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Review

Soft Robot Design, Manufacturing, and Operation Challenges: A Review

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Abstract: Advancements in smart manufacturing have embraced the adoption of soft robots for improved productivity, flexibility, and automation as well as safety in smart factories. Hence, soft robotics is seeing a significant surge in popularity by garnering considerable attention from researchers and practitioners. Bionic soft robots, which are composed of compliant materials like silicones, offer compelling solutions to manipulating delicate objects, operating in unstructured environments, and facilitating safe human–robot interactions. However, despite their numerous advantages, there are some fundamental challenges to overcome, which particularly concern motion precision and stiffness compliance in performing physical tasks that involve external forces. In this regard, enhancing the operation performance of soft robots necessitates intricate, complex structural designs, compliant multifunctional materials, and proper manufacturing methods. The objective of this literature review is to chronicle a comprehensive overview of soft robot design, manufacturing, and operation challenges in conjunction with recent advancements and future research directions for addressing these technical challenges.

Keywords: soft robotics; bionics; digital engineering; compliant multifunctional materials; smart manufacturing; biomimetics; soft sensors; soft actuators; biomotion

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1. Introduction

Conventional robots typically employ rigid materials, such as steel, aluminum, and hard plastics, and commonly rely on electric actuators for power. The majority of their components are manufactured using traditional machining techniques. However, these robots have limited flexibility due to their rigid structural elements and limited freedom of motion, which are hard to adapt to complex work environments and safe human–robot interactions. Collaborative robots (cobots) [1] are designed to facilitate safe human–robot interactions, but they still experience limitations due to their rigid structural elements and lack of motion freedom. Safe human–robot interactions can be facilitated by active compliance control with feedback sensors, such as force/torque sensors [2], proximity sensors [3], cameras [4], and other sensors [5]. Nonetheless, rigid robots have limited mobility due to physical constraints imposed by their rigid links and joints with the finite freedom of motion. Moreover, such rigid manipulators can potentially cause damage to delicate objects during handling. These challenges can be addressed by the use of soft robots that are made from flexible, compliant multifunctional materials like shape-memory alloys, silicones, or rubber materials. They possess an unparalleled ability to alter their shapes and sizes by providing theoretically unlimited freedom of motion [6], which allows them to operate in unstructured environments and handle delicate objects.

The stiffness levels of engineering materials broadly vary from hard rigid materials to soft compliant materials [7]. Soft robots are composed of less stiff, compliant materials as well as stiff rigid materials [8]. In contrast, conventional industrial articulated robots [9,10] are made from stiff rigid materials like metals or hard plastics to be able to perform manufacturing processes [11–13] that involve high process loads.

There has been a surge in the popularity of soft robots in medical applications [14–17], smart packaging [18], agricultural harvesting [19,20], architectural applications [21], and search-and-rescue operations [22,23]. Moreover, Feng et al. [24] developed a soft robot specifically designed for surface exploration. Even and Ozkan-Aydin [25] developed a soft robot that is capable of navigating through unstructured environments by integrating contact and photo-transistor sensors for obstacle avoidance. Dinakaran et al. [26] demonstrated that soft gripper end-effectors enhance material handling efficiency. A notable breakthrough in the field has been demonstrated by Gu et al. [27] through the development of a self-folding soft robot. This innovative robot possesses a remarkable capability to autonomously reconfigure itself to fulfill various functionalities.

Unlike conventional rigid robots that utilize electric motor actuators, soft robots employ soft actuators that can be activated through various means, such as pressure [28–30], magnetic fields [31,32], electric stimulation [33–36], light or photonic stimuli [37–39], moisture-responsive mechanisms [40–42], and explosive triggers [43–45]. Furthermore, Son et al. [46] have conducted an extensive review on the four-dimensional (4D) shape changes that can provide versatile functional advantages to soft robots in response to external environmental stimuli including heat, acidity (pH), light, electricity, or pneumatic triggers.

Three-dimensional (3D) printing, or additive manufacturing, has had a profound impact on advancing and enhancing the efficacy of soft robots by enabling the creation of intricate multifunctional designs. However, a key challenge in this domain is the limited range of printable soft materials. To overcome these limitations, it is imperative to develop a broader repertoire of soft materials that are compatible with 3D printing [47]. The majority of research on soft robotics involved experiments that provided in-depth explorations of the challenges associated with soft robot sensing and control. Additionally, the use of the finite element (FE) method has made significant contributions to soft robotics. For example, the FE method is used to optimize the structural designs of soft pneumatic bending actuators [48,49] and improve their overall performance [50]. Moreover, a promising solution was proposed by Xu et al. [51], which introduces an innovative approach that integrates a controlled buckling structure with a triboelectric nano-generator to accommodate motion tracking with haptic feedback.

Although soft robots offer numerous advantages, there are some fundamental challenges to overcome, which particularly concern motion precision and stiffness compliance in performing physical tasks that involve external forces. In this regard, enhancing the operation performance of soft robots necessitates intricate, complex structural designs, compliant multifunctional materials, and proper manufacturing solutions to unleash better soft robots that complement humans in future manufacturing. The goal of this literature review is to chronicle a comprehensive overview of recent advancements and future directions in the areas of soft robot design, manufacturing, and operation.

