Development and Applications of Bionic Robots

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Abstract: In recent years, significant progress has been made in the field of bionic robotics. This paper discusses the development of three major types of bionic robots, namely, bionic hummingbird robots, bionic dogs and bionic fish, and their applications in production and life. A comprehensive overview of the current status and future prospects of these robots is presented through an in-depth analysis of their research teams and achievements, technical key points, problems solved, and practical applications. The bionic hummingbird robot achieves efficient flight by simulating the wing beat pattern of real hummingbirds; the bionic dog excels in industrial inspection and disaster rescue; and the bionic fish achieves efficient swimming by simulating the propulsion mechanism of fish. These robots have a wide range of applications in agriculture, industry, environmental monitoring, ocean exploration and other fields, providing innovative solutions to practical problems. With technological progress and multidisciplinary integration, bionic robots will play a greater role in the future.

1 INTRODUCTION

With the continuous progress of science and technology, robotics technology is also developing rapidly, among which bionic robots have attracted much attention due to their unique design concepts and wide application prospects. After millions of years of natural selection and evolutionary adaptation, organisms in nature have developed highly optimized locomotion mechanisms and morphological and structural features, which provide a rich bionic research basis for the innovative development of robotics, and these organisms' locomotion patterns and physiological structures have become important imitation objects for researchers to develop bionic robots.

At present, research in the field of bionic robotics has achieved certain results, and various types of bionic robots have been introduced one after another, and they have shown unique advantages and potential in different application scenarios. However, despite the progress made, there are still many key technical problems to be solved, and its application scope and performance need to be further expanded and improved, especially in the adaptability of complex environments, the level of intelligence, and the integration of multi-disciplinary applications and other aspects of the many gaps, which need to be continuously explored and researched in depth by researchers.

This study focuses on bionic hummingbird robots, bionic dogs and bionic fish, three representative and biomimetic bionic robots with significant features in biomimicry. In-depth investigation of their R&D teams and achievements, and analysis of the key technologies involved behind them, such as bionic structure design, material selection, drive and control mechanisms, etc., which are the core support for realizing bionic robots to move efficiently and work accurately. At the same time, the problems solved by these robots in different application scenarios is analyzed in detail, including stability, mobility, and diversity of tasks in complex environments, etc., describe the important roles they play and the practical value they bring in many fields such as agricultural production, industrial inspection, disaster rescue, environmental monitoring, ocean exploration, etc., and explore their contributions to improving production efficiency, safeguarding human safety, and promoting. The article will discuss their contribution to improving production efficiency,

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safeguarding human safety and promoting scientific research.

The goal of this study is to comprehensively and systematically sort out the development lineage of bionic hummingbird robots, bionic dogs and bionic fish, to deeply explore their technical advantages and application potentials, to reveal the deficiencies in the current research, and to provide a clear guideline for future research directions. Through in-depth research and analysis of these three types of bionic robots, not only can human understanding and knowledge of bionic robotics been deepened, technological innovation and breakthroughs have been promoted in this field but also help to expand its application in more fields. Through the in-depth integration of bionic robotics technology with actual production and life, more efficient, smarter and more flexible solutions to solve practical problems can be provided, thus promoting the overall development of robotics technology to a new level and making greater contributions to the progress of human society.

2 BIONIC HUMMINGBIRD ROBOT

2.1 Research Team and Achievements

A research team from Nanjing University has developed a micro drone that can simulate the flight of a hummingbird. The robot imitates the hummingbird's efficient wing-flapping action and flexible steering ability, using lightweight materials to make the wings and built-in motor drive to achieve hovering in the air, forward and backward flight and rapid steering and other actions. The team analyzed the effects of hummingbird wing geometry and flapping frequency on flight performance, optimized the wing design parameters with the help of computational fluid dynamics simulations, and introduced flexible materials to enhance the stability and manoeuvrability of the robot in complex airflow environments (Jia, Guo and Cao, 2025).

