Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

Design and Fabrication of Long Soft-Robotic Elastomeric Actuator Inspired by Octopus Arm

Jian Jiao
Robotics Research Center
Peng Cheng Laboratory
Nanshan District, Shenzhen, Guangdong, 518055, China
jiaojian2jiaojian@163.com

Shengkai Liu
School of mechanical engineering
Beijing Institute of Technology
Beijing, 100081, China

Hao Deng, Yufeng Lai, Fuhua Li, and Tao Mei
Robotics Research Center
Peng Cheng Laboratory
Shenzhen, Guangdong, 518055, China

Haiming Huang
College of Electronics and Information Engineering
Shenzhen University
Shenzhen, Guangdong, 518060, China

***Abstract*— The biomimetic soft robotic actuators can provide stable flexible multi-point contact to safely grip delicate objects. A lot of soft robotic actuators have been fabricated using silica gel materials through molding methods. However, owing to the difficulty of the demolding process, existing soft robotic arms are often designed to be short. To fabricate a long soft robotic arm, this paper proposes a novel design approach for fabricating the long soft robotic arm (1000 mm) inspired by the octopus arm that is a fiber-reinforced pneumatic elastomeric actuator. First, we develop a set of molds of the long soft robotic elastomeric actuator. To easily achieve the demolding of the soft actuator chamber, we design the three core petals around the mandrels in the molds. Furthermore, there are also two half-segment mandrels. The two half-segment mandrels are respectively removed from both ends of the mold when demolding. Then, we manufacture the long soft robotic arm using the molds by the combination silica gel and non-extensible materials. We also perform the experiments to verify the feasibility of the long soft robotic elastomeric actuator. The experimental results show the proposed design method for fabricating the long soft robotic arm is feasible.**

***Index Terms*— Soft biomimetic robotics, long soft-robotic arm, octopus-inspired, pneumatic elastomeric actuator**

I. Introduction

Biologically-inspired approaches have been showing the plentiful growing presence in robotics [1], [2]. Actually, mimicking animals requires in many cases to investigate new components, such as like new materials, mechanisms, sensors, actuators, and control schemes [3]. The models and structures of the biomimetic robots, e.g., snake-like robots [4], jellyfish-like robots [5], earthworm-like robots [6] and octopus-like robots [7], [8], etc., come mostly from natural organisms. The octopus are mollusks and their bodies are completely soft structure, so they are well adapted to their surroundings. Although there is non-bone support in the octopus bodies, their arms are able to grasp and manipulate objects. Octopus are able to provide good examples for scientists and engineers who engage in the study of biomimetic soft robots. It is a fully soft structure, however, octopus can achieve a high flexible level and grip objects in the surrounding environment. Owing to these outstanding features, octopus arms have become a source of inspiration and attracted a lot of scholars interesting. Especially in bionic robots, many researchers have imitated their structures and designed various biomimetic soft octopus robots [9], [10], [11].

Compared with traditionally rigid robots, the soft robots have more degrees of freedom and are able to lead to the complexity of the action task due to their structures and materials are compliant. The grasping force is better than that of the traditional gripper with local contact area since the compliant robot gripper increases the contact area. The inherent flexibility of biomimetic robots enables to safely grip delicate objects. The soft robots can provide stable multi-point grasping actions and greatly reduce the contact impact, which are usually required by rigid structure counterparts [12]. Their excellent adaptabilities to various shapes also effectively improve the safety of the environment and themselves [13]. Due to these outstanding advantages, the soft robots present great promising application.

