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Research and Application of Bionic Robotic Arms

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Abstract: The research on bionic robotic arms originates from the aspiration to imitate and replicate the structure and functions of the human arm. With advancements in technology, particularly in the rapid development of robotics, sensor technology, and materials science, robust technical support has been provided for the study of bionic robotic arms. Additionally, as people's demands for a higher quality of life increase, so does the need for mechanical devices that can undertake arduous, hazardous, or high-precision tasks in place of humans. Especially in fields such as industrial production, healthcare, and military security, the research and application of bionic robotic arms have become a focal point in today's technological landscape. This article presents a comprehensive overview of the research background, development trajectory, and future prospects of three specific areas: flexible robotic arms for confined space operations, bionic robotic arms for rotorcraft, and bionic jellyfish robotic arms. The aim is to provide theoretical support and technical references for research and engineering applications in related fields.

Keywords: Bionic robotic arm, flexible robotic arm, bionic jellyfish robot.

1. Introduction

The human arm is one of the most intricate and sophisticated organs in nature, boasting high flexibility and precision. To imitate such complex functionalities, researchers have embarked on the study of bionic robotic arms, aiming to replicate the structure and functions of the human arm through technological means to meet the needs of specific fields. Advances in technology, particularly in robotics, sensor technology, and materials science, have provided robust technical support for the research of bionic robotic arms. Concurrently, as people's expectations for a higher quality of life increase, so does the demand for mechanical devices capable of performing arduous, hazardous, or high-precision tasks in place of humans.

Currently, significant progress has been made in the research of bionic robotic arms. Their structural designs are increasingly similar to human arms, with parameters such as the number of fingers, size, weight, degrees of freedom, gripping force, and fingertip force being optimized. Additionally, the application of new technologies like flexible joints and series elastic actuators has made the movements of bionic robotic arms more flexible and stable. With the continuous development of sensor and actuator technologies, the perception and control capabilities of bionic robotic arms have been significantly enhanced. Sensors can accurately detect the arm's movement status and changes in the surrounding environment, providing reliable data for the control system.

Meanwhile, actuators can output stable forces to meet the needs of arm movements. The control systems of bionic robotic arms are becoming increasingly intelligent and adaptive. For instance, prosthesis control systems based on myoelectric control interfaces have been successfully applied to amputees, enabling real-time control of dexterous robotic hands. Furthermore, research utilizing brain-machine interface technology has directly converted brain signals into movement commands for robotic arms, further improving control precision and efficiency.

However, research on bionic mechanical arms still faces gaps and challenges, such as in-depth exploration of biomechanical mechanisms, improvements in surgical techniques and magnet design, and the development of signal processing and machine learning algorithms. By optimizing structural design and control systems, it is hoped to enhance the flexibility and stability of bionic mechanical arms, enabling them to more accurately mimic human arm movements. Additionally, advanced sensors and control systems can be developed to bolster the perception and interaction capabilities of bionic mechanical arms, allowing them to better adapt to complex environments and task requirements.

This article will provide a detailed introduction to three types of robotic arms: flexible robotic arms for confined space operations, bionic robotic arms for rotorcraft, and bionic jellyfish robotic arms. It primarily covers their research backgrounds, development histories, and future prospects. The hope is to offer theoretical support and technical references for research and engineering applications in related fields.

2. Flexible robotic arm for working in confined spaces

2.1. Background of flexible robotic arms

In scenarios involving fire rescue, nuclear power plant maintenance, or search and rescue operations in ruins, conventional manual operations fall short due to the extremely confined and complex spaces, which may pose hazards to human bodies. Flexible robotic arms, characterized by their super-redundant degrees of freedom and minimal operational space constraints, have garnered increasing attention from researchers and have been extensively applied in exploration tasks within confined spaces, as well as in medical fields such as inspections within the human oral cavity and esophagus.

