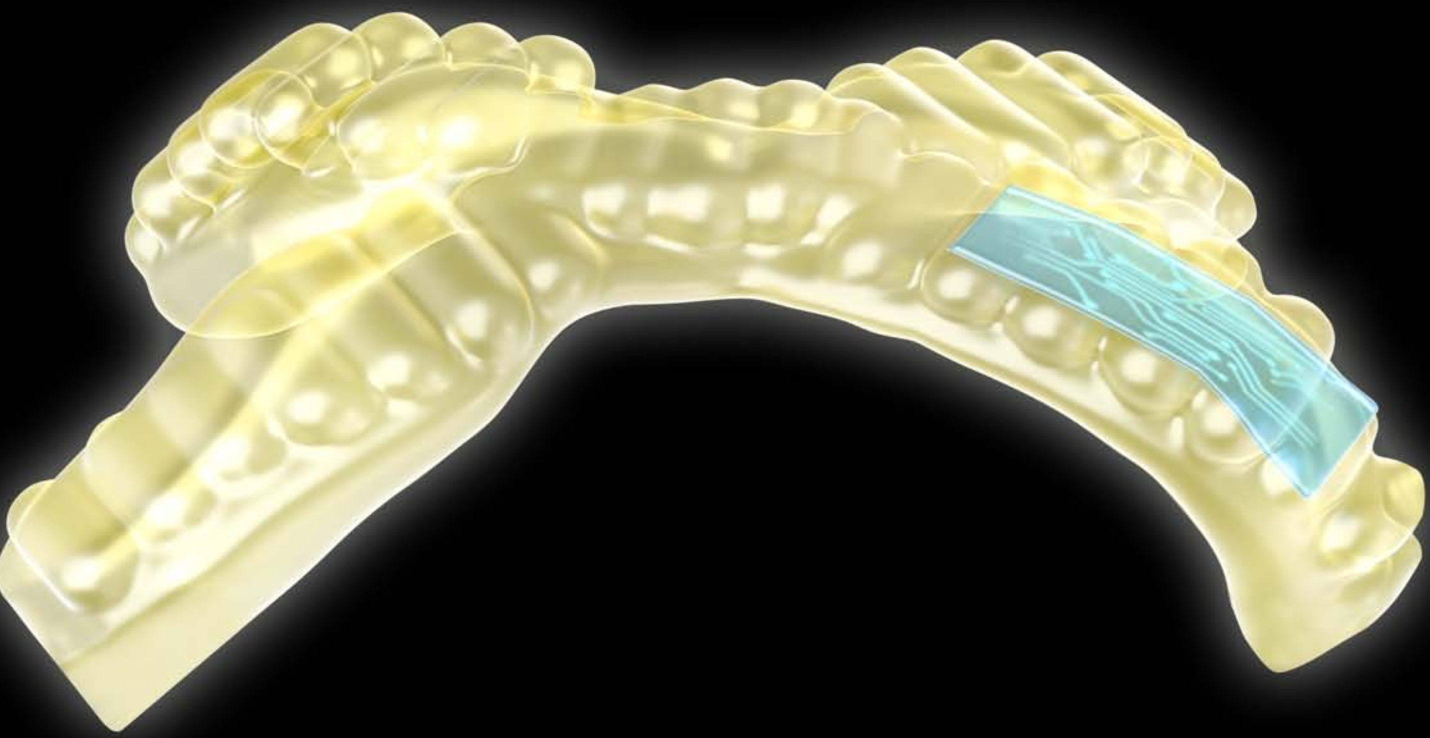
Introduction to Advanced Soft Robotics



Juntian Qu
Zhenkun Li
Qigao Fan
Hongchao Cui
Yueyue Liu

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Introduction to Advanced Soft Robotics

Authored by

Juntian Qu

Shenzhen International Graduate School,
Tsinghua University, Shenzhen, China

Zhenkun Li

School of Mechanical, Electronic and Control Engineering,
Beijing Jiaotong University, Beijing, China

Qigao Fan

School of Internet of Things Engineering,
Jiangnan University, Wuxi, Jiangsu, China

Hongchao Cui

School of Mechanical, Electronic and Control Engineering,
Beijing Jiaotong University, Beijing, China

&

Yueyue Liu

School of Internet of Things Engineering, Jiangnan University,
Wuxi, Jiangsu, China

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Introduction to Advanced Soft Robotics

Authors: Juntian Qu, Zhenkun Li, Qigao Fan, Hongchao Cui & Yueyue Liu

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PREFACE

This book “Introduction to Advanced Soft Robotics” is the Vol. 2 of the eBook series “Frontiers in Electrical Engineering”. It comprises seven chapters written by the leading researchers in this field. Soft robotics is an important emerging sub-discipline of robotics. To enable readers to better understand soft body robotics, the authors try to use an easy-to-understand, illustrated form to show the contents of this book, avoiding the excessive use of cumbersome mathematical theory knowledge. At present, many well-known colleges and universities have increased the teaching courses of soft body robotics along with robotics. Many of the terminologies used in this volume for many soft robotics are also directly quoted from the field of robotics.

In Chapter 1, Qu *et al*. focuses on the basics of soft-bodied robots. The chapter first introduces the definition, characteristics, and applications of soft robots, then, the origin of soft robots and how early scholars embarked on the study of this emerging field are described. Finally, we introduce the development of soft robots through a large number of literature surveys, list many landmark achievements that have had a significant impact on the field of soft robotics and provide analyses of the reasons for the popularity of the field and its rapid development.

In Chapter 2, Li *et al*. focuses on drive technology for soft-body robots. This chapter first introduces the definition of soft body drive. Then, the classification of soft body drives and the performance comparison of different types of soft body drives are introduced. Finally, this chapter introduces the commonly used soft body drive methods in detail, including fluid drive, cable drive, shape memory material drive, electroactive polymer drive, *etc.*, and puts forward the challenges of the current soft body drive.

In Chapter 3, Liu *et al*. mainly introduces the sensing technology of soft robots. This chapter first classifies the soft robot sensing technology, including the overview of soft robot sensing technology, and the comparison of different categories of sensing technology, *etc*. Then , we introduce the soft robot sensing technology in detail, including vision-based sensing technology, haptic-based sensing technology, and fusion sensing technology, *etc*. Finally, we briefly introduce the sensing integration technology for the control of soft robots.

In Chapter 4, Li *et al*. focuses on the materials, design, and manufacturing of soft robots. This chapter first introduces the commonly used soft materials for soft robots, including elastomers, electroactive polymers, shape memory polymers, hydrogels, liquid metals, *etc*. Then, the structural design methods for soft robots are introduced, which mainly include bionic structural design, variable stiffness structural design (*e.g*. antagonist principle, variable stiffness of shape memory materials, blocking principle, electric current variable fluid, low melting point alloy, magnetic fluid, *etc*.) as well as other special structural design methods. Finally, soft robot manufacturing methods are also described, including casting and molding, shape deposition manufacturing, 3D printing, and so on.