A number of soft robotic actuators reported in the literature has increased dramatically over the past few years. The soft actuator based on electro-strictive polymers was designed by Laschi et al. [10], which could be used for the development of completely soft robotic arms. Suzumori et al. [14] employed soft pneumatic actuators in which finger-like bending behavior was used to grasp small objects. The pneumatically actuated starfish gripper was developed by Ilievski et al. [15], which could manipulate delicate objects. Wang et al. [12] presented the design of soft and compliant grippers using

978-1-7281-6321-5/19//$31.00 ©2019 IEEE

the bimorph-like pneumatic bending actuators, which was able to grip delicate object without breaking such as an egg. The modeling of the spiral pneumatic fiber-reinforced actuator were investigated to capture the deformed behavior of the gripper by Uppalapati et al. [16]. Gong et al. [17] presented the design and modeling of an entire soft robotic arm with three-dimensional locomotion. More recently, the soft fluidic elastomer actuator evenly distributed with three elastic air chambers constrained by double spiral windings was designed by Zhang et al. [18], which could achieve the motions of three degrees of freedom in omnidirectional bending, elongation and contraction.

The actuations of soft robots mainly include mechanical-driven [9], rope-driven [19], [20], and fluidic-driven modes [21], etc. In particular, pneumatic and hydraulic powered soft actuators are promising candidates for robotics applications because of their lightweight, high power-to-weight ratio, low material cost, and ease of fabrication with emerging digital fabrication techniques [22], [23], [24]. Among them, Fiber Reinforced Elastomeric Enclosure (FREE) is a common type of soft robotic actuators [25], [26]. They are compliant pneumatic actuators that occur deformation in a predetermined manner when inflated [27]. When high-pressure air flows into a cylinder wrapped in reinforced fibers, FREE will cause a certain deformation due to the non-malleability of the fibers [27]. The Fiber Reinforced Elastomeric Enclosures are commonly constructed with flexible materials such as elastomers [28] and non-malleable materials such as fiber ropes and fabrics.

Fig. 1. Biomimetic soft octopus robot catching and recycling AUV.

A lot of soft robotic elastomeric actuators employed the fluidic actuation method, e.g., soft pneumatic glove [29], [30] and soft pneumatic gripper [31], [32]. A large proportion of soft robotic actuators were made using silica gel materials through molding approaches [33], [34]. However, the demolding process is a difficult problem for the long soft actuators. In this paper, we develop a novel approach for fabricating a long soft robotic elastomeric arm (1000 mm) inspired by the octopus arm which is a fiber-reinforced pneumatic elastomeric actuator. First, we develop a set of molds of the long soft robotic elastomeric actuator. To easily achieve the demolding of the soft actuator chamber, we design the three core petals around the mandrels in the molds. Moreover, the molds contain two half-segment mandrels as well. When demolding, the two half-segment mandrels are taken out from both ends of the molds. Then, we manufacture the long soft robotic arm using the molds by the combination silica gel and non-extensible materials. The long soft robotic arm can produce distortion to grasp objects through controlling pneumatic actuation. The design and fabrication of the long soft robotic elastomeric arm is our first step work. Our long-term goal is to develop a biomimetic soft octopus robot for catching and recycling autonomous underwater vehicle (AUV) under water. Fig. 1 is the scenario, where an AUV is caught and recycled by the biomimetic soft octopus robot.

The remainder of this paper is structured as follows. In Section II, the details of the design and fabrication procedures of the long soft robotic elastomeric arm. Section III describes the distortion deformation and object gripping experiment of the long soft robotic actuator. The discussion of the long soft actuator is conducted in Section IV. Finally, Section V concludes this work and points out the future work to be further completed.

II. MATERIALS AND METHODS

In this section, the long soft-robotic elastomeric actuator is designed and manufactured, which can achieve three-dimensional motion by pneumatic expansion actuation. A single chamber is used to drive the soft robotic arm to distort in multiple directions and motions. We will describe the progress of the design and fabrication of the long soft robotic elastomeric actuator below.

1) Design: The fabrication process of the long soft robotic elastomeric arm adopts molding technology. The main idea is to individually molded each single segment. We first design and manufacture the molds of the long soft robotic arm. The fabricating procedures of the soft robotic arm consists of four parts as shown in Fig. 2. Inner and outer layers are all soft elastomeric materials. The non-extendable fabric and fiber rope are used for restricting a specific direction expansion deformation, which can produce bending and twisting deformation at a particular direction and angle.