2.2. Current developments of flexible robotic arms

The development history of flexible robotic arms can be traced back to the 1960s, spanning over half a century to date. Flexible robotic arms can be categorized into snake-like robots and continuous robots.

The research on snake-like robots, which are relatively elongated, began in the late 1980s. Joel Burdick from the United States and his then-student at the California Institute of Technology, Greg Chirikjian, developed a continuum media theory to simulate the general shapes of snake-like robots [1]. In 1992, they constructed Snakey, which comprised of carriages or driving trusses with three degrees of freedom, capable of both manipulation and locomotion. Their focus was on creating a robust and precise mechanism, with less emphasis on snake-like motion and more on the challenges of programming mechanisms with multiple degrees of freedom.

In August 2004, OC Robotics developed a serpentine robotic arm specifically for repairing a pipeline located 5 meters beneath the core of the Ringhals 1 nuclear reactor [1]. This robotic arm measures 1200mm in length and 100mm in diameter, with each segment powered by motors to drive steel wires for articulated movement. The arm is capable of serpentinely navigating around obstacles in the pipeline, placing cameras in inaccessible locations to provide an optimal view of the work site. Furthermore, it can deliver fixtures, cutting tools, gas shields, and inspection equipment. Additionally, it performs tack welding and continuous welding tasks.

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In 2023, Chen Xu from Shenyang University of Technology addressed the issue of periodic maintenance for large-scale hydro-turbine generator units at the Three Gorges Hydropower Station by designing a highly flexible serpentine robotic arm to assist humans in inspecting the stator ends of generators [2]. This research focused on the serpentine robotic arm, conducting in-depth studies on its motion planning in complex and confined spaces. Firstly, the kinematics of the serpentine robotic arm were analyzed, and a kinematic model was established based on the constant curvature model. Subsequently, the mapping relationships among the joint space, driving space, and workspace of the serpentine robotic arm were investigated, with kinematic simulation analyses conducted in Matlab. Experimental results validated the feasibility and effectiveness of the proposed algorithm, fulfilling the practical application requirements of the serpentine robotic arm in complex and confined spaces. These findings enabled the planning of motion trajectories for the serpentine robotic arm while avoiding collisions.

The concept of continuum robots, derived from the "spinal column" of mammals, was first coined by Robinson and Davies, pushing the notion of serpentine robots to its extreme [3]. Conceptually, the backbone structure of such robots is maximized, with the number of joints approaching infinity while the link lengths tend towards zero. Currently, elastomers, pneumatic muscles, or shape-memory alloy materials are primarily utilized worldwide as the "spinal bodies" of continuum robots.

The elastomeric "spinal body" is primarily actuated by drive cables, leveraging the extensive degrees of freedom of the elastomer to execute complex movements. In 2013, Z. Li from The Chinese University of Hong Kong introduced a biomimetic cable-driven multi-segmented flexible robot with a diameter of 20mm[4]. It was inspired by snakes' skeletal structure and octopus arms' muscular arrangement. This robot comprises three segments, each consisting of several identical vertebrae connected by spherical joints and flexible spines. Each segment is actuated by two sets of cables, controlling bending movements in the X and Y directions. This design merges the structure of snake-like robots with the actuation of continuum robots. Consequently, it is more compact than traditional snake-like robots and possesses higher positioning accuracy than typical continuum soft robots. This makes the proposed robot highly suitable for confined spaces, particularly in applications such as minimally invasive surgery, nuclear reactor piping, and disaster debris management.

In 2014, the German company Festo introduced a flexible elephant trunk robotic arm composed of pneumatic muscles, with a length of 850mm and a maximum diameter of 130mm[5]. They proposed a novel variable curvature continuum kinematics for multi-segment continuum robots with arbitrary-shaped backbone curves assembled from segments with three degrees of freedom . For these robots, they derived the forward kinematics and differential forward kinematics. The proposed modeling approach can reproduce both constant and variable backbone curvatures in closed form. It describes the deformation of individual segments using a limited number of serially connected circular arcs, resulting in a segmented constant and thus variable-curvature segment model. Through simulations and experimental data, they demonstrated the accuracy of the model and its applicability in real-time kinematics control applications.