The Hummingbird Robot, designed by a team from the Swiss Federal Institute of Technology in Lausanne, has made a breakthrough in flight manoeuvrability. The team explored the complex deformation mechanism of hummingbird wings during high-speed flight and rapid steering, and used flexible materials and smart alloys to make wings that deform like real hummingbird wings during flapping, thus excelling in generating lift and thrust, and achieving difficult manoeuvres such as emergency stops, rapid steering and aerial circling. At the same time, the team develops bio-inspired control algorithms that enable the robot to adjust its flight attitude in real time according to environmental changes, demonstrating excellent autonomous flight capabilities (Karl.et al,2012).

The ‘Robohummingbird’ bionic hummingbird robot developed by a joint research team from the University of Reading and the University of Glasgow, UK, excels in the precise control of its flight attitude. The researchers analyzed the kinematics and dynamics of the hummingbird's wings during flight, especially the torsion and deformation mechanisms during the up and down flapping of the wings. Using advanced motion capture systems and sensors to monitor the flight attitude in real time, the team combined with intelligent algorithms to precisely control the frequency, amplitude and torsion angle of the wing beats, so that the robot can fly stably in complex airflow environments. The team also studied the role of the hummingbird's tail and introduced a similar structure into the robot design to improve flight stability and manoeuvrability (Coleman.et al, 2015)

2.2 Technical Key Points

Hummingbird flight capability relies on its unique musculoskeletal system. Researchers have found that hummingbird pectoralis major and supraorbital muscles are responsible for the downward and upward wing beats, respectively, in flight. The bionic hummingbird robot uses a combination of high-efficiency motors and transmission mechanisms to simulate muscle contraction and relaxation, and precisely controls the motor speed and torque to achieve precise wing flapping. Drawing on the lightweight and high-strength characteristics of the hummingbird skeleton, carbon fibre and other composite materials are used to make the robot's skeleton to reduce weight and improve structural strength.

The complex vortex structure generated by hummingbird wing beats is the key to its efficient flight. Using a combination of computational fluid dynamics simulations and wind tunnel experiments, the researchers investigated the characteristics of the flow field around the hummingbird's wings, especially the leading edge vortex formation and evolution mechanism. Based on this, the shape of the robot's wings and flapping trajectory are optimized, and the wing curvature, torsion angle and flapping frequency are adjusted to generate stronger lift and thrust in flight and reduce energy consumption.

Meanwhile, the mimicry of hummingbird wing surface microstructure is explored to further improve the aerodynamic performance.

Hummingbird wings and tails are critical to their flight stability and manoeuvrability. Researchers have analyzed in detail the morphology and movement of hummingbird wings and tails and their impact on flight. The tail of the bionic hummingbird robot is designed as an adjustable structure, so that precise attitude control and flight trajectory adjustment can be achieved by changing the angle and shape of the tail during flight. For example, the tail can be deployed or retracted to change the flight direction, adjust the flight altitude, or maintain the hovering state, which makes the robot more flexible in complex environments.

2.3 Problems Solved

Stable flight in a complex airflow environment is a major challenge for micro UAVs. The bionic hummingbird robot adopts multi-sensor fusion technology, combining gyroscopes, accelerometers and barometers, to monitor its own attitude and speed changes in real time. Based on these data, the feedback control algorithm quickly adjusts the frequency, amplitude and twisting angle of the wing beats to counteract the interference of external airflow. The adjustable tail design, which mimics the tail of a hummingbird, also provides important support for flight stability, enabling the robot to maintain a stable flight attitude when the wind is strong.