In Chapter 5, the modeling and control of soft robots are introduced by Fan *et al*. This chapter first introduces the kinematic modeling methods of soft robots, including the segmental constant curvature model and the Cosserat rod theory in the mechanical model. Then, this chapter introduces the dynamics modeling methods of soft robots, including the centralized parametric model, the "virtual" rigid linkage robot model, the Cosserat rod model, and the machine learning method. Finally, we introduce soft robot manufacturing methods, including casting, shape deposition manufacturing, 3D printing, and so on. In the end, the control strategies of soft robots are introduced, including model-based control methods, model-free control methods, and hybrid control strategies.

In Chapter 6, Cui *et al*. mainly introduces the application of soft robots. This chapter mainly introduces the scenario applications of soft robots in underwater, agriculture, medical and industrial fields. It has a broad application value in non-destructive grasping, safe operation, and wearable devices.

In the last chapter, Qu *et al*. focuses on the challenges and prospects of soft robots. This chapter mainly introduces the main challenges and future development trends of soft robots in the directions of materials, design and fabrication, actuation and sensing, modeling, and control.

We would like to express our gratitude to all the authors for their excellent contributions. In addition to the main authors participating in the writing, this book also benefits from the support and help of Zhenping Yu, Haozhi Huang, Jia You, Chengyao Deng, Yin Sun, Liping Jiang, Zhe Hou, Yunrui Zhang, Jiayi Zhang, Jiajia Zhang, Jingjing Lu, Baijin Mao, Yining Xu, and Weichen Wang. We also wish to thank the entire team of the Bentham Science Publishers, particularly Mrs. Fariya Zulfiqar (Manager Publications), Mrs. Humaira Hashmi (Editorial Manager Publications), and Mr. Obaid Sadiq (Manager Bentham Books) for their efficient handling of this book at all stages of its publication. We are confident that this volume of the eBook series will receive wide appreciation from the researchers.

Juntian Qu
Shenzhen International Graduate School
Tsinghua University,
Shenzhen, China

CHAPTER 1

Introduction

Abstract: Soft robots are an important part of the development of robotics. The research and development of flexible structures are important bases for the development of soft robots. In this chapter, we first introduce the design concepts of soft robots from different perspectives. The soft robot is systematically introduced from the perspectives of drive, material, and structure. In addition, the origin of soft robots is reviewed, and the early development of soft robots is systematically discussed. Finally, the further development of soft robots is researched and discussed, and the prospect of further development of soft robots is explored.

Keywords: Flexible structure, Robot design, Soft robot, Soft robot development.

WHAT IS SOFT ROBOTICS?

Introduction to Soft Robot

Opening Words

There is no denying that the biological system significantly inspires the innovation of soft robotics. Compared with the conventional rigid robot, most of design of the soft robot comes from various kinds of mollusks or animal’s soft organs, such as the long trunk of an elephant, the tentacles or sucker of an octopus, the soft body of a fish, and so on. While imitating these special creatures, soft robots achieve some brilliant functions that rigid robots cannot attain easily, such as safe human-machine interaction and adaptability to wearable device.

Due to its unique advantages, researchers fix their eyes on soft robotics especially, in recent years. As early as 1950s, American physicist McKibben designed the first pneumatic muscle actuator (PMA), which controls the muscle contraction by changing air pressure. In 2016, researchers from Wyss Institute for Biologically Inspired Engineering at Havard University developed the first entirely soft robot, called Octobot, which is powered by embedded pneumatic actuator [1]. The interesting part is that the compressed air inside the Octobot is produced by a chemical reation, instead of an electric pump.

Definition

Soft robots, which are continuum robots made of soft materials, should not contain rigid links and identifiable rotating joints. According to the pioneering paper on

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continuum robot [2], it is a robot type that undergoes continuous elastic deformation and generates motion by generating smooth trunk curve. Therefore, with the help of previous concepts, this paper gives a definition: the moving part of a soft robot should be made of soft materials and generate motion by generating smooth trunk curves, instead of including rigid links and identifiable rotating joints. As for other non-motion deformation mechanisms of robots, they are not necessarily made of soft materials.

WHAT MAKES A SOFT ROBOT?

Soft Robotics

Soft robotics is all of the techniques that are needed for making various kinds of soft robot. In this chapter, we divide soft robotics into 4 parts:

1. Actuation
2. Fabrication
3. Sensing
4. Modeling

Due to the deformable property of soft robot, most of the conventional robotics are no longer adaptable. Innovation is largely required in this new-born industry. State of the art in the above 4 parts are described below.

Actuation

According to the definition, soft robot locomotes by generating smooth trunk curves, such as bending, str*etc*hing and twisting. Hence, conventional steering engine or servo motor can be hardly applied. Typical ways of actuation include: fluid driven, wire driven, SMM driven and EAP driven.

Fluid Driven

Fluid driven soft actuator is often embedded with pressed air or liquid, and channels for them to flow. By controlling the fluid pressure in different chambers, which are made of soft materials, preset deformations can be generated. Penumatic actuator has been most widely applied for soft robots. The main reason is that air has the advantages of wide source, compressibility, light weight, and pollution-free. But it also has disadvantages:

1. Limited accuracy: The motion and deformation accuracy of pneumatic soft robots are limited by gas pressure, so they may not perform as well as rigid robots or other soft robots in tasks that require high accuracy.
2. Low speed: Due to the time required for the compression and release of gas, the motion speed of pneumatic soft robots is relatively slow, which may not meet the needs of certain high-speed movements.
3. Poor durability: Soft materials such as air chambers are usually fragile and prone to damage, so the lifespan of pneumatic soft robots may be shorter.

Despite all these disadvantages, researchers are working on it for performance improvement. Bobak Mosadegh *et al*. developed a fast penumatic network(fPN) by structural improvement [3], which resulted in high speed of actuation and good durability (Fig. **1**).

