Design and Implementation of Bionic Robot Structure Based on Flexible Joints

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Abstract. Bionic flexible joint combines biological joint structure and flexible motion mechanism, which can adjust the joint stiffness to adapt to the environmental changes through the dynamic changes of the external environment and its own load. Bionic flexible joints can realize robot running, jumping and some bionic movements, and can also meet the design of bionic hand, bionic foot robot and other robots, with a wide range of application prospects. This paper mainly introduces the current status of bionic flexible joint robot research, and explores in detail the production of robots through bionic muscles, flexible connecting rods and other structures, including bionic elephant trunk robots, bionic manipulators and bionic spider robots, etc., and also analyzes the effectiveness of the design of these robots, to provide ideas and methods for the future development of bionic flexible joints. With the development of technology, bionic flexible joints will move to more fields and have great research value.

Keywords: Keywords-bionic robot, flexible joints, flexible structure.

1. Introduction

With the continuous development of robotics technology, robots have been widely used in various industries, especially in the field of industrial production. Nowadays, the industrial production operation pays more and more attention to the robot accuracy and speed, not only the robot design puts forward more lightweight, more flexible, less energy consumption and other higher requirements, and the robot needs to minimize the impact of the robot in the process of movement, the traditional rigid robots have not been able to meet the needs of the recent years, so flexible joints have become one of the hot spots in the research of robots.

Most of the traditional robot joint drive adopts rigid structure, which makes the drive very suitable for high-precision control of position and speed, but at the same time, it also brings many disadvantages due to its rigid joint mechanism: large mass and volume, bulky and heavy, high output rigidity, safety and weak contact ability with the environment. With the development of science and technology and the continuous expansion of the field of robotics applications, the traditional rigid robot has not been able to perform some of the tasks that require contact occasions, especially some of the need to change the working position or the environment is unknown in advance, and can not be completely pre-designed the robot's workflow and other occasions. Therefore, the concept of flexible robots has been proposed, that is, a kind of light weight, low energy consumption, small inertia and a certain degree of flexibility of the robot [1].

2. Analysis of Bionic Robot Based on Flexible Joints

A research team conducted a study on the trunk of elephant and proposed a series-parallel elephant trunk robot based on flexible rod actuation and a 6-degree-of-freedom parallel module, as shown in Fig. 1 [2]. The structure of the robot is simple, and it has redundant kinematics for stiffness control. The study began with geometric and hydrostatic analysis of the flexible rod, followed by modelling of the 6 Degree-of-Freedom (DOF) flexible rod as well as forward and inverse kinematic analysis. Finally, kinematic analysis and simulation of the robot were conducted. The simulation results show that the flexible rod performs well in the tandem-parallel mechanism. The robot can bend in a particular direction with less curvature and at a larger angle, mimicking the grasping and feeding action of an elephant. The bionic elephant trunk robot proposed in this study could mimic the behavior of elephants very well.

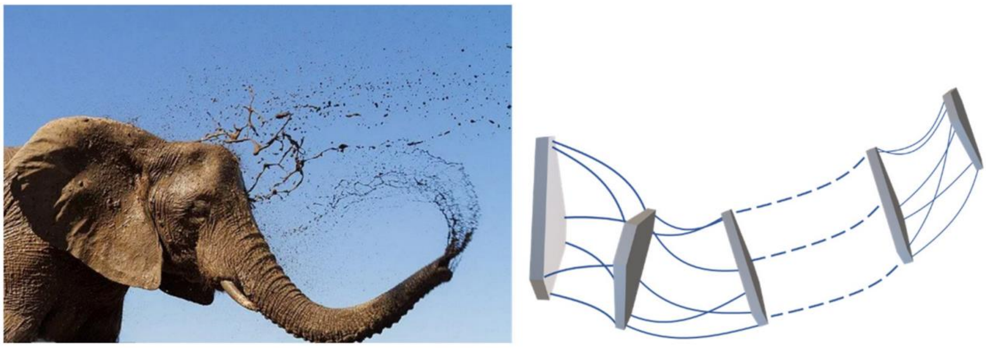
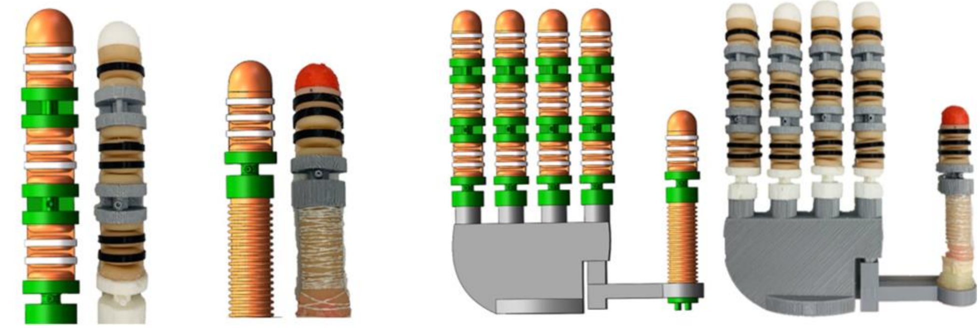