It is possible that the application readiness level of soft robots is in infancy. Nonetheless, soft robots exhibit potential impacts on various industries including manufacturing [52,53], medicine [15,54–56], food [19,20], etc. Although this literature survey focuses on soft robot design, manufacturing, and operation challenges, it is important to note that the precursors of these challenges are often defined by the applications of soft robots. An important aspect of soft robot applications is the integration of soft robots with existing platforms. Based on its application, a soft robot may need a certain mechanism or method for integration with existing platforms that may consist of either rigid or soft bodies. Such integration efforts require the joining or assembling of dissimilar soft or rigid materials. Soft–rigid material integration is still an open topic for future research. In general, a soft robot can be mounted on an existing soft or rigid platform through different bio-inspired attachment mechanisms, such as grasping or clinging [2,56–60], magnetism [61], and/or adhesion [52,62,63].

2. Methodology

The methodology of this literature review on soft robot design, manufacturing, and operation challenges comprised comprehensive searches on the Google Scholar website for relevant journal articles, conference proceedings, and book chapters that were sourced from various reputable publishers, such as IEEE, MDPI, Springer, Elsevier, Mary Ann Liebert, and others. The search was conducted using a set of targeted keywords including soft robots, deformable sensors, 3D-printed robots, bio-inspired robots, soft actuators, and tunable stiffness robots. Following the search process, articles published primarily between 2015 and 2023 were carefully selected for inclusion in this review.

This study surveyed the selected articles to chronicle a comprehensive overview of recent advancements and future research directions in the areas of soft robot design, materials, manufacturing, and operation. Although soft robots offer numerous benefits, there are various fundamental challenges to overcome. Figure 1 provides a visual representation of key technical challenges documented in recent literature.

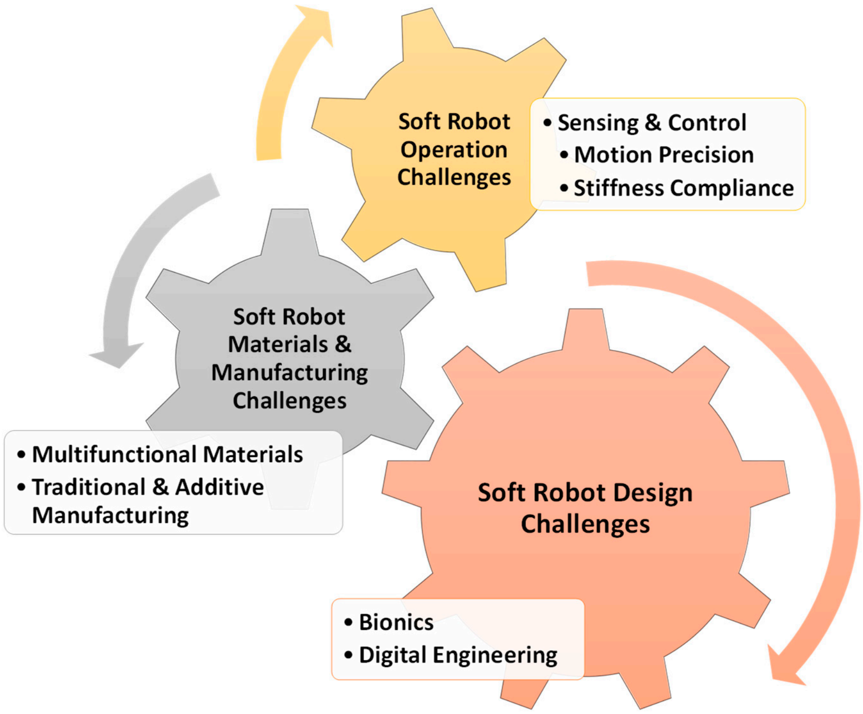

Figure 1. Key technical challenges.

Soft robot design challenges concern bionics, which is complemented by digital engineering. Soft robots often draw inspiration from biological organisms that have evolved through natural selection to achieve their optimal forms. Hence, bionic robots are designed to mimic the natural optimality of their biological counterparts. Furthermore, digital engineering tools offer more ways of optimizing bionic designs for better structural and operational performance levels and efficiencies of soft robots.

The manufacturing of soft robots with soft components poses significant challenges. The prevailing methods for manufacturing soft robot components include casting as a traditional manufacturing technique and 3D printing. Since casting methods are limited by their inability to produce intricate designs, 3D printing emerges as the preferred solution due to its ability to fabricate complex designs with multifunctional materials that offer compliance, stiffness, and versatility as well as regenerative aptitudes like bionic healing. Polymers are widely used for making soft robot components as they are lightweight, flexible, and multifunctional. Besides polymers, other materials with native functional properties like shape-memory alloys are instrumental in developing soft robot components.

Another major challenge in soft robotics concerns soft robot operation that involves sensing and control of soft actuators to achieve desired motion precision and stiffness compliance. Soft robot sensing is diverse in terms of perceiving various signal modalities, such as thermal, electromagnetic, tactile, and photoelectric forms. Controlling soft robots with the same level of precision as rigid robots still remains an open problem. The integration of rigid sensing and control components with soft robot structural components presents various difficulties and often makes the soft structural components more stiff and bulky to move around [64]. Hence, it is crucial to have in situ flexible sensors that can undergo significant deformation to facilitate seamless motion and stiffness control of soft structural components.

A soft actuator can be constructed from different types of stimuli-responsive polymers including liquid crystal polymers, liquid crystal elastomers, hydrogels, shape memory polymers, magnetic elastomers, electroactive polymers, and thermal expansion actuators [65]. Researchers have primarily focused on achieving controlled actuation, adhesion, and stiffness in soft robots [63].

In general, soft robotics concerns numerous challenges as it rapidly emerges as an interdisciplinary field that integrates mechatronics, bionics, biomimetics, material science and engineering, manufacturing, control systems, and artificial intelligence. The upcoming sections provide insights into the current state of soft robotics and future research directions in the areas of soft robot design, compliant multifunctional materials, manufacturing methods, and soft robot operation.