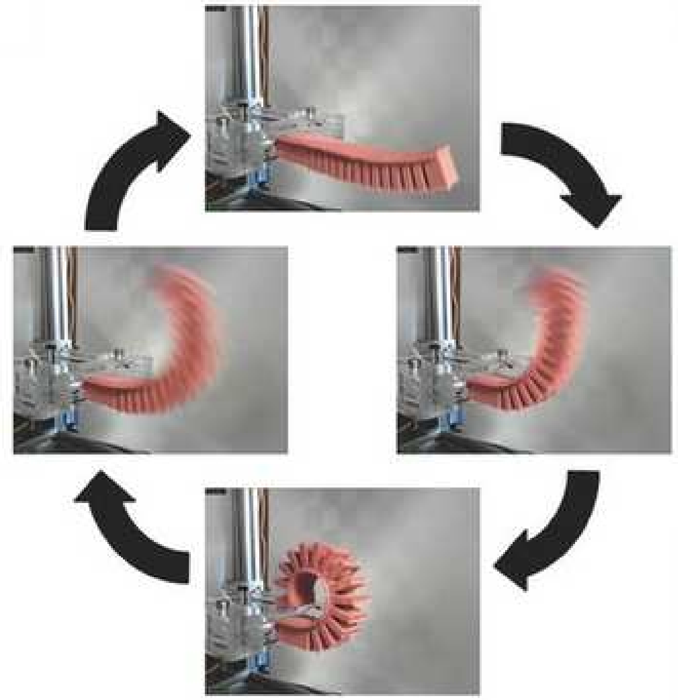

Fig. (1). Fast penumatic network (fPN) [3].

CHAPTER 2

Actuation Techniques for Soft Robots

Abstract: The objective of this chapter is to examine and explore the relevant aspects of soft actuation technology. Unlike traditional rigid robots, soft robots are predominantly composed of flexible materials. Soft robots exhibit exceptional adaptability and flexibility, enabling them to execute various tasks in complex environments. Nevertheless, the classification of soft robot driving modes presents a challenging problem due to the wide range of driving forms and materials utilized in their design.

Firstly, we present a comprehensive definition of soft actuation technology and classify robots into three groups based on their driving methods and motion forms: traditional rigid robots, soft-mimicking robots, and soft robots. Subsequently, our attention turns to the classification of soft robot driving modes. Based on the principles of different driving modes, we categorize the driving modes of soft robots into two groups: structure-function-driven and material-function-driven. Furthermore, we provide comprehensive explanations and analyses of several prevalent driving modes for soft robots, such as fluid-driven, magnetic-driven, cable-driven, shape memory material-driven, and electro-active polymer-driven, in addition to highlighting recent advancements in these domains.

Finally, we summarize the issues and challenges encountered in the advancement of soft robot actuation technology after examining various soft robot driving modes in recent years.

Keywords: Classification, Principle, Soft robots, Soft actuators, Soft actuation technology.

INTRODUCTION

Soft actuation technology has emerged as a promising area of research in the field of robotics, offering unique capabilities and potential applications. Unlike traditional rigid robots, soft robots are predominantly composed of flexible materials, allowing them to exhibit exceptional adaptability and flexibility. This enables them to execute various tasks in complex environments, making them suitable for a wide range of applications. However, the classification of soft robot driving modes presents a challenging problem due to the wide range of driving forms and materials utilized in their design.

In this chapter, we aim to provide a comprehensive understanding of soft actuation technology and explore the various driving modes and motion forms of soft robots. We first present a comprehensive definition of soft actuation technology and classify robots into three groups based on their driving methods and motion forms: traditional rigid robots, soft-mimicking robots, and soft robots. We then turn our

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attention to the classification of soft robot driving modes, categorizing them into two groups: structure-function-driven and material-function-driven.

Furthermore, we provide comprehensive explanations and analyses of several prevalent driving modes for soft robots, such as fluid-driven, magnetic-driven, cable-driven, shape memory material-driven, and electro-active polymer-driven. Additionally, we highlight recent advancements in these domains, providing insights into the current state of soft actuation technology and its potential for future development.

Definition of Soft Actuation

Robot driving technology is a crucial part of robot technology. Traditionally, like any other machine, a robot's basic structure consists mainly of structural components, power units, transmission devices, and executing units, among others. These devices ensure that the robot can perform basic movements. In addition, a variety of sensors (such as visual modules, force sensors, *etc.*) can enable the robot to perceive the external environment or its own status, combined with certain algorithms to achieve interaction with the external environment and better self-control. The driver components used by robots include electric motors, reducers, and gears, among other mechanical components. These mechanical components provide a reliable method for controlling the robot's movements. In the field of industrial robots, stepper motors, servo motors, and brushless DC motors are the most commonly used electric drivers. Traditional rigid robots such as Boston Dynamics' Bigdog [1] and Carnegie Mellon University's Ambler [2] are examples of rigid robots [3-5], as shown in Fig. (**1a**). However, rigid structures also greatly limit the robot's flexibility and environmental adaptability. To improve these deficiencies, some researchers have referred to the behavior patterns of soft-bodied animals or certain soft parts of animals to manufacture some imitation soft-bodied robots with rigid components, such as snake-like robot [6-8] , as shown in Fig. (**1b**). This can also be seen as a transitional state between traditional rigid robots and soft robots. The appearance of these imitation soft-bodied robots greatly improves the flexibility and adaptability of traditional rigid robots in complex environments.

Different from the driving mode of rigid robots, soft actuation refers to the use of soft materials (such as fluids [9-14], wires [15-19], SMA [20-24], EPA [24-28], *etc.*) as power transmission media or power sources for driving. Soft actuation uses soft materials that can better adapt to different environments, demonstrating better flexibility, toughness, and adaptability, as shown in Fig. (**1c**). The research of soft actuation technology can be traced back to the 1960s and 1970s, when it was mainly used in pneumatic system drive. However, due to the limitations of soft materials at that time, the shape and function of robots were relatively simple. With the continuous development of materials and control technology, the shape and function of soft actuation devices have also been greatly increased and improved. Currently, researchers have developed a variety of soft materials, such as liquid metal [29-31], liquid bubble [32-34], microsphere [35-37], airbag [38], and PAM (Polymer Actuated Materials) [39, 40], which can be used for the driving and control of soft robots [9, 21, 41-48].

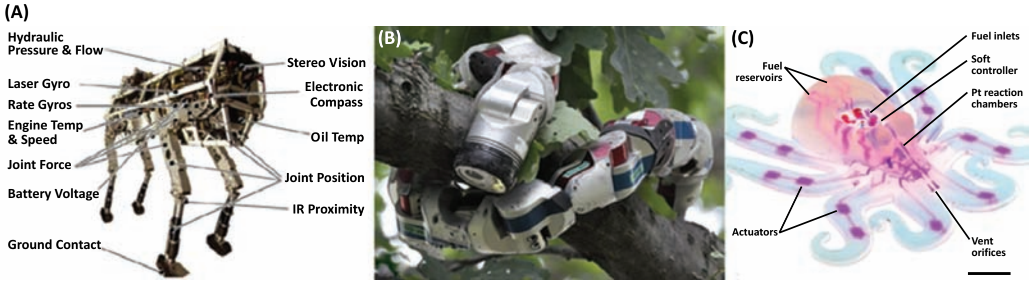

Fig. (1). Traditional rigid robots, Soft-imitation robots and Soft robots. (a). BigDog [1]. (b). Snake-like robot [6]. (c). Octobot [9].