Figure 1. The bionic robot based on series-parallel structure [2]

A research group presented a novel rigid-flexible hybrid design for a bionic hand, aimed to resolve the limited load-bearing capacity of soft robotic grippers, as shown in Fig. 2 [3]. Utilizing the Fast Pneumatic Network method, they crafted a finger flexion actuator, which forms the core of their human-like adaptable gripping hand. This hand comprises a versatile thumb and four modular, flexible fingers. To identify optimal materials, the team conducted comparative tests on silicone rubbers with varying properties. The prototype of this bionic hand was realized through a fusion of 3D printing and mold casting techniques. A mathematical framework was formulated to describe the behavior of the soft bionic fingers, based on the second-order Yeoh model. To ensure the practicality of the finger's bending mechanism, this model was validated using ABAQUS. For pneumatic control, a motor-driven micropump system was employed, while the human-machine interface was tailored using LabView. Comparative bending tests on the fingers were performed, and the data analysis confirmed the accuracy of both the mathematical model and simulation outcomes. The research encompassed the execution of human-mimicking finger gestures and grasping experiments. The experimental outcomes demonstrate that the design significantly enhances finger flexibility and lateral load-bearing capabilities.



The remaining four fingers of the software

Soft thumb

Soft bionic hand

Figure 2. Soft gripper combination [3]

Ronggui Song et al. designed a bionic cockroach robot model, which is built with its coxa link made of flexible material. The structure of the designed cockroach robot is shown in Fig. 3 [4]. It has six legs, each of which consists of four joints: coxa, femur, tibia, and tarsus. The first three are designed to drive the robot and the coxa rotates the legs. Wearable nylon 66 was chosen as the material for the coaxial linkage of the robot. The robot body has six DOF. The influence of flexible materials on kinematic performance is analyzed via statics when it is swinging and standing. The flexible connecting rod can be deformed to convert external energy into strain energy and store it in the connecting rod. The strain energy of the flexible connecting rod was analyzed by linear elastic deflection and the proposed rigid body model. A virtual bionic robot model is established, and its kinematics is simulated by ADAMS software. The analysis and simulation results show that flexible materials reduces the interference to the robot body. The flexible material improves the stability and the flexibility of the robot. Besides, drive torque of the joint is increased by flexible material.

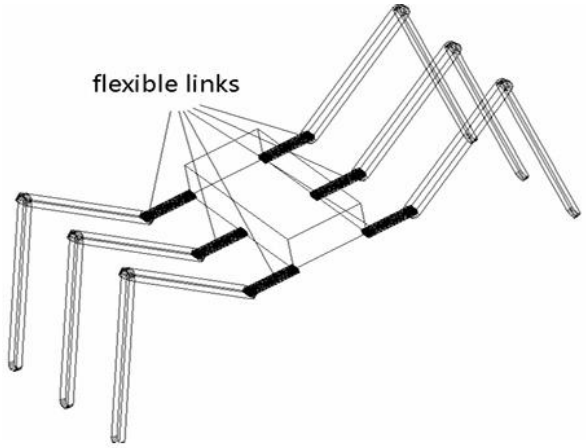


Figure 3. Configuration of cockroach robot [4]

