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Bio-inspired Octopus-mimicking Soft Robotic Grasping System

Chengyu Dong[1,a,*]
[1]*School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai, China*
a. uunme@ldy.edu.rs
**corresponding author*

Abstract: Octopus-inspired soft robots have emerged as a promising field of research, drawing inspiration from the remarkable dexterity and adaptability of this marine creature. Their ability to manipulate objects in complex environments, coupled with their soft, compliant bodies, offers significant advantages over traditional rigid robots. This paper provides a comprehensive overview of recent advancements in the design and development of octopus-inspired soft robots, focusing on shape control, grasping strategies, and potential applications. This paper presents a comprehensive review of recent advancements in biomimetic robotic design, focusing on octopus-inspired soft robots and soft grippers. This paper discusses various shape control algorithms and modeling methods for octopus-inspired soft manipulators, highlighting their applications in highly flexible and complex grasping tasks. The paper explores grasping planning strategies for soft grippers, such as force equilibrium and minimum grasping force control, to achieve precise grasping of diverse objects. Furthermore, this paper present various design schemes based on soft materials and actuation techniques, including tendon-driven and pneumatic actuation, each with its own structural and performance advantages. This paper provides theoretical support and practical guidance for the further development and optimization of octopus-inspired soft robots.

Keywords: Octopus-inspired, soft robots, Grasping.

1. Introduction

The octopus, a remarkable marine creature renowned for its dexterity and intelligence, has served as a compelling inspiration for the development of advanced robotic systems. Its highly flexible tentacles, capable of performing complex manipulations and adapting to diverse environments, offer a wealth of insights for researchers seeking to create more versatile and adaptable robots. Soft robots, constructed from soft materials and actuated using pneumatic, hydraulic, or other compliant mechanisms, have emerged as a promising paradigm in robotics. These robots offer several advantages over traditional rigid robots, including enhanced safety, adaptability, and the ability to interact with delicate objects without causing damage. One of the key challenges in soft robotics is the development of effective shape control algorithms. These algorithms enable the robot to precisely manipulate its body to achieve desired configurations and tasks. By studying the octopus's ability to control the movement and shape of its tentacles, researchers have developed innovative approaches to shape control for soft robots. These approaches often involve the use of mathematical models to

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describe the robot's kinematics and dynamics, as well as control algorithms that optimize the robot's movements to achieve specific goals.

Another critical area of research in soft robotics is grasping and manipulation. Soft robots, with their compliant bodies and tactile sensors, are well-suited for tasks that require delicate handling of objects. By studying the octopus's grasping strategies, researchers have developed algorithms and control techniques that enable soft robots to grasp objects of various shapes, sizes, and materials with precision and stability. In addition to shape control and grasping, researchers have also explored the development of novel materials and actuation techniques for soft robots. Soft materials, such as silicone and elastomers, provide the flexibility and resilience necessary for soft robots to operate in unstructured environments. Actuation techniques, including pneumatic, hydraulic, and electroactive polymers, offer different advantages and trade-offs in terms of force, speed, and controllability. The integration of soft robotics with emerging technologies, such as artificial intelligence, machine learning, and advanced sensors, is expected to further enhance their capabilities and broaden their potential applications. For instance, AI-powered soft robots could learn from their interactions with the environment to improve their performance and adapt to new tasks.

In conclusion, octopus-inspired soft robotics is a rapidly evolving field with significant potential to revolutionize various industries. By leveraging the insights gained from studying the octopus's remarkable abilities, researchers are developing innovative robotic systems that offer unprecedented flexibility, adaptability, and dexterity. As research in this area continues to advance, this paper can expect to see even more remarkable achievements in the field of soft robotics.

2. Bio-inspired Octopus-Mimicking Soft Robotic Grasping System

2.1. Control and modeling techniques for soft robots

The article proposes a shape control algorithm for a soft robot inspired by the octopus. It assumes that the soft robot arm bends with a constant curvature and ignores the shape changes caused by gravity during the bending process. The shape of the robot arm is described by two parameters: the curvature of the soft robot's bending and the deflection angle φ of the bending plane relative to the x-axis. A functional relationship between the control parameters of the soft robot and the length of the driving cables is established. Through this functional relationship, the differential kinematic equations of the control parameters and the length of the driving cables are established. Based on the rate of change of the robot arm's curvature and the deflection angle, the change rate of the driving cable length is obtained, thereby designing a corresponding controller to control the soft robot arm and using Lyapunov theory to prove its stability. The proposed algorithm provides a critical foundation for precise control of soft robots in dynamic environments [1].