Classification of Soft Actuators

Overview of Diverse Soft Actuators

One of the core components of soft robots is soft actuation, and the focus of research on soft actuation is on materials and structures. Traditional soft actuation methods, such as pneumatic, hydraulic, and cable-driven actuation, cannot react to external conditions, and therefore, they can only provide overall power to the robot without achieving specific functions. The implementation of these functions often relies on the unique structure of other materials. This type of actuation method can be called structure-function actuation, as shown in Fig. (**2**).

On the other hand, with the development of materials science, various new types of smart materials (such as SMA, EPA, magneto-sensitive polymers, and photo-sensitive polymers) have emerged. When exposed to external stimuli, they change in response to the changing environmental factors (such as light, temperature, magnetic field, voltage, *etc.*), just like the stress response of lower organisms. This type of material that has a stress response is commonly known as a smart material. Because these materials can respond to external stimuli and can be controlled by regulating these stimuli, they can inherently perform certain functions. These

CHAPTER 3

Soft Robot Sensing and Perception

Abstract: This section introduces the sensing and perception of the soft robots. First, the sensor of the soft robots are classified. Then, the state of the soft robot's sensing and perception model is introduced, *i.e*., passive mode, semi-active mode, active mode and interactive perceptive mode. Moreover, according to the sensing and perception mode, several sensing and perception technologies are presented. In the end, several challenges regarding the sensing and perception of the soft robots are summarized.

Keywords: Machine learning, Sensing and perception mode, Multi-sensory, Fusion perception.

OVERVIEW OF SOFT ROBOT SENSORS

Background

Soft robots, inspired by soft animals like worms, have gained significant attention and undergone rapid development. Made from materials like silicone rubber, soft robots possess advantages such as softness, portability, and multiple degrees of freedom. Their ability to passively change shape and motion allows them to adapt to various tasks and holds promise for revolutionizing humanoid robots and human-computer interaction. Unlike rigid robots, flexible soft robots exhibit infinite passive degrees of freedom due to continuous deformation of their silicone bodies. This necessitates the use of different sensing methods, modeling techniques, and control strategies. In this regard, the focus will be on discussing the principles and applications of sensors in soft robots [1].

Compared to rigid robots, soft robots can perform human-machine interaction (HRI) more safely and efficiently because of their seamless interaction with the human body. To further advance soft robots, the integration of high-performance electronic devices and the sensors within it need to be able to follow the movement of the robot's body. Recently, the focus of research on artificial skin has been on designing single sensor devices with high sensitivity, strong stretchability, and reliability. Specific performance characteristics are depicted in Fig. (**1**).

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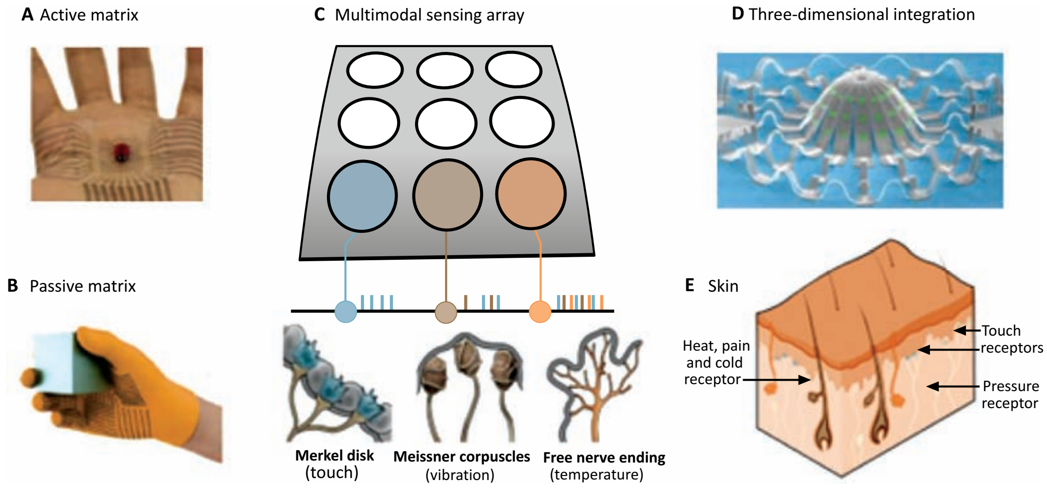

Fig. (1). Sensor arrays enable e-skins to extract information about their environment [2].

Once sensors are integrated into a system, the next critical step is to extract useful information related to the state of the system from the raw data of these sensors. Especially for soft sensors, their performance needs to be coordinated with the surrounding dynamic system. When modeling kinematics and contacts, it is critical to have an accurate understanding of dynamic behavior of the sensor and the dynamic nature of the system. To minimize the impact on system dynamics, according to the main body of the system, an ideal soft sensor needs to provide accurate state information along the way [3]. Embedded soft strain sensors are sensors that can measure parameters such as strain, stress, contact, and roughness. Unlike external sensing methods such as visual sensors, embedded soft strain sensors do not have issues such as occlusion or coordinate transformation. When sensors need to be embedded inside soft systems, these sensors need to be highly adaptable. In general, conductive nanocomposites are a common material for manufacturing soft strain sensors.

If a complete model can be obtained and the robot can run commands based on it, then controlling the robot will become very simple [4]. However, in lots of practical cases, a comprehensive simulation of the environment is unavailable, and achieving perfection over mechanical structures is unrealistic. Sensors play an important role in compensating for information incompleteness. Their purpose is to provide robots with information about their environment and state, in order to maintain the process of interaction with other subjects.

Early approaches to computational perception in robotics assumed the possibility of obtaining the entire model of the environment, which could then be used for decision making and action. Obviously, this method is not feasible. Due to the widespread application of robots containing sensors such as disaster relief, industrial production, medical services, and exploration, it is evident that both sensing and estimation methods require a high degree of adaptability to specific tasks. Therefore, the discussion on perception in this context is specially for external perception and estimation of tasks to be completed.

The source of input to the perceptual process usually consists of two components: (1) various sensors' digital data, and (2) a partial model of the environment It includes information about the state and related entities from other robots. Sensors can collect different types of data, such as scalars or vectors that vary over time. A system needs to integrate data from multiple sensors that provide different types of information. For example, when estimating the position of a mobile robot, data from the axis encoder can be integrated. In this book, the model of perception process (illustrated in (Fig. **2**) is adopted to illustrate the steps involved in receiving sensor information. The functionality of this model includes integrating sensor data with other models. Depending on the complexity of the task, some modules may be omitted, while others may have more complex structures. Nonetheless, this model is used to represent many key issues in sensing and estimation [5].