3. Soft Robot Design Challenges

3.1. Advancements

This section provides a survey on two design approaches implemented in soft robotics, which comprise a bionic design approach and a computer-aided design approach based on digital engineering.

3.1.1. Bionics

Bio-inspired manipulator designs have gained significant acceptance due to their ability to accommodate various biomotion modes [66]. Such naturally driven principles are commonly employed in various disciplines, including soft robotics [67–70], composite materials [71,72], path planning [73,74], energy optimization [75], etc. Soft robots inspired by earthworms [8,76,77], snakes [78,79], snails [80,81], insects [82,83], and caterpillars [84,85] have experienced a notable surge in research activities in recent years. Enhancing the elongation and compression capabilities of these robots is essential for achieving a remarkable motion performance. In 2016, a significant milestone was reached by Calderón et al. [86] with a soft actuator that can elongate extensively at 17.9 KPa (2.6 psi). Although achieving high elongation was a notable success, the compression ability of soft robots has been relatively poor. However, more recently, Das et al. [87] made significant progress in this area, achieving elongation and compression percentages of 21.9% and 22.3%, respectively, by demonstrating improved capabilities in both aspects. These are important achievements that allow soft robots to operate effectively.

Taking inspiration from desert iguanas, researchers have explored the implementation of compliant mechanisms in soft robot designs to enhance stiffness [88]. Furthermore, locomotion design principles, based on copepods and small crustaceans found in diverse aquatic habitats, have exhibited exceptionally rapid responses [89]. Also, Zhang et al. [90] have successfully designed and developed bio-inspired soft robotic fingers with motion sequences based on tendon-driven mechanisms as artificial muscles.

Biphasic materials like hydrogel offer enormous possibilities for researchers to design and develop bionic soft robots like hydrogel robots. Hydrogel robots have emerged as a promising advancement [91], offering a range of unique advantages that set them apart. These robots exhibit exceptional deformability, allowing them to undergo significant changes in shape and size. Their adaptability enables them to interact with and navigate through complex environments. One of the key strengths of hydrogel robots is their biocompatibility that makes them suitable for various applications in biomedical and healthcare domains. Hydrogel robots possess naturally embodied intelligence, meaning that their functionalities and responses are inherent in their material properties. These characteristics enable them to autonomously sense and respond to environmental stimuli, leading to enhanced interaction capabilities and improved motion performance. Given these remarkable advantages, it is evident that hydrogel robots hold great potential for shaping the future of soft robotics. Their impact is expected to be significant in the areas of manufacturing, medicine, and agriculture.

In recent years, there has been a growing research interest in leveraging the design and development of plant-inspired multifunctional materials, which can sense and move [92]. An intriguing example of such inspiration can be found in tendrils [58], which possess the unique capability to coil around a support pole while in their soft state and subsequently undergo lignification or hardening to reinforce the cling. This natural behavior is replicated in a soft robot using an artificial tendril with an electric control mechanism that enables or disables autonomous coiling and clinging.

Furthermore, drawing inspiration from the twisting and hanging behaviors observed in vines, Shan et al. [93] proposed and designed a passive variable-stiffness soft robotic gripper. This innovative gripper harnesses the principle of jamming to achieve a simple yet robust grasping mechanism for object handling. By embracing these plant-inspired concepts, researchers are advancing the development of soft robots and aiming to enhance their functionalities and capabilities in various applications.

3.1.2. Digital Engineering

In addition to the bionic design approach, researchers have also explored the use of digital engineering tools that accommodate finite element analysis (FEA) in soft robotics. This computer-aided design approach is extremely useful for design optimization based on engineering design principles. Figure 2 presents a soft actuator design inspired by an elephant trunk. The bending of the soft actuator is regulated by two asymmetric pressure chambers as demonstrated by FEA simulation models in Figure 2. FEA has been widely employed in numerous studies that focus on soft robot design performance [94,95]. For instance, Nguyen et al. [96] investigated the design of fabric soft pneumatic actuators for wearable assistive devices using FEA for performance analysis. Ferrentino et al. [97] developed an FEA simulator called Simulation Open Framework Architecture (SOFA) specifically for soft actuators. Naughton et al. [98] used the Elastica software to simulate and analyze the performance of a soft robot model that resembles an elephant trunk. Another advanced soft robot modeling and simulator, ChainQueen, has also gained acceptance among researchers that study robot dynamics and control [99–101].

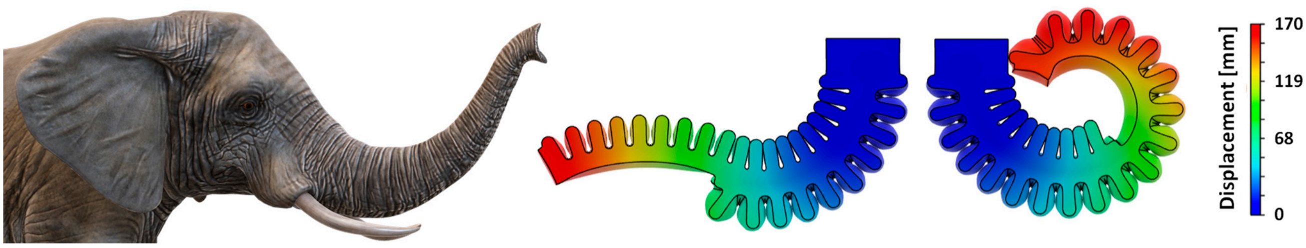

Figure 2. This figure presents FEA simulation models of a pneumatic soft actuator design that is inspired by an elephant trunk.