The molding procedures of the long soft robotic arm consist of the three steps, which mainly include the design of

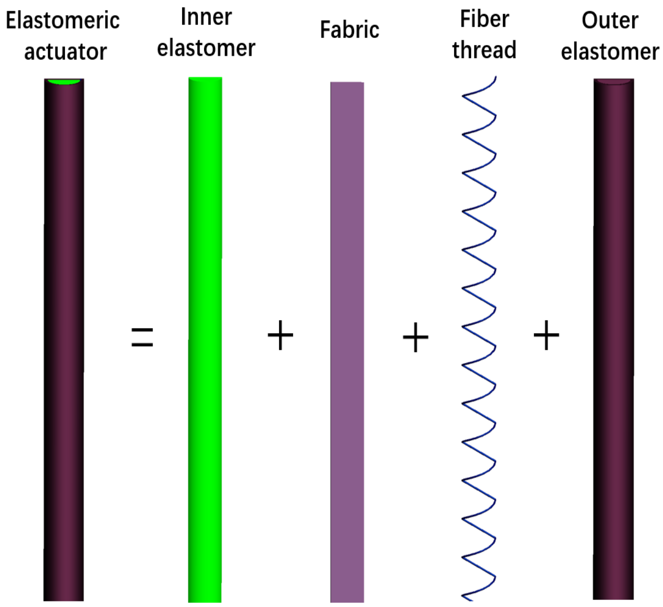


Fig. 2. Fabrication procedure of the soft robotic arm.

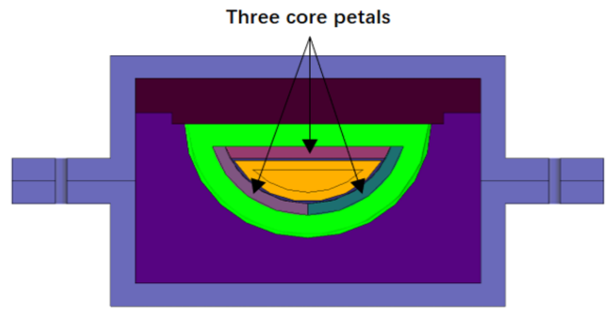


Fig. 3. Design of the core petals

the inner molds, the outer molds, and the air nozzle molds, respectively. The first step is the design of the inner molds. The inner molds mainly include the inner shell, inner cover, inner end cap, mandrels, and inner clips, etc. In order to easily demold, there are three core petals around the mandrel, as shown in Fig. 3. In addition, the mandrel adopted two half-section structure and can be joined together in the molding process. When the mold is released, the two mandrels is pulled out from both ends of the mold, respectively. Then three core petals are removed separately from the inside of the elastomer. The outer molds mainly include outer shell, outer cover, outer end cap, and outer chips, etc. The last step is the design of the mold of the air nozzle mold. In order to ensure air tightness of the long soft robotic elastomeric actuator, there is a sealing ring on the edge of inner mold during molding.

We adopted the molding methods for fabricating the long soft robotic arm. We first used computer aided design (CAD) to design the three-dimensional (3D) molds used for fabricating the soft robotic arm through the Pro/Engineer software (Wildfire 5.0, PTC, USA). And then, we exported the 3D models to the printer to a 3D printer (Lite 600, Union