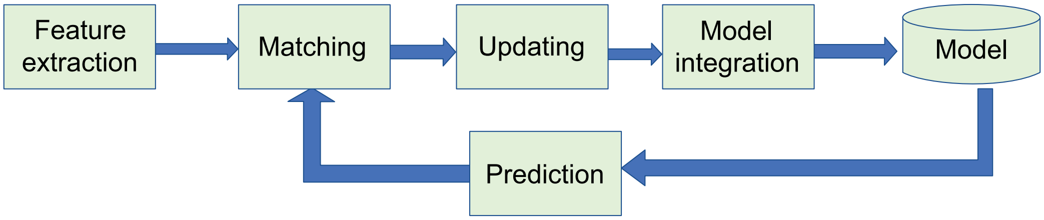

Fig. (2). Perception process.

With this system model, we can predict what will happen until we acquire new sensory data. This prediction process can take place in prospective predictions, making it easier to correlate new sensory data, as shown in Fig. (**2**).

Classification of Sensors Soft Robots

Sensors can be classified based on their measurement content and measurement method. Proprioceptive sensors measure the internal state of a robot, including position, temperature, voltage, motor current, and applied forces. External

CHAPTER 4

Material, Design and Fabrication of Soft Robots

Abstract: Elastomer, hydrogel, shape memory polymers, electro-active polymers, and liquid metal possess some advantages and special performance, especially in soft robots. The flexibility of soft robots, for example, also derives from biologically inspired structural designs and numerous additive manufacturing methods.

This chapter provides a detailed overview of the above five types of materials. The concepts, composition, classification, synthesis principles and properties of these materials are discussed in details. We also summarize and classify the design of release structures for soft robots, including crawling soft robots on land and underwater soft-bodied robots. We analysis and summarize the design and manufacturing methods of soft robots through the existing relevant research results, and finally elaborate on the problems facing future development, in the hope that it can help and guide the direction of research related to soft robots.

Keywords: Soft robotics, Soft actuators, Compliant materials, Dielectric elastomers, Shape memory alloy, 3D printing, Bionic structure.

INTRODUCTION

Interest in soft robots has grown significantly in recent years. This evolution is more than just a trend. Soft-bodied robots have taken another step forward in trying to benefit from mechanical compliance to provide safety while approaching the uncanny ability of evolved living systems in complex tasks. Bionic robots, which have long been controversial in the robotics community, are undoubtedly one of the pioneers of soft robotics. However, bionic systems that mimic the abilities of animals or humans have long been designed primarily using rigid body structures associated with soft parts. Pioneering works in the field of soft robotics are found in research efforts that propose to simultaneously draw inspiration from natural properties and imagine innovative ways to produce them. The enthusiasm generated by soft robots comes from the convergence of different scientific groups on the design of these new machines.

This chapter provides a detailed overview and insights into bionic soft robots. The concepts, composition, classification, principles of synthesis, and properties of the materials that make up bionic soft robots are discussed in detail. The design of release structures for soft robots is summarized and classified, including land crawling soft robots and underwater soft robots. The design and manufacturing methods of soft robots are analyzed and summarized through the existing relevant

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research results, and finally the problems facing the future development are elaborated in the hope of helping and guiding the research direction related to soft robots.

Soft Robot Materials

Soft robots are typically made of soft composite materials that have the ability to withstand large strains or change their shape within a wide range. These materials are capable of maintaining their inherent functionality even when compressed. Young's modulus (E) is a crucial measure of material stiffness used in soft robot manufacturing systems [1, 2]. As shown in Fig. (**1**), the biological modulus in nature ranges from about $10^4 \sim 10^9 Pa$, such as muscle tissue and skin. The material modulus of the soft robot system usually falls within this range. When $E > 10^9 Pa$, the material is considered "hard". The key to developing a controllable soft robot lies in the application of various flexible intelligent materials, including the materials that make up the robot body, as well as those used for electronic components such as circuits, electronic parts, and power supplies. Different materials determine the maximum load, deformation, endurance, and durability of the soft robot. Thus, the development of an intelligent material system that integrates sensors, actuators, and computation is essential to manufacturing controllable soft robots [2, 3]. Wehner *et al*. from MIT reported the first-ever fully soft robot composed entirely of soft materials, which is driven by catalytic decomposition of an on-board monopropellant fuel supply through wireless control of microfluidic logic, thereby avoiding the need for tethering to hard robotic control systems and power sources. The internal design and fabrication of the pneumatic actuator networks, on-board fuel reservoirs, and catalytic reaction chambers for movement were achieved through multi-material, embedded 3D printing technology, demonstrating a programmable assembly of multiple materials within the architecture of the soft robot. This design prototype lays the foundations for future research on completely soft and autonomous robots [4], as shown in Fig. (**2**).

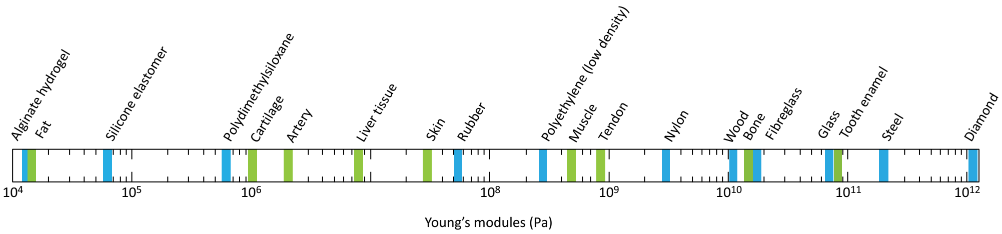

Fig. (1). Distribution of material Young's modulus [2, 5].

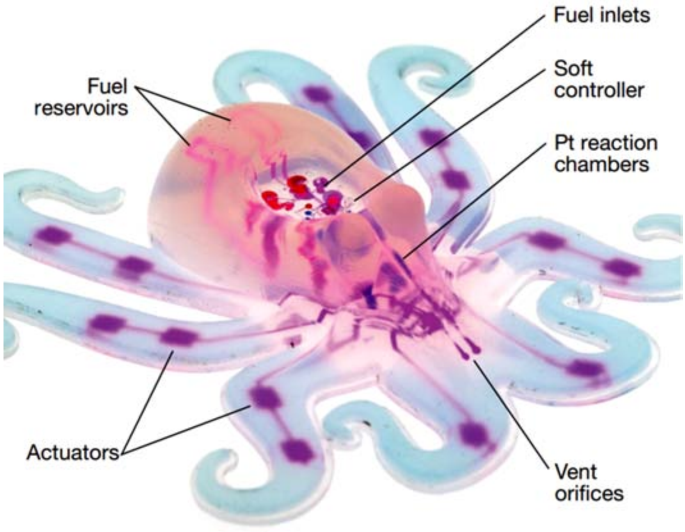

Fig. (2). The first fully soft material robot [4].