Sanaz Bazaz Behbahani et al. designed a novel flexible joint for pectoral fins of robotic fish pectoral fins. The structure of the designed robot is shown in Fig. 4 [5]. This study presents a pectoral fin flexure joint for robotic fish that mimics the fin motion of various aquatic animals for swimming behavior. Each pectoral fin follows a paddle motion specified by a servo motor, which symmetrically drives the proximal end of the fin in power and recovers the blow. To achieve this, a flexible feather joint was designed to add another DOF to the pectoral fins, allowing the pectoral fin feathers to move passively as they are rowed back during the recovery stroke, minimizing drag during the recovery stroke. The dynamics of the pectoral fin were modeled based on blade unit theory, with the joint being modeled as a torsion spring and damper pair. Experimental results demonstrate the effectiveness of this joint mechanism and validate the proposed model. The results also illustrate how the joint can be used to optimize joint depth and stiffness through trade-offs in swimming speed and mechanical. The design proposed in this study reduces both cost and complexity associated with pectoral fin movement.

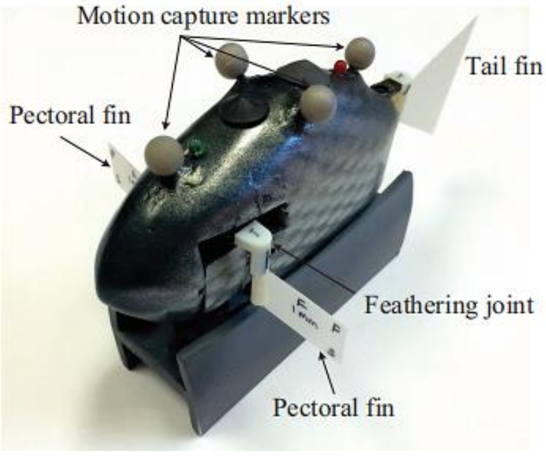


Figure 4. Structure of robotic fish prototype along with mounted fins [5]

Octopus has a very flexible arm, which is an inspiration for the bionic design of flexible jointed robots. Xuecheng Zhang et al. analyzed the octopus and proposed a method of geometric segmentation modelling of the flexible arm. They used SolidWorks to establish a multi-section flexible arm structural model, as shown in Fig. 5 [6]. The kinematic model of single-section flexible arm is established on the flexible arm, and the kinematic model of multi-section flexible arm is solved through the relationship between each section of flexible arm. The robot model is co-simulated by MATLAB and SolidWorks for kinematics and dynamics simulation, and the results of the flexible arm's movement in the three directions of X-axis, Y-axis and Z-axis are obtained, and the simulation results verify the correctness of the modelling.

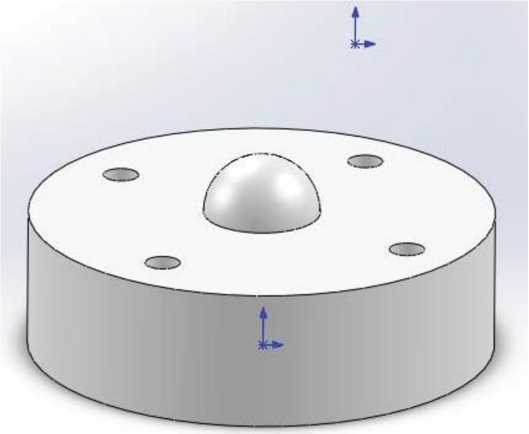


Figure 5. Single segment model [6]

Spiders rely on hydraulic and muscle composite drive and have strong locomotion ability, Ming Xu et al. designed a Bio-Inspired flexible joint actuator based on the movement of spiders [7]. This study proposed a novel actuator, which utilized a double-constrained balloon brake with a corrugated folding structure similar to that of the joint membrane of a spider's leg, based on which a flexible joint robot structure model is established, as shown in Fig. 6. A mathematical model is established for the flexible joints, force analysis is performed on the joints, and a finite element analysis model is established in ABAQUS to analyze the robot motion. Measure the robot in the experimental platform to get the relationship between the joint rotation angle and the inflation pressure in the joint, the relationship between the joint output force and the air expansion pressure in the joint, and the relationship between the efficiency of the joint actuator and the volume of air expansion in the joint. The experimental results show that the robot's travelling speed increases with the increase of the expansion pressure in the case of the same air expansion and tightening cycle.