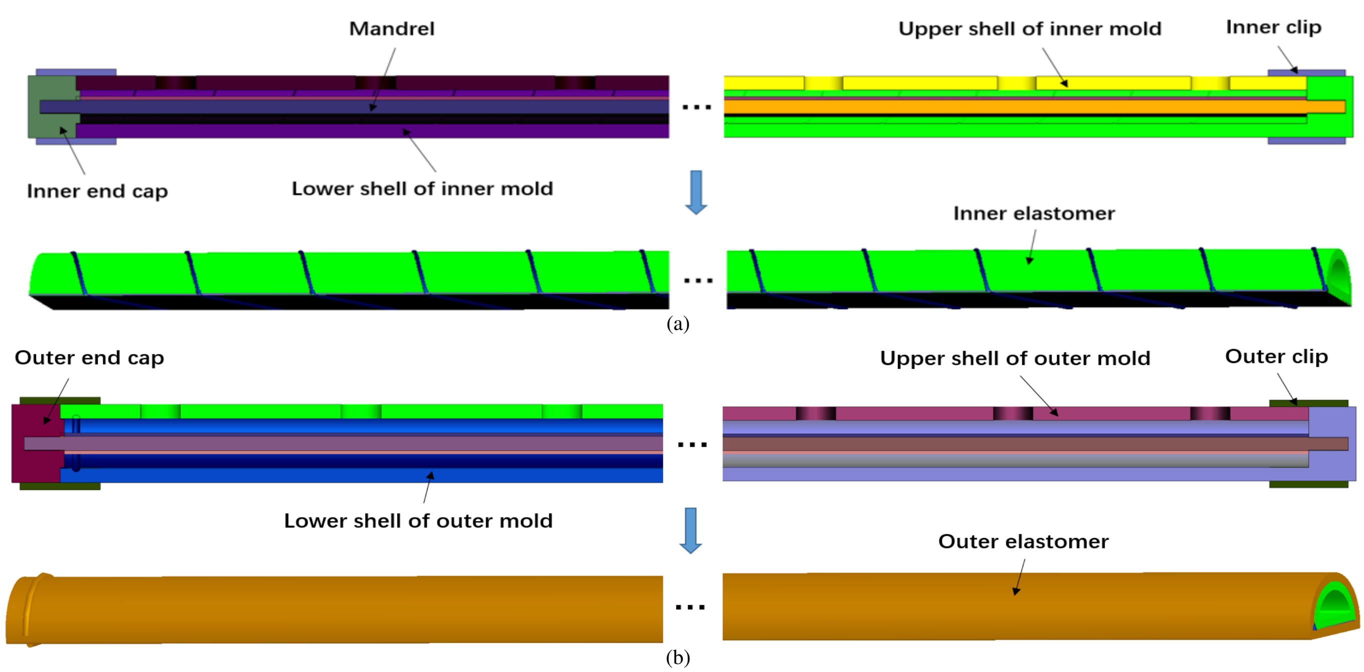


Fig. 4. The fabrication of this three-dimensional soft robotic arm is a process of multi-step molding procedures. (a) The process of preparation technology of the inner elastomer. (b) The process of preparation technology of the outer elastomer

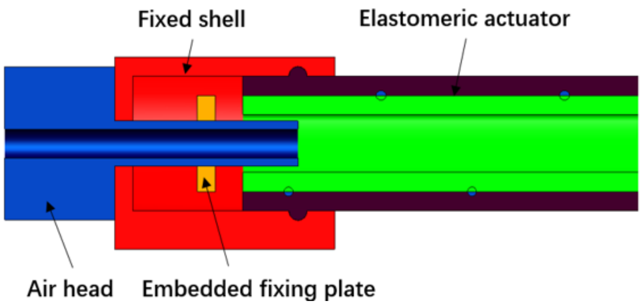


Fig. 5. Design of the air nozzle structure

Tech, CHINA) to manufacture the molds. The material of the molds was prepared with the plastic photosensitive resin. The process of preparation technology of the elastomer is mainly divided into two steps, as shown in Fig. 4. The first step is to fabricate the inner elastomer. The second step is to manufacture the outer elastomer.