In 2012, LASCHI et al. introduced a flexible robot composed of Shape Memory Alloy , with a diameter ranging from 30mm to 35mm, capable of achieving a circular arc bend with a diameter of 63mm[6]. Inspired by the hydrostatic muscle system of common octopuses, they developed a robotic arm prototype based on an artificial hydrostatic muscle system. This prototype mimics the morphology of biological models and the approximate arrangement of longitudinal and transverse muscles. Actuation is achieved through cables and SMA springs. The mechanical properties of the arm's morphology and tissue enable it to leverage interactions with the environment (i.e., water) to simplify control. Thanks to this effective embodiment of intelligent mechanisms, a significant number of degrees of freedom can be controlled with relatively limited computational resources.

2.3. Future outlook of flexible robotic arms

The flexible robotic arm has successfully accomplished numerous extremely challenging tasks to date, demonstrating its feasibility as a solution for various complex access missions across all industries, including aerospace, pharmaceuticals, military sectors, and the nuclear industry. However, there are still issues and room for improvement. Firstly, due to the use of soft materials in its manufacture, the precision and stability of the flexible robotic arm are relatively low. This becomes particularly evident when performing fine and complex operations. Furthermore, the material properties of the flexible robotic arm limit its load-bearing capacity. Its high nonlinearity and large deformation characteristics complicate mathematical modeling and control. Current linkage mechanism dynamics modeling methods still have room for improvement when applied to flexible bodies.

3. Bionic robotic arms for a rotorcraft

3.1. Background of bionic robotic arms for a rotorcraft

In recent years, the research field related to unmanned aerial vehicles (UAVs) has achieved rapid development, with quadrotor UAVs being widely applied in scientific exploration, military reconnaissance, photography and entertainment, inspection, plant protection, and other fields. These application scenarios do not require the UAVs to make contact with objects or have the need for active operations. However, in certain scenarios, UAVs must transition from passive operations (such as inspection, surveillance, and remote sensing) to active operations (such as grasping and manipulation). Considerable progress has been made in related research over the past decade or so.

3.2. Current developments of bionic robotic arms for a rotorcraft

Traditional flying robots are equipped with rigid robotic arms, which are relatively heavy and have high rotational inertia, resulting in excessive energy consumption during operation. For energy-sensitive carriers like aerial vehicles, rigid robotic arms are not ideal. In 2020, ZHAO et al. proposed a novel adaptive fractional-order nonsingular terminal sliding mode control scheme based on time delay estimation (TDE), and designed a new cable-driven robotic arm for flying robot platforms to address the issue of high-precision tracking control for cable-driven robotic arms under overall uncertainties [7]. This robotic arm uses flexible cable transmission, with the drive motor placed at the base of the arm. The arm itself has low rotational inertia and requires less energy for driving, achieving certain results in reducing energy consumption and extending operating time. However, this also complicates the system control.

In 2022, Wang Yaoyao and his colleagues proposed a biomimetic robotic arm for rotorcraft and, addressing the control issues of this biomimetic robotic arm, designed a nonsingular terminal sliding mode controller based on time-delay estimation and fuzzy adaptive gain adjustment [8]. This method employs time-delay estimation technology to estimate the unknown dynamic parameters of the biomimetic flying robotic arm system, eliminating the need for a precise dynamic model and enhancing practicality. The main component of the controller is the nonsingular terminal sliding mode, which exhibits excellent tracking accuracy and robustness in the presence of time-delay estimation errors and external disturbances. The research results indicate that, compared to traditionally structured flying robotic arms, the biomimetic robotic arm for rotorcraft consumes less driving energy and offers higher interaction safety. Furthermore, compared to traditional nonsingular terminal sliding mode controllers, this controller demonstrates faster error convergence speed, ensuring superior overall control performance.