The versatility of the FEA method extends beyond the use of a single material, as it allows the incorporation of layers of different soft robot materials. Ferrentino et al. [102] developed a quasi-static FEA model for a multi-material soft pneumatic actuator in SOFA. SOFA, an FEA simulator, has been widely utilized in various soft robot studies, such as solid meal digestion in a soft gastric robot [103] and soft robot optimal control [104]. By employing digital engineering tools, such as SOFA and Elastica, researchers [105] analyzed and optimized certain soft robot structural designs and structural materials to achieve enhanced functional performance and application potential.

3.2. Opportunities

Although the bionic design approach offers naturally proven design principles in soft robotics, such design principles still need further improvements and adaptation with the use of digital engineering tools. The lack of proper computer-aided modeling and simulation may lead to the heavy reliance on numerous trial-and-error attempts during the soft robot development process [106]. Hence, there is a surge in the research emphasis on combining the bionic design approach with the computer-aided design approach in soft robotics. By using bionics and digital engineering tools, researchers are able to explore unchartered design principles and new innovative engineering solutions to making better soft robot designs that have the potential to revolutionize the design process, facilitate soft robot manufacturing, and unleash better soft robots that complement humans in future manufacturing.

4. Soft Robot Materials and Manufacturing Challenges

4.1. Advancements

A material shape can change in many ways. Some changes are reversible, but some changes are irreversible. Since compliance is a desirable property of soft robot materials, highly compliant materials, such as silicone, elastomers, hydrogels, fibers, shape memory materials, etc., serve as the main building blocks of soft robots. Such compliant materials can undergo large deformations without losing their properties and functionalities.

Table 1 presents a list of common soft materials documented in the selected literature. Soft materials demonstrate multiple functions, such as actuation, stiffening, structural support, healing, control, sensing, etc., in reaction to various stimuli. Therefore, Table 1 also presents common functions and common stimuli for each soft material as reported in the selected literature.

Table 1. This table presents common soft materials and their properties documented in the selected literature.

Soft Materials	Common Functions	Common Stimuli	References
Magnetic Soft Materials	Actuation; Stiffening; Healing; Control; Sensing; Structural Support	Magnetism (M); Electricity (E); Temperature (T)	[31,32,61,78,107–113]
Liquid Metals	Stiffening; Control; Sensing	M; E; T	[108,113–117]
Shape Memory Materials	Actuation; Healing; Sensing	Tactility, M; E; T	[33,118,119]
Artificial Tendon Fibers	Actuation; Stiffening; Control; Structural Support	Tactility; M; E; T	[67,71,90,118,120–130]
Liquid Crystal Polymers	Actuation; Stiffening; Control; Sensing	Light; M; E; T	[37–39,80,112,131]
Elastomers or Silicones (i.e., Ninjaflex™, Dragon Skin™, Ecoflex™)	Actuation; Stiffening; Healing; Structural Support	Pneumatics (P); Hydraulics (H); E; T	[80,112,118,131–135]
Hydrogels	Actuation; Stiffening; Healing; Sensing; Structural Support	H; M; E; T; Chemical Reaction	[29,91,117,136,137]

Sensing, actuation, and control are the primary operation challenges in soft robotics. Consequently, integrating sensing and actuation functionalities with compliant materials to achieve the feedback control of motion and stiffness is cumbersome. Multifunctional materials are essential for this purpose. There is a possibility that materials with different properties and functionalities can be integrated to provide different actuation and sensing modalities [124]. Incorporating functional materials [138] into soft robots can greatly enhance their capabilities. Proper manufacturing methods must be implemented in implanting multifunctional elements in soft robot bodies for efficiency and effectiveness [126]. In this case, the casting of silicone material can be employed for simple designs, while additive manufacturing can be a pathway to creating multifunctional materials with customizable designs.

Synthesizing various functional materials to achieve new actuation, control, and sensing capabilities is possible. For instance, enhancing the elastomer with various fibers offers better stiffness, particularly when such stiffness is necessary to deal with external loads. Li and Diller [110] conducted a study on multi-material fabrication for magnetically driven miniature soft robots using stereolithography.

Silicone casting is a widely employed method for manufacturing soft robot actuators. This technique is particularly suited for producing actuators that perform certain motion tasks, i.e., bending [139], gripping [60], and crawling [140]. When faced with more intricate engineering challenges, the fabrication of soft robots necessitates the utilization of multi-material 3D printing techniques [141]. This advanced manufacturing approach empowers the creation of soft robots with complex structures and the integration of multiple materials to achieve more functionalities and versatility. For instance, Figure 3 shows an illustration of multi-material 3D printing based on fused filament fabrication (FFF), which uses restricting and actuating materials along with certain design parameter settings to fabricate bio-inspired flexible parts with self-shaping properties. The design parameters are used as shape-tuning factors to enable materials programming and 4D printing [92,142].