The air nozzle is an important area for the sealing of the long soft robotic elastomeric actuator. If this part is not handled properly, the long soft robotic elastomeric actuator could cause the air leakage. Therefore, the sealing of air nozzles is a key part in the design process of the long soft robotic actuator. In order to achieve the good sealing performance of the air nozzle, we design the following structure of the air nozzle as shown in Fig. 5. The structure includes three components, which are embedded fixing plate, fixed shell, and air head, respectively. The embedded fixing plate was first placed in the fixed shell and twisted on the air head. Next, the liquid silica gel material was inlet into the fixed shell. Last, the elastomeric actuator was inserted into the fixed shell. After the solidification of the silica gel material, the air nozzle of the long soft elastomeric actuator is formed. In addition, a concavo groove was designed on the outer edge of the end of the elastomer as well. While the elastomer was inserted into the fixed shell, the convex lip of the elastomeric actuator was embedded in the concavo groove of the fixed shell to enhance the air tightness.

2) Fabrication: The fabrication process of the long soft robotic elastomeric actuator adopted the multi-step molding methods. The manufacturing process of the long soft robotic arm prototype is as shown in Fig. 6. Its fabrication process mainly consists of the following procedures:

1. All the mold components were spliced together and placed flat on the experimental table;

2. Mold release agent (Ease Release 200, Smooth-On, USA) was sprayed in the inner molds, and the talcum powder (Wisegreen, LiangFeng, CHINA) was applied to surfaces of the mandrel and core petals. They can reduce the adhesion between silica material and molds to enable easy to demold to avoid the difficulty of mold release;

3. The pre-stirred liquid silica gel (Nasil 4230, Chu-hai Nabu Co., Ltd, CHINA) was injected to the inner molds and wait for the silica gel for solidifying Fig. 6(a);

4. The inner silica elastomer was demolded from the inner molds after the silica gel is dried;

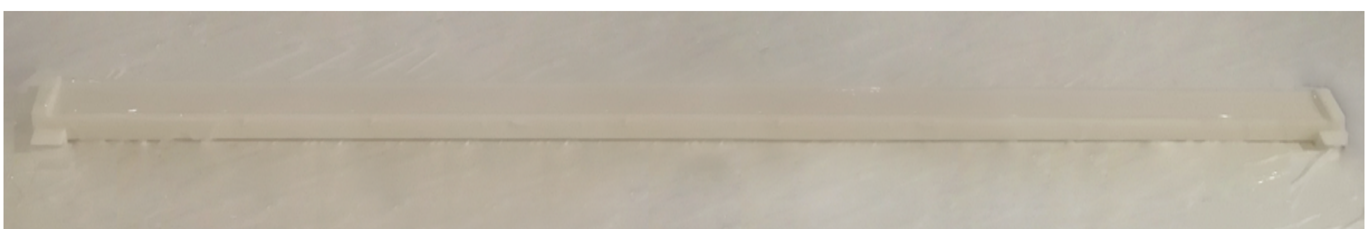
5. The fabric (LY105, KEVLAR, CHINA) was placed on the surface of the inner silica elastomer, and then the fiber thread (LSY1, UNDERBACK, CHINA) was winded the inner silica elastomer and fabric;

6. The inner silica elastomer with the fabric and the fiber thread was placed in the outer mold;

7. The liquid silica gel was injected to the outer molds and wait for silica gel solidifying;

8. The outer silica elastomer was demolded from the outer molds after the solidification of silica gel;

9. The liquid silica gel was injected to the air nozzle molds



(a)

(b)

Fig. 6. The molding process of the long soft robotic arm. (a) The molding process of the inner silica elastomer.(b) The molding process of the air nozzle.

Fig. 7. The long soft robotic arm after demolding.

(a) (b)

Fig. 8. The distortion experiment of the soft robotic actuator. (a) the deformation of the soft robotic actuator under the pneumatic pressure at 160 kPa. (b) the deformation of the soft robotic actuator under the pneumatic pressure at 240 kPa.