The hummingbird's manoeuvrability provides an excellent mimic for bionic robots. By precisely controlling the movements of its wings and tail, the bionic hummingbird robot achieves complex manoeuvres such as rapid steering, emergency stops and hovering in the air. The researchers developed a high-performance motor drive system and advanced control algorithms to respond quickly to changes in flight attitude. The flexible deformation characteristics of the hummingbird's wings are mimicked to generate more thrust and lift for rapid manoeuvring in flight. The fine control of the tail also further enhances the robot's manoeuvrability, enabling it to travel flexibly in tight spaces.

2.4 Application of Production and Life

In agricultural production, the bionic hummingbird robot can enter greenhouses and orchards in low-altitude areas to monitor crop growth, pest control and pollination assistance. Its flexible flight capability allows it to travel between crop plants, capture high-definition images and collect environmental data to help farmers understand crop growth. In terms of pest control, it can accurately deliver pesticides, reducing the use of chemicals and environmental pollution. By simulating the pollination behaviour of hummingbirds, it can also pollinate crops, improving pollination efficiency and crop yields, and making up for the lack of pollination caused by the reduction in the number of bees.

In industrial environments, bionic hummingbird robots can be used for complex facility inspections, such as high-rise shelf inventory, pipeline leakage detection, and power equipment inspections. With its small and flexible body, the robot can enter areas that are difficult for traditional inspection equipment to reach, such as narrow pipelines and the tops of tall shelves. Equipped with high-definition cameras and sensors, the robot can transmit images and data in real time to help staff find equipment failures and safety hazards in a timely manner, reduce the risk and cost of manual inspection, and improve the safety and efficiency of industrial production.

The bionic hummingbird robot has unique advantages in the field of environmental monitoring and can be used for environmental monitoring work in ecological reserves, urban and industrial areas to collect data on air quality, water pollution and noise levels. Its stealthy and low-noise characteristics allow it to observe the behaviour of wildlife at close range for long periods of time and collect biodiversity data without disturbing them. In air pollution monitoring, it can quickly reach the vicinity of the pollution source and monitor the distribution of pollutant concentration in real time, providing a scientific basis for environmental management. In the event of natural disasters, such as earthquakes and floods, it can quickly enter the affected area, assess the degree of environmental hazards, and provide key information to support rescue efforts.

3 BIONIC DOG

3.1 Research Team and Achievements

The Spot robot dog developed by Boston Dynamics integrates multi-modal sensors to achieve accurate perception and understanding of the environment. At the same time, Spot perceives the environment based on meta-learning, and can update its environmental perception in time to improve its understanding of the real environment, and then realize a more flexible and agile movement with high speed, agility and endurance. For example, Yushu Technology's Go1 robot dog can run at a speed of up to 4.7m/s and can cover a large area in a short time(Raibert.et al,2008). The ‘Jue Ying’ series of quadruped robots developed by Hangzhou DeepCloud Technology Co., Ltd. have performed well in the fields of electric power inspection and emergency rescue. For example, the ‘Jue Ying’ X20 has a speed of 4.95 m/s, a payload capacity of 20 kg, and can cross 20 cm obstacles, 1 m gullies, and move stably in complex terrain such as 45-degree slopes and ruins. Its IP66 protection level supports operations in extreme environments such as rainstorms and snow, and it is equipped with a dual-light head, robotic arm and other modules to achieve fully autonomous navigation and dynamic obstacle avoidance(Semini. et al,2011) (Bellicoso. et al, 2018).

3.2 Technical Key Points

The design of the limbs and body structure of the bionic dog is crucial. For example, Boston Dynamics' Spot adopts lightweight, high-strength and flexible materials to build its limbs and body structure, so that it can move flexibly like a real dog, and at the same time, it has strong stability and support ability. The design of the joints is based on the physiological structure of the dog to achieve a wide range of motion and flexible steering.

In order to make the bionic dog walk, run and jump stably in different terrains and environments, the researchers develop advanced gait planning and control algorithms. Take the Hangzhou Cloud Deep's Jade Shadow series of robotic dogs as an example, it adopts advanced control algorithms, adjusts its gait in real time according to the terrain and task requirements, and realizes stable walking and fast running under complex terrain.