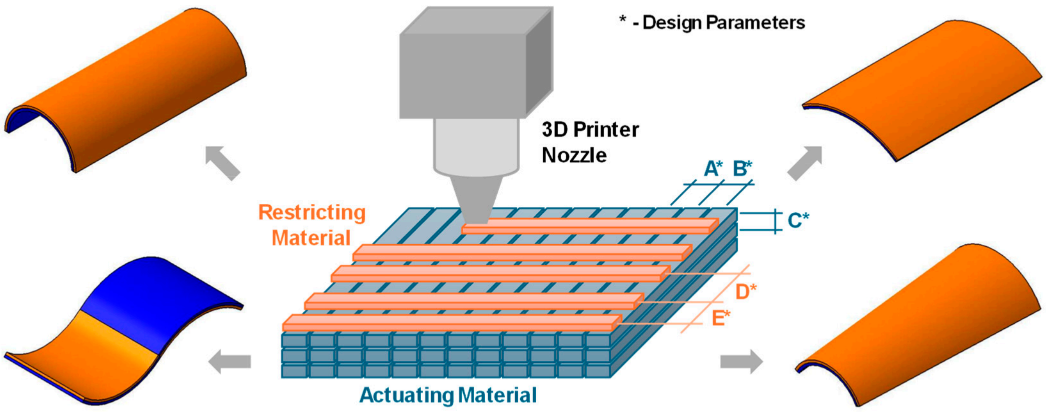

Figure 3. This figure shows an illustration of multi-material 3D printing that uses restricting and actuating materials along with certain design parameter settings, such as A, B, C, D, and E, to fabricate bio-inspired flexible parts with self-shaping properties.

Additive manufacturing (AM), such as 3D printing, involves adding material layers, one after another, to build objects, which is distinguished from traditional machining methods that rely on subtractive manufacturing. The main advantage of 3D printing lies in its capability to produce intricate and elaborate geometries without requiring extensive post-processing [143]. Moreover, it enables the development of customized materials and composites by minimizing material wastage. This versatile technology can be applied to a broad range of materials, including shape-memory polymers and other stimuli-responsive soft materials. Due to these inherent advantages, 3D printing plays a pivotal role in the fabrication of soft robots. It enables the production of various structural and operational components, simultaneously, with the use of multiple source materials, which makes it highly suitable for diverse manufacturing needs in soft robotics [144].

Another significant advantage of 3D printing in the realm of soft robots is the ability to integrate and manufacture different sensors alongside soft actuator components. Unlike traditional approaches to integrating tactile sensing, which requires separate manufacturing processes for sensor integration, multi-material 3D printing, i.e., fiber-reinforced printing [128], enables the direct printing of tactile sensors onto a soft robotic hand with distributed tactile sensing and 3D-printed air chambers [145]. This advancement facilitates the development of a soft robotic hand equipped with distributed pneumatic touch sensing in the fingers and an active palm. For prosthetic applications, a 3D-printed soft robotic hand with embedded soft sensors has been designed and developed to seamlessly interface with next-generation myoelectric control systems [56]. In the areas of embedding flexible electronic devices into soft robots, Mathai et al. [125] proposed a novel additive manufacturing method of tailored flexible inductive coils via patterning steel electroconductive fibers for soft robots and wearable devices.

Furthermore, the integration of non-assembly 3D-printed joints with soft robotic muscles has been pursued to create tendon-driven robotic fingers. This approach incorporates a finger-type structure actuated by an electro-thermal soft actuator mechanism for bio-inspired 3D-printed compliant joints and 3D-printed finger elements [146].

During additive manufacturing, the curing process of soft robot materials is time-consuming, leading to delays in the manufacturing flow. To address this issue, various methods have been employed with the use of stereolithography (SLA) and digital light processing (DLP) that emerge as the most recent solutions. SLA and DLP utilize the polymerization of photopolymer resin under ultraviolet (UV) irradiation, offering significantly higher printing resolution compared to other techniques [147].

Among these methods, DLP 3D printing stands out for its rapid printing speed. By utilizing a DLP system that uses UV light projection, an entire layer can be cured with a single exposure. In fact, a standard SLA 3D printing facility can achieve a very high printing speed by employing a green and cost-effective hydrogel as a separation interface against the cured part [136]. Notable works utilizing DLP methods include the development of 3D-printed untethered soft robots [148] and the creation of super stretchable and processable silicone elastomers [135]. These studies have demonstrated excellent performance and advancements in employing the DLP technology for soft robot fabrication.

4.2. Opportunities

Synthesizing compliant multifunctional materials with distinct sensing and actuation modalities remains a challenge. Combining various materials that can leverage the bionic functionalities of soft robots requires a multifaceted understanding of materials, mechanics, and manufacturability in conjunction with soft robot design principles. Functional materials that are easy to manufacture and assemble are essential for advancing the maturity of soft robotics. The development of new functional materials for soft robots highly depends on the ability to produce or synthesize such materials. Therefore, challenges in this growing research field inarguably focus on the fabrication of functional elements synthesized from various source materials. Although some prototypes [149,150] have shown great promise with the use of multi-material 3D printing, they lead to new unexplored manufacturing challenges to address. Moreover, in the areas of additively manufactured functional elements, the process of embedding long fibers is time consuming, laborious, and prone to errors. To facilitate the fiber embedding process, an automated fiber embedding mechanism [126] as well as a textile-based method [118] have been proposed. Additionally, Eroglu et al. [52] have presented a simple manufacturing process for miniaturized underwater soft robotic grippers inspired by octopuses. These innovations in 3D printing demonstrate important manufacturing advancements toward seamlessly integrating sensors into complex soft robot components via opening up new possibilities for various soft robot design and operation principles.