Fig. 9. The soft robotic arm gripping a long rod.

and the outer silica elastomer was insert to the air nozzle molds, as shown in Fig. 6(b);

10. The air nozzle of the silica elastomer was formed after the silica gel is dried, as shown in Fig. 7.

III. EXPERIMENTAL SETUP

In order to confirm the effect of the fabricated long soft robotic elastomeric actuator, we performed two pneumatic pressure experiments to observe the deformation of the long soft elastomeric actuator.

Fig. 8 shows the deformation of the long soft robotic elastomer actuator under different pneumatic pressure conditions. During the experiments, an adjustable air compression pump (TYW-2, TONGYI, CHINA) was used to provide the pneumatic supply to the soft actuator. When the pneumatic pressure is 160 kPa, the soft actuator product the small distortion deformation (bend plus twist) in relatively low pneumatic pressure as shown in Fig. 8(a). While pneumatic pressure was up to 240 kPa, it is quite obvious that the soft actuator occurred the greater distortion deformation as shown in Fig. 8(b).

In addition, an object winding experiment was also performed to verify the grasping function of the long soft robotic arm. A long rod was used as the gripped object in the experiment. During the experiment, the driving air pressure was adjusted from 0 to 320 kPa. The soft robotic arm gradually produced the distortion deformation and winded around the rod with the increase of the pneumatic pressure as shown in Fig. 9.

IV. DISCUSSION

In the pneumatic pressure experiment, the long soft robotic elastomeric arm was able to occur the distortion deformation with the increase of the pneumatic pressure, while the high pressure air inflates the soft actuator. In the griping experiment, the long soft robotic actuator could achieve to grip a long rod when it was driven by the pneumatic pressure. The experimental results show the long soft robotic elastomeric arm developed is feasible.

The long soft robotic arm can successfully distort and grip the long rod in the pneumatic pressure driving experiment, However, there are still some limitations in the current work that can be further mitigated in future work. For example, the silica gel material selected is so hard that a higher pneumatic pressure needs to be provided to drive the soft robotic arm to occur distortion deformation. Moreover, the long soft robotic elastomeric actuator can only complete the distortion deformation in single certain direction. Therefore, it is difficult to change the distortion in the multi-direction for the long soft robotic elastomeric actuator.

V. CONCLUSION AND FUTURE WORK

In this work, we developed a long soft robotic elastomeric actuator, of which the length is up to 1000 mm. Although, there were some previous studies on the soft actuators, due to the difficulty in the demolding, the length of soft elastomer actuator is often less than 300 mm. In this paper, we aimed at the solution to the difficulty of mold release in the manufacturing process of the long soft robotic arm. We first design the molds of the soft arm, which adopt the split-type design. To easily achieve the demolding of the soft actuator chamber, we design the three core petals around the mandrels in the molds. In addition, there are also two half-segment mandrels. The two half-segment mandrels are respectively removed from both ends of the mold when demolding. We then add the non-extensible fabric and fiber thread to restrict deformations in one direction during manufacturing process of the inner mold. This can ensure that the soft actuator produce the certain distortion. The outer molding structure can enforce the long soft robotic actuator to avoid the explosion when high pressure air was fills into the soft actuator. In order to improve the air tightness of the long soft robotic elastomeric actuator, the edge of the air nozzle is designed to have a protuberant sealing ring.

The experimental tests indicate that the long soft robotic elastomeric actuator can produce the distortion deformation. As the driving pneumatic pressure increases, the distortion deformation of the long robotic actuator gradually increases. The experiment results also show the long soft robotic arm can grip a long object when a high-pressure air was filled in the soft actuator.

This work is only a portion of our ongoing studies. Our ultimate goal is to develop an underwater biomimetic octopus robot for catching and recycling the AUVs under water. Due to the underwater environment, the water medium could be considered as more suitable driving source of the underwater robots. In next work, we plan to improve the long soft robotic arm structure and use the water medium as driving pressure source. In addition, we found the silica gel material used in the current study is very hard in the experiment. It takes a very high pressure air to drive the soft robotic arm to produce deformation. We intend to explore and attempt other new elastic materials as the molding material for soft robotic arm in future work as well.