This paper conducts an in-depth study on the contact dynamics of octopus-inspired soft manipulators. This article models the octopus-inspired soft robotic arm as a variable cross-section flexible beam using the low-order full-parameter beam element in the absolute nodal coordinate method. Then, based on the minimum distance criterion and contact detection method along the beam axis, a surface-to-surface contact model suitable for variable cross-section flexible beams is proposed, and the validity of the model is verified through static mechanics examples of surface-to-surface contact. The article conducts an ideal state force analysis on the cable-driven octopus-inspired soft robotic arm, theoretically deduces the force model when the arm is subjected to cable load, and verifies the correctness of this force model. Strategies for retrieving oblique contact areas and multiple contact areas are proposed for the winding behavior of the octopus-inspired soft robotic arm. To simulate the winding behavior of the octopus-inspired soft robotic arm, a simulation analysis of the contact system is carried out. This analysis focuses on the large contact area of variable cross-section flexible beams. The results are then compared with ABAQUS calculations to verify the accuracy of

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the variable cross-section beam surface-to-surface contact dynamics model. This theoretical framework underpins the application of soft robots in complex work environments [2].

Researchers employed a low-order, fully parameterized beam element model to simulate the deformation behavior of soft robots. The research team used soft robotic technology, combining hard and soft silicone materials, to design a conical soft robotic arm that mimics the structure of an octopus's arm. They modeled it using a low-order fully parameterized beam element and derived the associated dynamic model. Employing a minimum distance criterion and penalty function method, they proposed a multi-contact area detection algorithm based on the beam surface to determine the contact area between a variable cross-section flexible beam and a constant cross-section cylindrical object. This method effectively models the kinematics of soft robotic arms, providing a robust foundation for shape control [3].

2.2. Grasping and manipulation in soft robotics

Building upon the concept of the octopus-inspired soft robot, this article proposes an innovative space debris capture device. Utilizing bionics principles, the capture device employs a single chain and multiple chains working in concert to achieve cross-scale target capture, demonstrating high fault tolerance and flexibility. The surface of the tentacle adopts gecko toe-setae mimicry, which is known for its excellent adhesive properties, to achieve reliable adhesion to debris. This design further ensures the reliability of the capture process. The soft tentacles of the device are driven by air inflation, showcasing characteristics of lightweight and high adaptability, effectively capturing debris of different scales in unstructured environments, and mitigating collision impacts and absorbing energy during the capture process. Simulation results indicate that the capture device can achieve a large area of contact after contacting the target, verifying the feasibility of its capture effect. This design showcases the potential of biomimetics in addressing complex grasping tasks [4].

This study addresses the compliant grasping issues of existing soft hands for thin-skinned fruits. It proposes an optimal grasp planning based on a stability evaluation mechanism and a prospective intelligent force control method based on minimum grasping force. Four grasp planning methods suitable for the configuration of soft hands are proposed, each designed for specific object shapes: (1) Cross Grasp Planning (CGP): Suitable for grasping objects with approximately symmetric shapes, such as ellipsoids and spheres. (2) Equidistant Optimal Grasp Planning (EOGP): Based on the constraint of equal moment symmetric distribution, suitable for grasping objects with a large aspect ratio to solve the problem of large differences in the moment of force on each finger. (3) Comprehensive-Index Optimal Grasp Planning (COGP): For irregular objects with a trapezoidal shape, it considers not only the balance of moments but also the contact area and the offset of the grasping center. (4) Trigonometric Division Grasp Planning (TDGP): Used when the grasping object is a triangular prism-like shape, where one arm does not participate in the grasping, and a three-finger method is used to obtain the optimal grasping point.

These methods provide a flexible operational space for soft hands to grasp objects of different shapes and sizes. Additionally, they optimize the grasping performance through a grasping stability evaluation mechanism. A nonlinear regression prediction model based on radial basis function neural networks is constructed, and a prospective intelligent force control algorithm based on minimum grasping force is proposed. The structure of the grasping system is analyzed, a hierarchical modular soft hand control system is designed, and finally, a soft hand grasping experimental platform is built to conduct grasping performance testing. The experimental results are promising: compared to two other methods, the proposed grasping force control method reduces the grasping force by 10.64% and 6.91% respectively. Moreover, it increases the grasping success rate by 2.67% and 5.00% respectively, achieving an impressive average success rate of 98.00% [5].

The core academic contribution of this study lies in the development of a soft robotic arm inspired by the octopus. This innovative arm integrates soft materials and vacuum suction cup technology, enabling it to grasp and manipulate objects in confined environments. By utilizing tendon-driven motion and fluid channel-activated suction cups, they constructed a contact dynamic model for the soft robotic arm and validated it through experiments. The soft arm is capable of grasping complex and irregularly shaped objects and can move objects in air, water, and oil, even operating in oil under pressures as high as 18 bar. The integration of suction cups significantly enhances the mechanical arm's capabilities. It allows the arm to grasp objects that would be impossible to grasp without them, and substantially increases the gripping force: up to 1.4 times in air, 2.4 times in water, and an impressive 12.5 times in oil. The maximum gripping force of the mechanical arm in air can reach 3.3 Newtons, which is 3.9 times its own weight [2].