In 2024, LIU Jiuqing and his team designed a robotic arm mechanism for rotorcraft UAVs to biomimetically perch on tree branches, inspired by the shape and function of birds' legs and claws, as

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well as their perching behavior on branches [9]. This design aims to address the issue of battery life consumption during fixed-point monitoring in forests using rotorcraft UAVs. They based the structural design on the leg and foot structure of the Rose-ringed Parakeet. Based on simulation analysis results, they conducted flexion/extension tests on the toes of the prototype to verify that the range of toe movement matched the design. Vertical perching tests were conducted on 40mm branches, validating that the robotic arm could maintain a preset posture during landing and achieve perching. Inclination tests were also performed, showing that the robotic arm had sufficient gripping force to maintain balance even when the UAV's body was tilted up to 30 degrees.

3.3. Future outlook of bionic robotic arms for a rotorcraft

Numerous studies have proven that biomimetic robotic arms designed for rotorcraft can effectively accomplish tasks, demonstrating significant application potential. However, various issues still persist at present. Firstly, there are concerns regarding quality and energy consumption. In scenarios where robotic arms are mounted, the already limited onboard energy becomes even more strained, significantly limiting control quality and operational capabilities. The endurance of rotorcraft is inherently constrained by their size and takeoff mass, and the integration of bionic robotic arms may further exacerbate this issue. Despite ongoing efforts by scholars in technological innovation related to power sources, the reliability, portability, and endurance of current mainstream power sources such as lithium-ion batteries and fuel cells still need improvement. Additionally, the coupling between rotorcraft and robotic arms may result in force and torque disturbances to the rotorcraft during the arm's movement or operation, increasing the difficulty of flight control. This is detrimental to the positional and attitude control of flying robots, reducing operational accuracy and stability, and in severe cases, could lead to the overturning of the flying robotic arm. Lastly, the dynamics model of bionic robotic arms is complex, and the operational environment may include various interfering factors such as airflow disturbances and load variations. This necessitates control algorithms with high robustness and adaptive capabilities to address various uncertainties.

4. Bionic jellyfish robotic arm

4.1. Background of bionic jellyfish robotic arms

As global climate change intensifies and human activities increase, the marine ecological environment is facing unprecedented challenges, and marine bionics has become a field of great concern. Scientists are conducting in-depth research on the morphology, structure, and functions of marine organisms in an attempt to draw inspiration from them and design more efficient and intelligent robotic systems. Jellyfish, as a unique marine organism, have attracted the attention of many researchers due to their graceful and efficient swimming manner. Therefore, research on jellyfish-like robotic systems has become an important direction in the field of marine bionics.

Underwater robot technology plays a significant role in underwater exploration, environmental monitoring, marine resource development, and other fields. However, traditional underwater robots often suffer from issues such as insufficient endurance, poor stealthiness, and limited adaptability to complex environments. By mimicking the swimming manner of jellyfish, jellyfish-like robotic systems have the potential to achieve more efficient, energy-saving, and stealthy underwater operations.

4.2. Current developments of bionic jellyfish robotic arms

In 2007, Yunchun Yang and colleagues developed a prototype model of a new underwater jellyfish-inspired micro-robot[10]. The micro-robot measures approximately 75 mm in length, 55 mm in

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diameter, and weighs approximately 6.5 grams. It employs shape memory alloy (SMA) and ion conductive polymer film (ICPF) as actuators, and features four collaborative tentacles. Each tentacle consists of a binding mechanism and an ICPF actuator, which work in conjunction with the SMA actuator to increase the range of motion and provide more propulsion. When the SMA is energized, its internal volume contracts, driving the water or other aqueous medium inside the micro-robot to move backward, thus generating propulsive force. By changing the frequency of the input voltage on each SMA and ICPF driver, the moving speed and direction of the micro-robot can be controlled to achieve three degrees of freedom.