Soft materials are elastic, typically composed of groups or macromolecules that enable them to stretch, compress, bend, twist, and yield. Thus, soft robots are considered to have infinite degrees of freedom, which provide an advantage in confined environments and safer human-robot interaction. Complexity and flexibility are two primary characteristics of soft materials [6-8]. Various soft robot materials including elastomers, hydrogels, shape memory polymers, electroactive polymers, and liquid metals play different roles in the miniaturization, high speed, strong robustness, and easy integration of soft robot materials.

Elastomer

Elasticity refers to the ability of a material to recover its original length after being subjected to a certain tensile load. When an elastic body is subjected to small deformations, its stress and strain are approximately linear and its modulus of elasticity (E) can be determined. The typical E values for elastic materials range from 0.1 to 10 MPa. However, when the material is subjected to large strains, its stress-strain relationship becomes significantly nonlinear. In the case of elastomers, the volume change is small and can be ignored, thereby exhibiting hyperelasticity. The stress-strain relationship of an elastomer can be derived from the strain energy density. Elastomers are polymers that exhibit nonlinear viscoelasticity. During the first stretch, the required stress is the highest, but the stress required for the same strain is reduced after multiple stretches. After 5-6 stretches, the stress tends to stabilize. This is known as the Mullins effect. The compliance of a soft robot refers

CHAPTER 5

Soft Robots Modeling and Control

Abstract: This section introduces the classification of soft robots modeling and control methods. In this section, we present the following modeling methods of soft robots, *i.e*., mechanics models, geometrical models, discrete material models and surrogate models. In addition, based on above models, three kinds of control framework are described, which consist of model-based control, model-free control and hybrid control approach. In the end, the summaries and challenges are also presented to conclude the modeling and control framework of the soft robots.

Keywords: Dynamic control, Manipulation, Neural network control, Position and force control, Soft robot modeling.

MODELING

The model classification of soft robots can be classified as:

- Mechanics models: These models describe the deformation of soft robots by considering the constitutive relationship of soft materials, which relates the stress tensor to the strain tensor. The aim is to establish a stability between internal forces and external influences (such as gravity).
- Geometrical models: These models are based on geometry and make assumptions about the deformed shapes of flexible bodies when specific loads are applied. The generalized coordinates play a central role in this group, as they define kinetic and potential energy of the system. Two main groups have emerged in this category. Firstly, it consists of "functional" models, which can represent the shape of the model’s body deformation using a specific mathematical function, often resembling a theoretical space curve. In these cases, the generalized coordinates are typically absolute in nature. Secondly, it comprises the piecewise-constant-curvature (PCC) models. These models discretize the continuous body into a limited number of arc-shaped sections, utilizing inherent relative coordinates.
- Discrete material models: These models discretize the continuous body into scant discrete material elements. They employ a low-dimensional configuration space, consisting of both absolute and relative coordinates. In practice, it is generally preferable to use coordinates that are relative.

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- Surrogate models: This approach involves deriving the system configuration through datasets and a studying process, with many methods in the category employing neural network models and machine learning.

Mechanics Models

The dynamics of many continuum robots are effectively characterized by Cosserat rod partial differential equations (PDEs). These equations take into account different deformations like bending, twisting, shear, and extension. The inclusion of these deformation modes makes the Cosserat rod method particularly accurate in modeling the behavior of soft and continuum robots. In the Cosserat rod theory, the homogeneous transformation matrix $g(s)$ is employed for describing the motion of rods with $s \in [0,1]$ as parameters. The definition of the progression of $g(s)$ with respect to s is expressed as.

$$\dot{R}(s) = R(s)\hat{u}(s), \dot{p}(s) = R(s)v(s)\dot{p}(s) = v(s)R(s), \dot{R}(s) = \hat{u}(s)R(s) \quad \textbf{(1)}$$

where $\dot{(\cdot)}$ represents the derivative of s; R and p are the rotation matrix and position vector of g at s; $v(s)$ and $u(s)$ represent the linear rate of change and angular rate of change of $g(s)$, respectively; the $\widehat{(\cdot)}$ operator is used to convert the angular velocity vector to the corresponding antisymmetric matrix, as shown in equation ((2)).

$$\hat{u} = \begin{bmatrix} 0 & -u_z & u_y \\ u_z & 0 & -u_x \\ -u_y & u_x & 0 \end{bmatrix} \quad \textbf{(2)}$$

The reference configuration for the undeformed given rod g is $g^*(s)$, and the desired variables v^* and u^* can be extracted from equation ((3)).

$$[v^* \quad u^*]^T = ((g^*(s))^{-1}\dot{g}^*(s))^v \quad \textbf{(3)}$$

n and m represent the internal force and moment vectors, with the force distribution of units s being f and the moment distribution of units s being I. The classical form of the equilibrium differential equation for the Cosserat rod is

$$\dot{n}(s) + f(s) = 0 \quad \textbf{(4)}$$

$$\dot{m}(s) + \dot{p}(s) \times n(s) + l(s) = 0 \quad \textbf{(5)}$$

The rod’s constitutive law is employed to relate variables to internal forces and moments:

$$n(s) = R(s)K_{se}(s)[v(s) - v^{*}(s) \tag{6}$$

$$m(s) = R(s)K_{se}(s)[u(s) - u^{*}(s) \tag{7}$$

K_{se} is the stiffness matrix for tensile, and K_{bt} is the stiffness matrix for bending . Assuming that the stiffness matrix does not change with s, a collection of explicit equations that furnish values for $j(s)$, $R(s)$, $i(s)$, and $u(s)$ can be acquired. This method is suitable not only for linear constitutive relations, but also for nonlinear constitutive relations.

Various forms of rod theory are employed for kinematic modeling of soft robots. An example of this form is the Kirchhoff rod, a specialized instance of the Cosserat rod. It has been employed in formulating concentric tube robots. The Kirchhoff rod theory surmises that the rod is not elongated and neglects transverse shear strain, making it particularly suitable for modeling elongated rods like concentric tubes. In a study by Wenlong *et al*., the Timoshenko beam theory is employed to map the driving load to the attitude of a continuum manipulator, taking into account shear deformation and beam twisting [1]. The Euler-Bernoulli beam theory, which only considers lateral external loads, represents a specific scenario within the framework of the Timoshenko beam theory and can simplify the mechanical calculations for concentric tubes.