3.3 Problems Solved

Traditional wheeled or tracked robots in rugged mountain roads, ruins, swamps and other complex terrain action is limited, while the bionic dog with flexible limb movement and good balance ability, can freely shuttle in these terrains. For example, Yushu Technology's B1 industrial robotic dog, with its self-developed motion control algorithms, has superb obstacle-crossing capabilities, can easily climb stairs and traverse rugged terrain, and can adapt to ruins, railway tracks and other complex terrain.

Compared with single-function robots, bionic dogs can be integrated with multi-tasking equipment to complete a variety of complex tasks such as rescue, inspection, security and other tasks. For example, DeepCloud's ‘Jue Ying’ X30 is designed for power inspection and factory corridors, and can autonomously complete tasks such as substation equipment inspection and abnormality warning; it can also carry life detectors, gas sensors and other modules in emergency rescue, and carry out reconnaissance and material transport tasks in dangerous areas.

3.4 Application in Production Life

In the industrial environment, bionic dogs can be used for equipment inspection, logistics handling and other work. For example, the ‘Jue Ying’ X20 in the depths of the clouds is outstanding in electric power inspection, and can replace manpower to complete autonomous inspection in complex environments such as substations, underground cable tunnels, etc. It collects data in real time through high-precision sensors to reduce safety hazards and operation and maintenance costs.

After the disaster, the bionic dog can quickly enter the ruins, collapsed buildings and other dangerous sites, looking for survivors, delivering rescue supplies. For example, Boston Dynamics' Spot robot dog has been used in earthquake rescue simulation exercises, which can traverse narrow gaps and complex ruins to find trapped people and provide material support.

4 BIONIC FISH

4.1 Research Status

The Yinbo research team of the Institute of Mechanics of the Chinese Academy of Sciences has conducted an in-depth study on the propulsion mechanism and energy efficiency improvement of intelligent robotic fish, and has established a three-dimensional autonomous swimming model by observing the swimming of tuna, analyzing the force and the process of formation and shedding of tail vortexes, and providing theoretical foundations for the development of an intelligent robotic fish that swims fast and has low energy consumption. The robot fish imitating manta rays and lionfish developed by Zhejiang University and other units adopts intelligent drive of dielectric elastic material, and realizes the drive experiment in the Mariana Trench at 10,000 meters(Li.et al,2021)

An innovative wire-driven elastic bionic fish (WE-RoFi) has been proposed by a research team consisting of Xiaocun Liao, Chao Zhou and others. The design is inspired by natural fish muscle and spine structure, and adopts multi-wire drive to simulate fish muscle, combined with fish spine design based on elastic elements, to achieve continuous tail swing and C- and S-shaped swing modes, solving the problems of traditional multi-jointed bionic fish, such as unbalanced loads and uneven servomotor output power, and verifying its propulsive performance through the Lagrange Dynamic Model, with the maximal swimming speed reaching 0.58 m/s (04 times the length of the fish body) in experiments. 0.58 m/s (1.04 times the length of the fish/sec)(Zhou.et al,2022).

MIT researchers in the US have used SoFi, a soft robot fish, to spy on fish living in Fiji's coral reefs, minimizing the environmental disruption of human behaviour(Katzschmann.et al,2018). University of Florida researchers install artificial tendons in bionic tuna and make them adjust tail stiffness based on speed, halving energy consumption on average(Liu.et al,2021).

4.2 Technical Key Points

Mimicking the way fish swim is the key to achieving efficient swimming for bionic fish. Researchers have developed various drive technologies to mimic this propulsion mode, such as bionic muscle drive and electromagnetic drive, by studying fish muscle movement and hydrodynamic principles. For example, the bionic robotic fish integrates tail and pectoral fin structures, and the propulsion efficiency of the robotic fish is derived through calculations, and a comparative analysis of the hydrodynamic and swimming performance of different fin structures is conducted using computational fluid dynamics methods to optimize the swimming performance of the robotic fish.