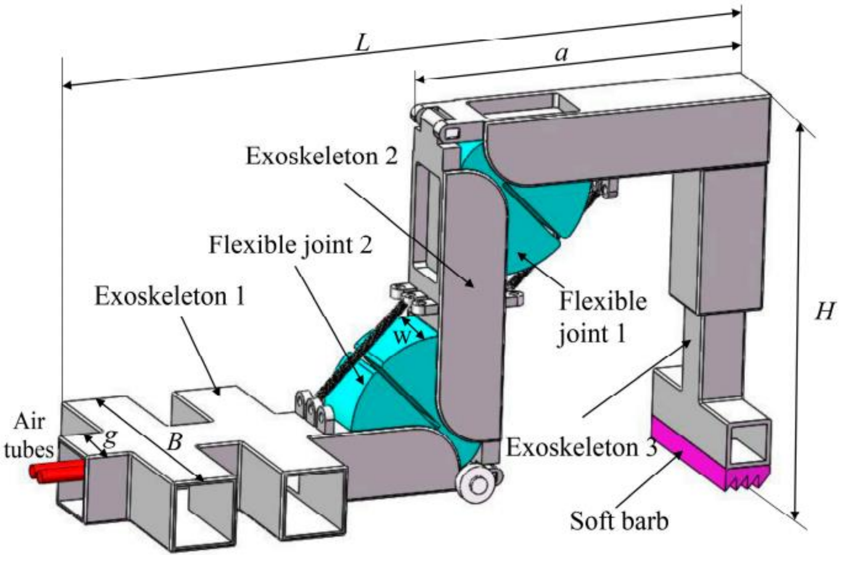


Figure 6. Model of the soft arthropod robot [7]

Drawing inspiration from the diverse movement patterns of snakes and caterpillars, a research team designed and analyzed the structure of a multi-jointed bionic robot. They 3D printed a model the robot using ABS material, as shown in Fig. 7 [8]. For the control problem of joints, the research team proposed a control method combining distributed control and centralized control. Through experiments on this multi-jointed robot, the researchers analyzed the forces at play movement, ultimately achieving seamless and fluid movement.

Figure 7. Entity of multi-joint bionic robot [8]

Zhang et al. proposed a new adaptive robotic hand with flexible fingers based on the study of human hand, as shown in Fig. 8 [9]. Two aluminum alloy holders support the fingers, the whole hand structure and the gearing mechanism installation. The wrist mount contains the control circuit board and the passive rotary joint. There is a transmission mechanism between the two supports. The robotic hand is coated with a glove so as to beautify the appearance of the robotic hand, increase the surface friction coefficient and improve the gripping performance. The kinematic modelling and analysis of the fingers is carried out by D-H method and simulated by MATLAB. Experiments are carried out on the designed flexible hand and rigid hand to compare the impact resistance of the two fingers, and the results dispaly that the flexible hand can cope with the impact better.

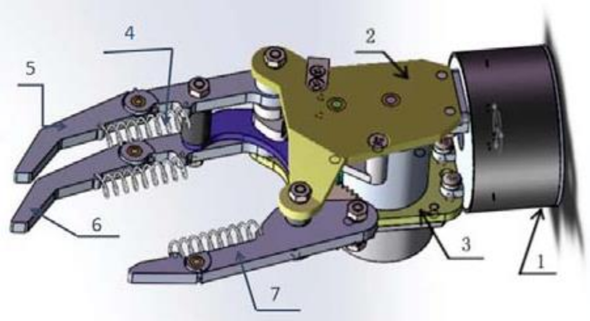


Figure 8. The 3D model of the hand [9]