While the aforementioned elastic models can yield quick computations, their parameterization and implementation can be complex. Furthermore, closed-form solutions for the mechanical behavior of continuum objects exist only under specific conditions, and often numerical solutions of partial differential equations are obtained. Although rod theory provides highly accurate kinematic models, it is currently more suitable for soft robots with simple geometries and may not capture motion related to morphology. Another approach for accurately representing the geometry and nonlinear deformation of irregular models is the finite element model.

Finite element analysis is a numerical method used for solving complex problems by dividing them into small finite elements or cells. Every element engages with adjacent nodes, imparting displacements and exerting forces. By augmenting the quantity of elements, the accuracy of finite element model improves, but this also leads to higher computational costs, making real-time applications challenging. Thus, striking a balance between solution accuracy and time is often necessary.

CHAPTER 6

Applications of Soft Robots

Abstract: Soft robots have become increasingly prevalent in today's AI era due to their ability to meet the specialized needs and technological advancements that rigid robots cannot. Soft robots are characterized by their flexibility, deformability, and variable stiffness, which greatly compensate for the limitations of rigid robots in specialized environments. This chapter aims to provide extensive examples of how soft robots are being applied in various areas including underwater exploration, agriculture, medicine, industry and space. The chapter will discuss the types of soft robots, their movement characteristics, driving methods, and the advantages they bring to different applications. By showcasing the vast potential and research value of soft robots, this chapter underscores their significant role in promoting technological innovation and societal progress.

Keywords: Underwater soft robots; Agriculture soft robots; Medical soft robots; Industrial soft robots; Space soft robots; Applications.

UNDERWATER SOFT ROBOTS

Introduction

Driven by mechatronics, we are experiencing a "robot revolution" [1]. Unprecedented numbers of robots are emerging, with capabilities that were once considered omnipotent. Innovations are being made in all fields, including the marine sector. The ocean contains valuable mineral and biological resources. With increasing human exploration of the ocean, underwater robots are playing an important role and their applications are becoming more extensive [2]. Traditional underwater robots use propellers, which can be harmful to marine life due to noise and the risk of accidental capture. In contrast, soft underwater robots - a new type of underwater robot - integrate the swimming principles, morphology, and softness of aquatic animals. They are highly flexible and adaptable, move in a way similar to biological organisms, have a simple structure, are lightweight, possess good flexibility and agility, operate silently, and produce low pollution. Therefore, they are better suited to adapt to their surrounding environment [3].

Underwater soft robots are a type of flexible robot with materials and structures that allow for greater flexibility, and their movement and form are more similar to biological organisms. Based on their structural morphology and mode of movement, underwater soft robots can be classified into different types such as crawling, swimming, and creeping [4]. Among them, the crawling soft robot moves

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like snakes, mainly through undulatory motion for locomotion. The swimming soft robot, on the other hand, moves like fish, mainly propelled by the wave-like motion of its tail. Finally, the creeping soft robot moves like crawling animals, mainly through the swinging and stretching of its limbs. Therefore, underwater soft robots can adapt more effectively to the complex underwater environments and task requirements, providing greater flexibility and agility compared to traditional rigid underwater robots.

The development of underwater soft robots can be traced back to the 1960s when scientists began to imitate the movement and form of biological organisms, and developed the first batch of soft robots. Since then, the performance and application scope of underwater soft robots have been continuously improved and expanded due to the development of material science and control technology. This section will mainly focus on the applications of underwater soft robots in underwater exploration, sampling, and grabbing.

Underwater Exploration

Underwater exploration has always been a focus of marine scientists, and soft robotics, as a new type of robotics technology, holds tremendous potential for oceanic exploration. With their flexible structure and high adaptability, soft robots can adapt to different underwater environments and perform various tasks, such as marine environmental monitoring, deep sea exploration, underwater pipeline inspection, and more.

Due to the significant time and resources required for manual monitoring of the ocean environment, the development of soft robots for marine environmental monitoring has become a popular research direction. RoboJelly [5], a soft robot developed by Harvard University in the United States, is capable of conducting environmental monitoring in underwater environments, inspired by the natural movement of jellyfish as shown in Fig. (**1**). Robojelly's design is based on biomimicry, transforming the natural movement of jellyfish into a machine design. Its main components consist of a central mechanical structure and a surrounding soft exterior shell. The mechanical structure is a flexible chamber that includes a motor, a gear, and a set of linkages, while the soft exterior shell consists of eight tentacles made up of thin polymer films with internal steel wires. The movement of Robojelly is similar to that of real jellyfish, as it generates power through the flow of water and produces natural undulating movements driven by a motor. The forward motion and direction are controlled by controlling the wave motion through a remote controller. When the motor drives the gear to rotate, the mechanical structure starts to move, causing a series of undulating deformations in the soft exterior shell, propelling the robot forward. Robojelly is also equipped with a set of sensors and control systems to monitor and adjust its movements. For example, when the robot approaches obstacles or encounters water currents, the sensors will detect this information and automatically adjust the frequency and amplitude of the wave motion to ensure stable forward motion.

The design of Robojelly makes it highly suitable for exploring tasks in underwater environments. Equipped with multiple sensors, such as temperature, pressure, oxygen, and carbon dioxide sensors, RoboJelly can monitor the changes in marine environments in real-time, detect pollutants in marine ecosystems, or conduct underwater survey missions, and upload data to remote control centers. Although Robojelly still has limitations in certain aspects, such as its slow wave motion speed and the need for an external power source, its flexible structure and biomimetic design still give it enormous potential for various applications.

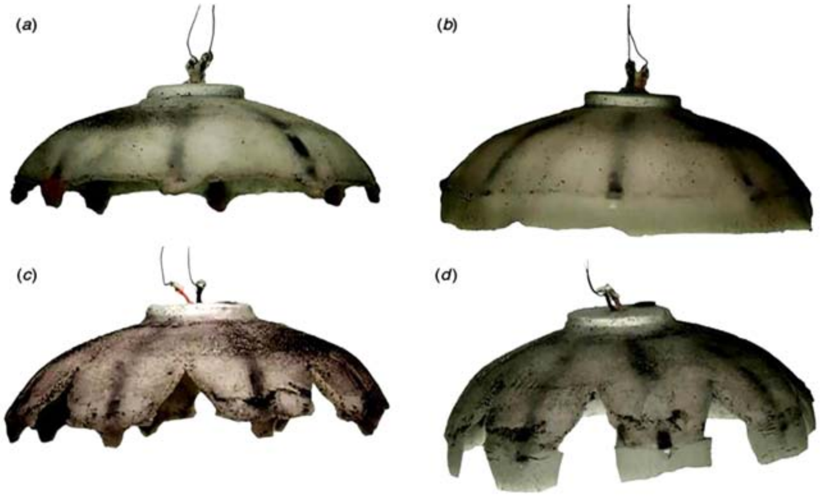

Fig. (1). Robojelly in various configurations [5].