5. Soft Robot Operation Challenges

5.1. Sensing and Control of Motion

5.1.1. Advancements

In the field of soft robotics, the use of deformable sensors is crucial to achieve the desired accuracy and repeatability [132]. These sensors possess important characteristics, i.e., compliance, flexibility, and seamless integration with the robot's surface, while meeting requirements for stretchability. Multifunctional sensors capable of sensing operational and environmental parameters like shape, temperature, force, and surface finish are extremely useful for soft robot operation [151]. Commonly employed deformable sensors for mounting on soft actuators include resistive strain sensors, such as liquid metal-based sensors, fabric and textile-based sensors, flex sensors, and elastic compressive foam sensors. There is research [57,114,117,129,152–163] documenting the use of capacitive sensors, such as pressure sensors, tactile sensors, strain sensors, and pneumatic pressure sensors, in soft robotics. In terms of positioning, soft robots can be guided by embedded ultrasonic range sensors for navigation [164]. The use of resistive flex and magnetic curvature sensors enabled the precise, fast achievement of certain soft actuation curvatures [165].

Recently, Xing et al. [166] proposed fibrous inductance-based soft sensors with very high repeatability and ultra-low hysteresis, which can be embedded in soft robots or can even be implanted as replacements of the air channel restriction fibers of pneumatic actuators. In addition, Yang et al. [130] designed and developed a twining plant-inspired single-channel pneumatic soft spiral gripper with an embedded high birefringent (HiBi) fiber optic sensor for monitoring the twining motion, characterizing a target object as small as 1 mm in diameter, and detecting undesired external perturbation. Fiber optic sensors possess a compact size and shape and offer several advantages compared to their electronic counterparts. These advantages include easy multiplexing, immunity to electromagnetic interference, and an ability to function reliably in chemically aggressive, explosive, and humid environments [127].

As discussed in Section IV, noticeable advancements have been made in addressing soft robot manufacturing challenges using various materials and manufacturing methods to facilitate certain soft robot design and operation principles. Soft robots that are made of multifunctional soft materials may be able to demonstrate various biomotions shown in Figure 4, such as shortening or elongation [167,168], twisting or untwisting [130,169], wrapping or unwrapping [112,170], bending or unbending [48,163,165,171], and contraction or expansion [112,168]. These soft matter biomotions can be triggered by common stimuli, such as magnetism [2,31,32,61,67,78,107–113,116,172], electricity [33–36,51,131,134,173], temperature [18,85,111,112,116,122,173], tactility [51,121,145,158–161], chemical reactions [137,174], pneumatics [6,30,76,102,140,168,174–176], hydraulics [69,132,153,177], and light [18,37–39,80, 111,135,136,147]. Some polymers even exhibit healing or recovering abilities [112,117] as shown in Figure 4 with the use of magnetism and electricity.

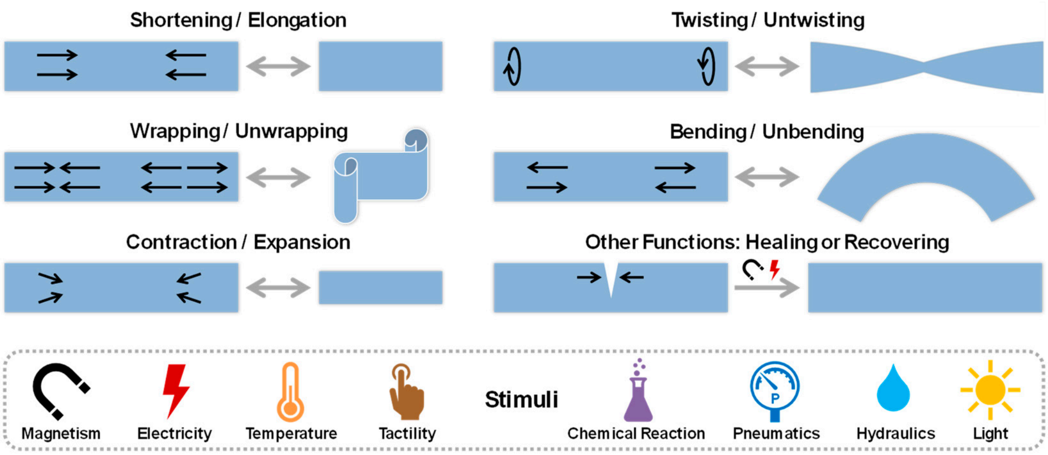

Figure 4. This figure presents the illustrations of common soft actuator functions and their stimuli. Soft actuators can be triggered by their associated stimuli to perform these common functions.

However, the kinematics, dynamics, and control of soft actuators [53] still experience the challenge of mimicking natural biomotion. In this essence, the nonlinear nature of soft body dynamics makes it extremely difficult to model and control soft robots with necessary motion precision and stiffness compliance. To overcome this challenge, simplified kinematic and dynamic models are mostly used to control soft robots, which may not provide necessary motion precision and stiffness compliance. Gong et al. [178] developed untethered cable-driven soft actuators and discovered a promising performance that may lead to a repeatable motion pattern that mimics a tendon-driven biomotion pattern.

Pneumatics is widely used in soft robotics. Drotman et al. [179] evaluated 3D-printed pneumatic soft actuators with angled leg bellows and regular horizontal bellows to compare their manipulation performance. They concluded that the angled leg bellows perform significantly better than the regular horizontal bellows. Walker et al. [180] conducted a literature review study on pneumatic soft actuators. Owing to the inherent limitations of complex and bulky air compressors and tubes, pneumatic actuators are being progressively replaced by alternative actuation methods.

In the case of soft pneumatic robots, pneumatic pressure sensing is not woven into the fabric of soft robots all the time. Therefore, sensor-less control is common for regulating the pneumatic pump motors of pneumatic soft robots. In general, the sensor-less control of a brushed direct current (DC) motor uses a method that the estimation of the motor performance without using sensor feedback. Such sensor-less control methods are classified into model-based control and non-model-based control.