The use of new materials, such as flexible materials, is an important trend in the development of bionic fish. These materials have good elasticity, flexibility and biocompatibility, which can make the bionic fish closer to the movement characteristics and adaptability of real fish, and at the same time reduce the interference to the environment. For example, SoFi is made of flexible materials and can swim freely in coral reefs without causing damage to fragile corals (Keennon, Klingebiel and Won, 2012).

In order to enable bionic fish to autonomously swim, avoid obstacles and perform tasks in an underwater environment, advanced sensing and control systems need to be developed. By integrating various sensors, such as pressure sensors, acceleration sensors, and vision sensors, the bionic fish can perceive information about its own motion state and the surrounding environment. Then, intelligent control algorithms, such as central pattern generator (CPG)-based control methods and fuzzy neural network control, are used to process and analyze the information fed back from the sensors, so as to achieve effective control of the bionic fish's movement. For example, the bionic robot fish obstacle avoidance control technique based on augmented learning can improve the autonomy and flexibility of the bionic fish in complex underwater environments.

WE-RoFi uses two pairs of thin wires to transmit the servo motor torque to a specific position on the tail to realize fish-like oscillations. This multi-wire coupled drive not only allows the tail to oscillate continuously, but also realizes complex oscillation patterns, increasing bionicity and flexibility of movement, which is a significant advantage over traditional single-wire drives.

4.3 Problems Solved

Traditional underwater robots mostly use propellers for propulsion, which has problems such as low efficiency and high noise. By simulating the efficient swimming mechanism of fish, the bionic fish has significantly improved its propulsion efficiency, which can realize faster swimming speed with lower energy consumption, extend the underwater working time and expand the operation range.

Fish are extremely maneuverable in the water, and the bionic fish inherits this advantage to achieve flexible and maneuverable movements in complex underwater environments, such as weaving through narrow gaps and quickly avoiding obstacles, to better adapt to the needs of various underwater tasks.

The bionic fish with flexible materials and bionic propulsion method produces less noise during underwater movement, and the disturbance to the water current is relatively small, which will not affect the normal life and behavior of underwater organisms too much, and is conducive to obtaining more accurate and natural data in application scenarios such as underwater biological observation and ecological monitoring.

4.4 Application in Production and Life

Bionic fish can swim freely in complex environments such as deep oceans, narrow coral reef areas, or dangerous shipwreck sites to perform tasks such as marine environmental data collection, undersea topographic mapping, and marine life monitoring, providing richer and more accurate data support for marine scientific research. For example, it monitors changes in environmental parameters such as temperature, salinity, acidity and alkalinity, and pollutant concentration in the ocean, as well as observing the types, numbers, distribution and behavioral patterns of marine organisms.

In the field of underwater archaeology, the bionic fish can penetrate into some archaeological sites that are difficult to reach by humans or dangerous for human divers, and carry out detailed exploration and research on shipwrecks and ancient harbors, etc., so as to obtain precious historical relics and archaeological information. In underwater rescue operations, bionic fish can rely on flexible mobility and small size to quickly arrive at the scene of an accident, search for missing persons or detect dangerous environments, buying time and providing effective support for rescue work.

Bionic fish can be used to monitor water quality conditions, fish health and growth in aquaculture environments, helping farmers to adjust farming parameters in a timely manner and improve farming efficiency. At the same time, bionic fish can be used to monitor and guide wild fish populations to achieve sustainable management of fishery resources. For example, specific signals or actions emitted by bionic fish can be used to induce the direction of fish swimming and prevent fish from being overly dense or entering dangerous areas.

In the field of education, bionic fish can be used as an intuitive and vivid teaching tool to show students the principle of fish swimming, ecological habits and other knowledge, and stimulate students' interest in marine science and engineering technology. In the field of entertainment, bionic fish can be used in aquarium exhibitions, underwater photography and other activities to bring visitors a new visual experience and enhance people's understanding of marine life and awareness of protection.