In 2019, Yan Xingkun and his team designed a multi-degree-of-freedom (DOF) biomimetic jellyfish robot[11]. They utilized the Robotic Toolbox in Matlab analysis software to establish a model of the jellyfish's robotic arm for motion simulation. By analyzing its kinematics and dynamics, they derived curves such as angular velocity and angular acceleration. Based on the derived torque curves, they conducted driving simulations on the 3D model imported into Adams. They employed the Jtraj function to plan a quintic polynomial trajectory for the robotic arm of the four-DOF biomimetic jellyfish robot and constructed a simple BP neural network control algorithm. The simulation results indicated that all motion curves were continuous, smooth, and without abrupt changes, meeting practical requirements.

4.3. Future outlook of bionic jellyfish robotic arms

This can not only improve the operational efficiency of underwater robots but also reduce the disturbance to marine ecosystems, making them valuable in practical applications. As a new type of underwater monitoring tool, jellyfish-like robots excel in stealthiness and minimal interference with marine ecosystems, enabling long-term and continuous monitoring of the marine environment. This is of great significance for protecting marine ecological environments and preventing marine disasters. Still, there are some issues with biomimetic jellyfish robots in terms of mechanical structure, noise control, energy consumption, motion patterns, function realization, as well as bioethics and safety. Future research should focus on addressing these problems in order to enhance the performance and broaden the application scope of biomimetic jellyfish robots.

5. Conclusion

In recent years, research on bionic robotic arms has made significant progress. By mimicking the structure and functions of human arms, researchers have designed devices capable of simulating biological limb movements. Experimental results indicate that these bionic robotic arms meet experimental requirements in terms of mechanical structure, sensors, actuators, and control systems, demonstrating certain practical value. During experiments, bionic robotic arms can achieve basic movements such as bending, extending, and rotating, with smooth motion trajectories and coordinated actions. This suggests that bionic robotic arms have immense application potential in various fields.

In the medical field, bionic robotic arms bring good news to those with limb amputations. Through precise control systems and highly realistic mechanical structures, these arms can help patients regain partial or full arm functionality, thereby improving their quality of life. In disaster rescue operations, bionic robotic arms can replace humans in performing dangerous and complex tasks, such as searching for and rescuing trapped individuals, lifting heavy objects, and more. This not only enhances rescue efficiency but also reduces risks for rescue personnel. In the industrial manufacturing sector, bionic robotic arms can complete various high-precision and high-intensity tasks, including precision machining, assembly, painting, and so forth. This not only boosts production efficiency but also lowers production costs and labor risks. Furthermore, research on bionic robotic arms has driven

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advancements in related fields such as sensor technology, control theory, and materials science, fostering technological innovation and industrial upgrading.

With the continuous advancement of technology, bionic robotic arms will develop in the direction of diversification, high added value, and high efficiency. An increasing number of enterprises are beginning to develop intelligent robotic arms, utilizing robot artificial intelligence technology to achieve more intelligent and reliable functionalities. Meanwhile, with the development of the Internet of Things (IoT) technology, robotic arms will further achieve intelligent, adaptive, and collaborative operations. In future research, it is hoped that more attention will be paid to enhancing the performance and accuracy of bionic robotic arms. By optimizing mechanical structures, improving sensor and actuator technologies, refining control system algorithms, and other means, the motion flexibility and control precision of robotic arms can be improved, and the application fields of bionic robotic arms can be further expanded. Beyond medical, rescue, and industrial manufacturing fields, robotic arms will also be widely used in daily life assistance, sports entertainment, and other sectors.

In summary, research on bionic robotic arms holds significant scientific importance and application value. Through continuous innovation and development, it is believed that greater breakthroughs will be achieved in future research and play a more pivotal role in various fields.

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