Soft pneumatic actuators (SPAs) are compliant and customizable [176]. Their motion performance relies on factors, such as pneumatic chamber shapes and cross-sectional geometries under variable loading conditions. Manfredi et al. [181] designed and developed a wireless compact control unit for untethered pneumatic soft robots. Davarzani et al. [55] studied the finger kinematics of a human hand and developed a 26-degree-of-freedom pneumatic soft robotic hand with good dexterity [182]. Although SPAs offer simplicity, their weight and bulkiness may limit the mobility of untethered soft robots.

The model-based control utilizes a dynamic model of a DC motor and incorporates various types of model-based observers, such as a sliding or pseudo-sliding mode observer or an observer that is combined with proportional-integral (PI) control [183]. These model-based methods use a mathematical model of the motor to estimate the motor speed to control. On the other hand, the non-model-based control does not rely on an explicit mathematical model of the motor. Instead, it exploits the ripple components of the DC motor current for speed estimation. In this case, the measured motor current is processed through a discrete bandpass filter with a variable bandwidth to determine the motor speed. Both model-based and non-model-based control approaches offer their own unique advantages and disadvantages in the context of sensor less control for soft robots. Ongoing research aims to further explore and enhance the sensing and control capabilities of soft robots.

Accurately modeling the dynamics of soft robots for model-based control is extremely difficult and time-consuming. This is partly due to the infinite motion freedom of soft robot manipulation. Gillespie et al. [184] investigated a nonlinear dynamic model and predictive control using a neural network and achieved motion accuracy within 2° of the commanded joint angle. In another study, a dynamic motion control strategy for a multi-segment soft robot [185] has been developed using a piecewise constant curvature and an augmented rigid body model.

Open-loop control is generally unsuitable for soft robot manipulation due to the nonlinear dynamics, which is unpredictable. For instance, pneumatic "muscle" actuators regulated by open-loop control often face challenges in achieving motion precision [168]. Furthermore, controlling the deformation levels of a flat, thin, soft material can be challenging due to uncertainties associated with the nonrigid body dynamics. To address these challenges, closed-loop control [186] is necessary for better motion precision, robustness, stiffness compliance, and adaptability to dynamic, uncertain environments [187]. Closed-loop control can be constructed by system identification techniques, which involve creating a transfer function that emulates the actual soft actuator to study the actuator response characteristics [188]. Soft robots are well-suited for data-driven system identification techniques since they can collect data during the operation [189].

In a study by Azizkhani et al. [190], an experiment was conducted to compare standard proportional derivative (PD) feedback linearization control with adaptive passivity control. The results showed that the adaptive passivity control of soft robots offers a promising level of performance. Moreover, using equilibrium-based modeling, Dou et al. [191] developed a hybrid soft robot with the adjustable elongation that is controlled by a multi-chamber soft body with a rod-driven compliant mechanism that provides a push-pull drive.

Hydrogel actuators driven by chemical reaction networks have been explored by Fusi et al. [137] for soft robot actuation. In the pursuit of environmental protection, researchers have also developed bio-degradable electrohydraulic actuators [177]. Additionally, noticeable advancements have been made in the field of chemically driven oscillating soft actuators [174].

Temperature has emerged as another handle on soft actuator control. Tang et al. [170] utilized a twisted and coiled actuator, which could be precisely controlled through temperature manipulation. Furthermore, Yoon et al. [173] developed a thermo-pneumatic untethered actuation module based on a gas-liquid phase transition that is controlled by a soft thermoelectric device. A possible drawback of thermal control can be the time delay needed for temperature manipulation that may slow down the soft robot reaction.

Nowadays, magnets are also frequently used as actuators [61]. The shape and motion of a soft actuator with strategically embedded magnets may be controlled by electromagnetic fields [111]. This gives the robot the ability to perform various actions, such as grasping things or bending in a certain manner. By instantaneously changing and synthesizing certain internal electromagnetic vectors (EVs) in each magnetic flux subdomain, self-vectoring electromagnetic soft robots (SESRs) offer additional operational dimensions [109].

A magnetically controlled microswitch (MCSM) may be well-integrated into soft actuators by using highly stretchable, electroconductive liquid metal (LM) [115]. Such an LM-based soft actuator can sense and act with the internal MCSM system that provides robust, practical feedback control [108].

Magneto-rheology (MR) and shape memory alloys (SMAs) [21] are instrumental in developing artificial muscles. Pure SMA artificial muscles demonstrate sluggish recovery speed and limited holding capacity. The incorporation of MR into SMA resulted in an artificial muscle with a remarkable 440% increase in the recovery speed by outperforming conventional SMA artificial muscles by 333% [119].

Xing et al. [33] studied a shape-memory soft actuator with reversible electric/moisture actuating and strain sensing in a compact sandwich structure, where silver nanoparticles are used to form a middle composite layer by connecting a hygroscopically deformable polyvinyl alcohol (PVA) layer with a high-performance flexible shape memory polymer (FSMP) layer. This actuator can bend and grip an object as well as perceive its presence.

The complexity of manufacturing and the integration of dissimilar materials are the major drawbacks of the aforementioned actuation methods. They can be complemented by a liquid crystal elastomer, an artificial muscle with the reconfigurable design and reprogrammable strain, which was proposed by He et al. [131] for making soft tubular actuators. These soft tubular actuators demonstrated homogeneous contractions of up to 40% as well as multidirectional bending.