ACKNOWLEDGMENT

The authors would thank Shan He of Peng Cheng Laboratory for his assistance on picture processing. Moreover, the authors also thank Zhengkun Cheng of Peng Cheng Laboratory for his assistance on 3D kinematic model simulation analysis.

REFERENCES

[1] R. A. Brooks, "New Approaches to Robotics," Science, vol. 253, no. 5025, pp. 1227-1232, 1991.

[2] P. Rolf, L. Max, and I. Fumiya, "Self-organization, embodiment, and biologically inspired robotics," Science, vol. 318, no. 5853, pp. 1088-1093, 2007.

[3] S. Clment, A. Herv, and M. M. G. Guille, "Biomimetism and bioinspiration as tools for the design of innovative materials and systems," Nature Materials, vol. 4, no. 4, p. 277, 2005.

[4] K. Ito, A. Takayama, and T. Kobayashi, "Hardware design of autonomous snake-like robot for reinforcement learning based on environment," in IEEE/RSJ International Conference on Intelligent Robots and Systems, 2009.

[5] A. Joshi, A. Kulkarni, and Y. Tadesse, "FludoJelly: Experimental Study on Jellyfish-Like Soft Robot Enabled by Soft Pneumatic Composite (SPC)," Robotics, pp. 1-20, 2019.

[6] X. Zhou, T. Yan, and X. Li, "Development of a new pneumatic-driven earthworm-like soft robot," in International Conference on Mechatronics and Machine Vision in Practice, 2017.

[7] K. Ito and S. Hagimori, "Flexible manipulator inspired by octopus: development of soft arms using sponge and experiment for grasping various objects," Artificial Life and Robotics, no. 5536, pp. 1-6, 2017.

[8] M. Sfakiotakis, A. Kazakidi, A. Chatzidaki, T. Evdaimon, and D. P. Tsakiris, "Multi-arm robotic swimming with octopus-inspired compliant web," in IEEE/RSJ International Conference on Intelligent Robots and Systems, 2014.

[9] CeciliaLaschi, MatteoCianchetti, BarbaraMazzolai, LauraMargheri, MaurizioFollador, and PaoloDario, "Soft Robot Arm Inspired by the Octopus," Advanced Robotics, vol. 26, no. 7, pp. 709-727, 2012.

[10] C. Laschi, B. Mazzolai, V. Mattoli, M. Cianchetti, and P. Dario, "Design and Development of a Soft Actuator for a Robot Inspired by the Octopus Arm," Neuroimage, vol. 77, no. 12, pp. 133-147, 2014.

[11] C. Laschi, B. Mazzolai, V. Mattoli, M. Cianchetti, and P. Dario, "Design of a biomimetic robotic octopus arm," Bioinspiration and Biomimetics, vol. 4, no. 1, p. 015006, 2009.

[12] B. Wang, A. Mcdaid, T. Giffney, M. Biglariabhari, and K. C. Aw, "Design, modelling and simulation of soft grippers using new bimorph pneumatic bending actuators," Cogent Engineering, vol. 4, no. 1, 2017.

[13] Y. Shapiro, A. Wolf, and K. Gabor, "Bi-bellows: Pneumatic bending actuator," Sensors and Actuators A Physical, vol. 167, no. 2, pp. 484-494, 2011.

[14] K. Suzumori, S. Iikura, and H. Tanaka, "Development of flexible microactuator and its applications to robotic mechanisms," in IEEE International Conference on Robotics and Automation, 2002.

[15] F. Ilievski, A. D. Mazzeo, R. F. Shepherd, X. Chen, and G. M. Whitesides, "Soft robotics for chemists," Angewandte Chemie, vol. 123, no. 8, pp. 1930-1935, 2015.

[16] N. K. Uppalapati and G. Girish, "Towards Pneumatic Spiral Grippers: Modeling and Design Considerations," SOFT ROBOTICS, 2018.