Drawing inspiration from the crawling behavior of crabs, Junjun Xu et al. designed a new quadrupedal soft robot that can crawl over obstacles, as shown in Fig. 9 [10]. The robot is made of rubber material with super-elastic properties, and the leg joints are driven by wire drawing mechanism to achieve flexible bending. The robot has a crab-like structure with four legs that are raised alternately. Each of the leg is divided into a thigh and a calf. The thighs can be bent upwards to lift the legs, and the lower legs can be bent downwards under the body. Gait analysis and mechanical analysis of the robot was carried out and through simulation analysis, it was found that the designed robot was more capable of overcoming obstacles than the creeping robot.

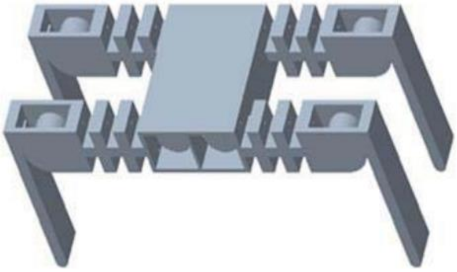


Figure 9. The 3D model of the muti-legged robot [10]

Drawing inspiration from the oculomotor law and Listing's law, Yonghao Xie and colleagues introduced an innovative bionic eye, as shown in Fig. 10 [11]. The design incorporates four adaptable ropes as its actuation mechanism. This approach entailed identifying the optimal locations for the fundamental anchor points of these flexible ropes, guided by the underlying logic of Listing's law. To emulate the agility of human extraocular muscles, the researchers devised a unique mirrored symmetry pattern alongside an intersecting rope configuration, ensuring seamless motion for the rope-actuated bionic eye. Additionally, they incorporated a pulley system into the design, facilitating a redirection of the rope's driving force, thereby distinguishing this approach from conventional rope-driven mechanisms by physically separating the driving components from the bionic eye's core structure. Subsequent experiments successfully corroborated the validity and accuracy of the proposed eyeball model.

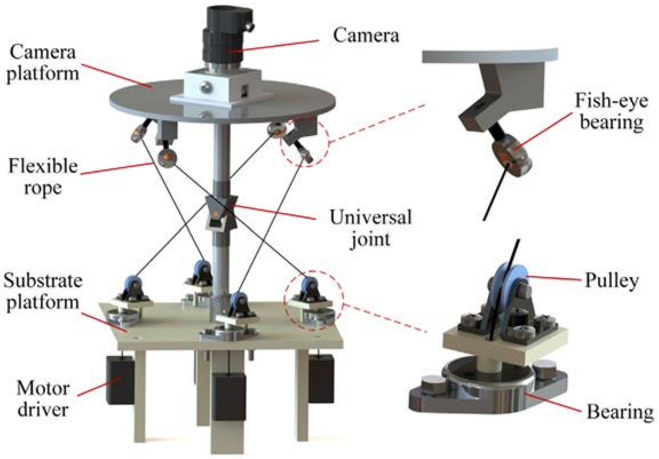


Figure 10. Structure of the bionic eye simulation platform and the flexible rope connection [11]

3. Conclusion

This paper discusses the structural design and realization of bionic robots based on flexible joints, showing how bionic flexible joints combine biological joint structures with flexible movement mechanisms, and adjust the joint stiffness through dynamic changes in the external environment and their own loads to adapt to complex and changing environments. By analyzing the application of bionic muscles, flexible connecting rods and other structures in robot manufacturing, this paper analyzes the effectiveness of the innovative designs of bionic elephant trunk robots, bionic manipulators and bionic spider robots, which not only broaden the application field of bionic robots, but also provide a new way of thinking about the design of bionic flexible joints for robots. At present, bionic flexible joints can realize flexible features and be applied, but there is still a gap compared with the performance of biological joints. It is still necessary to carry out further research on the joint flexibility generation mechanism, flexible structure design and flexible control methods, in order to provide technical support for the design of more effective bionic flexible joints.

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