianda, et al. Independent Control of Force and Stiffness for Antagonistic Joints of Pneumatic Artificial Muscles [J]. Robot, 2018, 40(05): 587-596. DOI: 10.13973/j.cnki.robot.180256.
[9] Cai WJ. Development of controllable energy system for quadruped bionic robot [D]. Supervisor: He Qiao. Harbin Institute of Technology, 2018.
[10] Guo Tianying, Mao Xiaoyang, Duan Qijun. Application and Development Analysis of Bionic Robots in Disaster Search and Rescue [J]. Robotics Technology and Application, 2024, (05): 6-10+15.
[11] Ruquan Liang, Xiaoyang Li, Jianhui Shi, Yuanmei Song, Zhuo Zhang, Dengbo Zhang. Correction: research on the design and application of bionic hexapod Correction: Research on the design and application of bionic hexapod robot system [J].Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2025, 47(9).
[12] Kondoyanni Maria, Loukatos Dimitrios, Maraveas Chrysanthos, Drosos Christos, Arvanitis Konstantinos G.. Bio-Inspired Robots and Structures toward Fostering the Modernisation of Agriculture [J].Biomimetics, 2022, 7(2).
[13] LI Mu, LI Chengqun. Research on the development trend of robot based [J]. Shandong industrial technology, 2018, (24): 230.