This study presents a novel soft robotic gripper inspired by the glowing octopus. The gripper is designed for adaptive grasping and sensing in underwater environments. The research team designed a 3D-printed linkage mechanism to actuate the silicone cast soft suction cup to deform, creating a soft gripper with a structure similar to the octopus's webbed membrane. The gripper uses suction generated by a pump to lift objects. Upon contact with the underwater target object, the suction cup can lock, while internal flow changes serve as tactile sensing signals. Additionally, its funnel-shaped end can adapt to both smooth and rough surfaces. The gripper's maximum grasping force in air is approximately 100 Newtons, which is three times that of a soft fingerless gripper of the same surface area. The gripper's performance underwater demonstrates its grasping and sensing capabilities in complex underwater environments, effectively exploring and grasping even in turbid underwater conditions where visual perception is limited [6]. This study designed a pneumatically driven soft robotic arm (SRA) inspired by the octopus arm. Made of elastic materials, the SRA includes four integrated pneumatic chamber sets that enable multi-degree-of-freedom bending and variable stiffness grasping. By controlling the pressure and selecting channels, the SRA can demonstrate specific movements and achieve complex three-dimensional motion through parallel control.

To understand the behavior of the SRA, researchers conducted extensive experiments and utilized finite element (FE) modeling to determine its force response and motion characteristics. Experimental results show that the SRA can achieve nearly 360° large bending deformation. At a pressure threshold of 45 kPa, the bending force and relative stiffness of the SRA change significantly, which is related to the mutual compression of the pneumatic chambers. By adjusting the pressure inside the pneumatic chambers, the bending direction and stiffness of the robotic arm can be controlled, significantly increasing within the pressure range of 0 to 100 kPa. Researchers explored the relationship between the bending force and displacement of the SRA and designed experiments to measure its stiffness. In addition, researchers also demonstrated the application potential of the SRA, including grasping objects of different shapes through winding strategies, and using a four-arm gripper composed of multiple SRAs for grasping, which can adjust the grasping mode according to the shape of the object [7].

This study has developed an octopus-inspired soft underwater robotic gripper. The gripper possesses the ability to crawl and swim, enabling adaptive grasping and sensing in structured underwater environments. The gripper integrates six independently controlled arms capable of performing eight different grasping motions, adapting to objects of various shapes and sizes, including irregular hard/soft objects, elongated objects in any orientation, and planar/curvilinear objects larger than the gripper itself. Additionally, the soft gripper can achieve omni-direction crawling and three-dimensional swimming, allowing it to release, crawl, swim, grasp, and retrieve objects in confined underwater environments.

The research team used 3D printing technology and modular mold silicone casting techniques to manufacture the gripper, endowing it with excellent adaptive grasping capabilities and full-range motion capabilities. Experimental results show that the gripper can achieve a maximum grasping force of 3.8 Newtons in air and can stably grasp a variety of objects underwater. In terms of mobility, the gripper can crawl at a maximum speed of 25 mm/s and is capable of performing three-dimensional swimming motions, including vertical and diagonal swimming. The design and manufacturing methods of this soft gripper open up new possibilities for underwater robots. It is particularly suitable for highly integrated and labor-intensive tasks, including marine debris collection, fishing, and underwater archaeological exploration. The gripper's multimodal adaptive grasping and full-range motion capabilities allow it to perform tasks in narrow spaces that are inaccessible to traditional robotic arms, significantly expanding the application range of underwater robots [8].

3. Conclusion

Inspired by the octopus's remarkable dexterity and adaptability, biomimetic soft robots have demonstrated unique advantages in complex environments. This review summarizes the recent advancements in shape control, grasping planning, and materials and actuation techniques for soft robots. With their inherent compliance and intelligent grasping capabilities, soft robots have shown promising applications in various fields such as medical, industrial, and marine exploration. Future developments in soft robotics are expected to focus on intelligence, miniaturization, and material innovation. The integration of advanced sensors and artificial intelligence will enable soft robots to possess autonomous perception and decision-making capabilities, particularly in dynamic or unstructured environments, enhancing their adaptability and operational precision. Miniaturization will facilitate broader applications in medical fields, such as minimally invasive surgery and drug delivery. The development of self-healing and shape memory materials will improve the durability and functionality of soft robots in extreme environments. Through the implementation of swarm intelligence, future soft robots will be capable of executing more complex and diverse tasks, driving further advancements in the field of robotics.

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