5 FUTURE DEVELOPMENTS

5.1 Performance Enhancement

In the future, the performance of bionic robots is expected to make further breakthroughs. Taking the bionic hummingbird robot as an example, researchers will continue to optimize the design of its wings and tail, and use new smart materials and advanced manufacturing processes to improve the strength, flexibility and durability of the wings. For example, the use of carbon fiber composite materials to make the robot skeleton and wings, its high strength and low density characteristics can significantly reduce the weight of the robot, reduce the lift required for flight, reduce the power requirements of the drive motor, optimize energy consumption. At the same time, the overall structure of the robot is optimized and designed to remove unnecessary parts and simplify mechanical connections to further reduce weight. In addition, efficient gear transmission or linkage transmission systems are designed to reduce energy transfer losses and improve energy utilization efficiency. Introduce advanced transmission technologies such as harmonic transmission to more accurately control the frequency and amplitude of wing beats and reduce energy loss.

5.2 Intelligent Development

Bionic robots will be deeply integrated with artificial intelligence and machine learning technology to develop in the direction of intelligence. Researchers use deep learning algorithms to train robots to learn flight strategies and environmental characteristics autonomously. For example, through reinforcement learning methods, the robot optimizes its flight path planning and target recognition ability through continuous trial and error in a simulated environment. Based on computer vision and pattern recognition technology, the robot realizes more accurate object detection, tracking and obstacle avoidance functions, demonstrates higher autonomy and adaptability, and reduces its dependence on human intervention.

5.3 Multidisciplinary Integration

Bionic robots will be deeply integrated with biology, medicine, materials and other multidisciplinary fields to expand the scope of application. In the field of biomedicine, researchers develop miniature medical robots for in vivo surgery, drug delivery and biological tissue repair. Mimicking the precise flight ability of hummingbirds, the medical robots travel through narrow spaces in the human body, such as blood vessels, to realize precise drug release and lesion treatment. In the field of materials science, the development of new bionic materials provides better performance characteristics for robots, such as self-repairing ability and shape memory function. This kind of interdisciplinary integration and innovation promotes the continuous progress of bionic robotics and provides the possibility of solving more practical problems.

6 CONCLUSIONS

In this paper, bionic hummingbird robots, bionic dogs and bionic fish have been thoroughly studied and their research results and key technologies have been summarized. By simulating the flight mechanism of hummingbird, the bionic hummingbird robot has made significant progress in flight stability, energy consumption optimization and maneuverability, and has been successfully applied in the fields of agricultural monitoring, industrial inspection and environmental monitoring. The bionic dog, with its efficient locomotion ability and multi-functional integration, excels in complex terrain adaptability and task diversity, and is widely used in industrial production, disaster rescue and other fields. The Bionic Fish improves energy efficiency and maneuverability and reduces interference with the environment by imitating the swimming mechanism of fish, and is suitable for scenarios such as ocean exploration, underwater archaeology and aquaculture.

These bionic robots play an important role in their respective fields of application and provide innovative solutions to practical problems. They not only improve work efficiency, but also enhance the ability of humans to operate in complex and hazardous environments, bringing much convenience and value to production, life and scientific research.

In the future, the field of bionic robotics still has great potential for development. With the continuous progress of technology, bionic robots are expected to make greater breakthroughs in performance, such as higher flight speed, stronger load capacity and longer endurance. The improvement of intelligence level will enable bionic robots to have stronger autonomous learning and environmental adaptation capabilities, and be able to accomplish tasks more flexibly in complex and changing environments. At the same time, the integration of multiple disciplines will further expand the application scope of bionic robots and promote their innovative applications in more fields such as biomedicine and materials science. This will bring more possibilities and opportunities for the development of human society.

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