[17] Z. Gong, Z. Xie, X. Yang, T. Wang, and W. Li, "Design, fabrication and kinematic modeling of a 3D-motion soft robotic arm," in IEEE International Conference on Robotics and Biomimetics, 2016.

[18] J. Zhang, J. Zhou, S. Yuan, and C. Jing, "Design, Fabrication and Experiments of a 3D-motion Soft Elastomer Actuator," in 2019 IEEE International Conference on Mechatronics and Automation (ICMA), 2019.

[19] Z. Zhao, G. Yang, and H. Y. Song, "Inverse kinematics of modular Cable-driven Snake-like Robots with flexible backbones," in Robotics, Automation and Mechatronics, 2011.

[20] A. Yeshmukhametov, K. Koganezawa, and Y. Yamamoto, "Design and Kinematics of Cable-Driven Continuum Robot Arm with Universal Joint Backbone," in 2018 IEEE International Conference on Robotics and Biomimetics, 2018, pp. 2444-2449.

[21] J. Frame, N. Lopez, O. Curet , and E. D. Engeberg, "Thrust force characterization of free-swimming soft robotic jellyfish," Bioinspiration and Biomimetics, vol. 13, pp. 1-10, 2018.

[22] R. Daniela and M. T. Tolley, "Design, fabrication and control of soft robots," Nature, vol. 521, no. 7553, pp. 467-75, 2015.

[23] S. Kim, C. Laschi, and B. Trimmer, "Soft robotics: a bioinspired evolution in robotics," Trends in Biotechnology, vol. 31, no. 5, pp. 287-294, 2013.

[24] D. Trivedi, C. D. Rahn, W. M. Kier, and I. D. Walker, "Soft robotics: Biological inspiration, state of the art, and future research," Applied Bionics and Biomechanics, vol. 5, no. 3, pp. 99-117, 2008.

[25] J. Bishop-Moser, G. Krishnan, C. Kim, and S. Kota, "Design of soft robotic actuators using fluid-filled fiber-reinforced elastomeric enclosures in parallel combinations," in IEEE/RSJ International Conference on Intelligent Robots and Systems, 2012.

[26] G. Krishnan, "Kinematics of a new class of smart actuators for soft robots based on generalized pneumatic artificial muscles," in IEEE/RSJ International Conference on Intelligent Robots and Systems, 2014.

[27] G. Singh and G. Krishnan, "A constrained maximization formulation to analyze deformation of fiber reinforced elastomeric actuators," Smart Material Structures, vol. 26, no. 6, p. 065024, 2017.

[28] N. K. Uppalapati and G. Krishnan, "Design of Soft Continuum Manipulators Using Parallel Asymmetric Combination of Fiber Reinforced Elastomers," IEEE TRANSACTIONS ON ROBOTICS, vol. 1, pp. 1-13, 2014.

[29] P. Polygerinos et al., "Towards a soft pneumatic glove for hand rehabilitation," in IEEE/RSJ International Conference on Intelligent Robots and Systems, 2014.

[30] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh, "Soft robotic glove for combined assistance and at-home rehabilitation," Robotics and Autonomous Systems, vol. 73, no. C, pp. 135-143, 2015.

[31] Y. Hao et al., "A Soft Bionic Gripper with Variable Effective Length," Journal of Bionic Engineering, vol. 15, no. 2, pp. 220-235, 2018.

[32] Y. Hao et al., "Universal soft pneumatic robotic gripper with variable effective length," in Control Conference, 2016.

[33] K. C. Galloway et al., "Soft Robotic Grippers for Biological Sampling on Deep Reefs," Soft Robot, vol. 3, no. 1, pp. 23-33, 2016.

[34] B. Gorissen, D. Reynaerts, S. Konishi, K. Yoshida, J. W. Kim, and V. M. De, "Elastic Inflatable Actuators for Soft Robotic Applications," Advanced Materials, vol. 29, no. 43, p. 1604977, 2017