Deep sea exploration has always been a major focus for marine scientists. Due to the high-water pressure and temperature in deep sea environments, deep sea exploration robots require high durability and heat resistance. Traditional hard mechanical structures are difficult to withstand these conditions and have slow movement speeds. Soft robotics with their flexible structures and adaptability are well-suited to solve these challenges, making them an ideal type of robot for deep sea exploration. Zhu and Josep *et al*.[6] have designed and tested a soft robotic platform named Tunabot based on Thunnus albacares and Scomber scombrus, as

CHAPTER 7

Challenges and Perspectives of Soft Robotics

Abstract: In recent years, soft robotics has developed very rapidly and has been widely used in industrial, agricultural, marine and military fields. However, the field of soft robotics still faces many problems. This chapter introduces the current challenges in the field of soft robotics, including actuation, sensing, materials, design, fabrication, modeling and control. Finally, we propose some suggestions and outlooks to overcome these challenges.

Keywords: Challenges, Soft robotics, Prospects.

ACTUATION AND SENSING TECHNIQUES

Soft robotics primarily employs materials and structures endowed with intelligence, enabling the execution of predefined actions *via* mechanical pre-programming to achieve an integrated drive-body mechanism. The advancement in embedded flexible sensors and flexible electronics has facilitated the incorporation of drive sensing capabilities within soft robotic systems. This integration of sensory technology into the soft robot's structure enhances its ability to acquire and process a broader spectrum of external stimuli.

Actuation

Soft-bodied robotics diverges significantly from the conventional robotic paradigm, particularly in terms of actuation mechanisms. Traditional robotics rely on rigid mechanical frameworks to ensure stability and bear the system's weight, necessitating considerable power for movement, while soft robotics adopts a fundamentally different design philosophy. The construction of soft robots involves pliable, deformable materials characterized by lower density and mass, which inherently demand reduced actuation energy. This reduction in necessary actuation force opens up a diverse array of propulsion techniques not typically feasible for their rigid counterparts. Among the myriad actuation strategies employed in the domain of soft robotics, notable methods encompass pneumatic, hydraulic, chemical, electrical, thermal, optical, and magnetic responses, each offering unique advantages in terms of responsiveness, control, and applicability to varied environments and tasks.

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Pneumatic-driven Soft Robot

Pneumatic-driven soft robot is a common type of soft robot, wherein gas pressure facilitates the locomotion and morphological alterations of the device. This category of soft robot is fundamentally composed of a duo of elements: a core structure crafted from supple materials and an ancillary system for gas inflation. The intrinsic benefits of such pneumatic-driven configurations include enhanced precision in control, a high degree of adaptability to various environments, and an inherently straightforward architectural design.

Despite the wide-ranging applicability of pneumatic-driven soft robots across diverse sectors, they are not without their limitations. Primarily, these robots exhibit suboptimal precision and control capabilities, attributed to the challenges in achieving accurate positioning and motion trajectory due to their flexible nature. Additionally, operational noise presents a significant issue, as the air supply mechanism inherent to pneumatic systems generates sound that can disrupt the ambient environment and affect the robot’s stability. The fabrication and maintenance costs associated with pneumatic-driven soft robots are also considerable, stemming from the complexity of their manufacturing processes and the necessity for specialized pneumatic supply and control apparatuses. Moreover, the stability and reliability of these robots necessitate enhancements, as their susceptibility to oscillations and instability can compromise their performance in tasks requiring meticulous precision.

Hydraulically Driven Soft Robot

Hydraulic drives, which utilize a liquid medium for pressure transmission, offer a parallel mechanism to pneumatic drives in powering soft robots. These systems are distinguished by their capacity to produce superior forces and velocities, alongside heightened control precision and output power, attributed to the incompressibility of the fluid used. This fundamental characteristic allows for more accurate control over pressure and flow rates, thereby enhancing the precision with which the movement and deformation of hydraulically driven soft robots can be managed. Such precise control renders hydraulic systems particularly beneficial for applications demanding meticulous manipulation, including surgical interventions and precision assembly operations. Furthermore, the potential for high-pressure and flow outputs endows hydraulically driven soft robots with significant advantages in scenarios where elevated power outputs are essential.

Hydraulic drive mechanisms, while effective, are not devoid of challenges. A primary limitation lies in the system's complexity, necessitating intricate assembly, calibration, and rigorous maintenance protocols. This complexity significantly escalates both the initial manufacturing and ongoing maintenance expenses associated with hydraulically driven soft robots. Additionally, the considerable size and mass inherent to these systems may impede their applicability in scenarios demanding rapid movement or operation within constrained spaces. Moreover, issues such as fluid leakage and operational noise not only pose potential environmental and safety risks but also contribute to the operational drawbacks of hydraulic drives, particularly in terms of maintaining a clean and quiet working environment.

Electrically Responsive Drive for Soft Robots

Electro-responsive actuation involves utilizing electrical energy to directly manipulate the properties of soft materials within a robot, facilitating its shape transformation and movement. This approach primarily employs materials such as dielectric elastomers and piezoelectrics. The simplicity of the system architecture, coupled with its high efficiency and rapid responsiveness, stands out as a significant advantage. However, the electrical characteristics and long-term durability of these materials remain pivotal challenges, constraining further advancements in electro-responsive drive technologies.

Dielectric elastomers are increasingly favored as actuators in soft robotics. These actuators comprise an elastomer sandwiched between two flexible electrodes, where applying a voltage induces electrostatic pressure across the membrane. This pressure expands the membrane's surface area while diminishing its thickness, leading to deformation. The simplicity of control and precision of electrically driven systems are notable advantages. However, their operational scope and mobility are constrained by the power density limitations of batteries and other energy sources. Furthermore, the necessity for high voltages, often up to 1,000 volts, in electric drive systems poses significant safety risks that warrant careful consideration.

Chemically Driven Soft Robot

Chemically driven soft robots represent a novel propulsion approach, leveraging chemical reactions to produce mechanical movement. This method offers enhanced flexibility and adaptability due to its capacity to operate under varied environmental conditions, with controllable reaction rates and directions. A key benefit of

SUBJECT INDEX

Juntian Qu

Juntian Qu is an assistant professor and a Ph.D. supervisor at Tsinghua University. He received Ph.D. from McGill University and served as research assistant at the University of Toronto, from 2017 to 2019. He was the Shuimu postdoctoral fellow in the Department of Mechanical Engineering at Tsinghua University, from 2019 to 2021. He has published more than 50 high level SCI/EI papers in flagship SCI journals and top robotic conferences, being authorized/published over 25 patents, and has written 2 academic books and 2 book chapters. He is the PIs of more than 10 national/provincial/ministerial projects and the co-PIs of over 10 national projects.