Yan et al. [192] introduced a laser-patterning approach to embedding 2D functional structures directly into electroactive polypyrrole (PPy) films. This technique transforms the typical bending of PPy films into various actuation modes including squeezing, gripping, flapping, and lifting, when the PPy films are immersed in an electrolyte solution analogous to a biological body fluid. Qing and Qingchao [122] developed a temperature sensing artificial finger using an optical fiber grating. The finger prototype was then tested under various temperatures and bending conditions, which proved that it yields highly accurate and repeatable actuation performance values.

All aforementioned advancements in soft robot sensing and actuation showcase diverse methods and strategies for various needs that naturally arise in soft robotics and open doors to new fundamental research opportunities and applications in the areas of soft robot design, manufacturing, and operation.

5.1.2. Opportunities

The development of soft sensors remains a major challenge in the field of soft robotics. Additive manufacturing enables the integration of soft sensors into soft robots [121]. However, existing soft sensors often suffer from slow response times, short lifetimes, and hysteresis, which negatively impact the overall performance and reliability of soft robots [193]. Addressing these issues is crucial for advancing the field.

Recently, an innovative breakthrough has been achieved in the field of soft robotics, so that a soft robot can be actuated using strain energy stored in a structural member. This significant advancement relies on the behavior exhibited by elastomers when they are pre-stretched to the point of buckling [133]. In fact, the final length attained by an elastomer is remarkably greater than its pre-stretched length. This remarkable characteristic of elastomers opens up new avenues for creating untethered autonomous soft robots. Once the initial pre-strain is applied, these robots operate independently without requiring additional chemical or electrical energy sources and without relying on external stimuli for activation. Even after the applied force is removed, the growth process of the elastomer continues, leading to further elongation. This autonomous adaptability and shape-changing ability of soft robots offer significant advantages in various applications. They can dynamically respond to their environments and perform tasks without the need for continuous external control. This breakthrough enables new, highly versatile, self-sustaining soft robots with the potential to revolutionize industries, such as manufacturing, healthcare, etc.

Overall, the kinematics, dynamics, and control of soft robots still experience the challenge of mimicking natural biomotion. The nonlinear nature of soft body dynamics makes it extremely difficult to model and control soft robots with necessary motion precision and stiffness compliance. Although machine learning offers some promise [194–199], soft robot kinematics, dynamics, and control still remain subject to future research opportunities. For instance, Figure 5 presents a soft actuator with two asymmetric pneumatic chambers. Its input pressures and actuator responses exhibit nonlinear kinematics and dynamics, which cannot be easily characterized by methods used for standard rigid bodies.

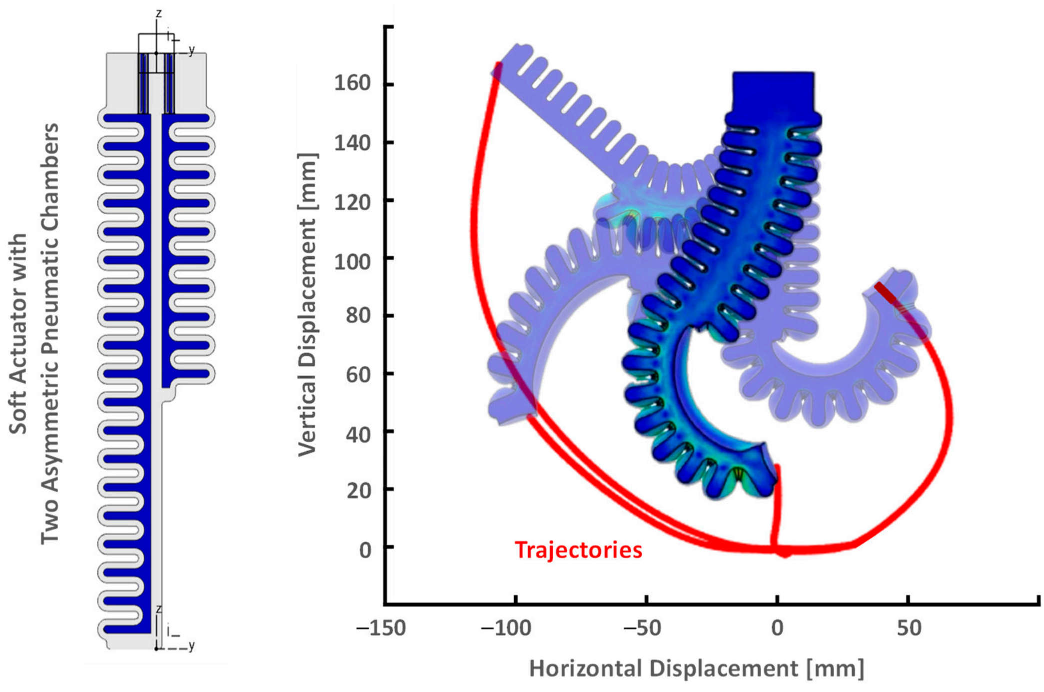

Figure 5. This figure presents the movements of a soft actuator with two asymmetric pneumatic chambers. The soft actuator design, left, is inspired by an elephant trunk. The end trajectories of soft actuator movements are illustrated in a reference frame, right. The bending movements are planar.

5.2. Sensing and Control of Stiffness

5.2.1. Advancements

Despite facilitating safe human–robot interaction, compliant soft robots exhibit inherent low stiffness that makes them too weak to handle certain tasks that involve external forces. Therefore, soft robots often need variable stiffening mechanisms [200]. The direct modulation of stiffness proves to be an effective approach to adjusting the soft robot stiffness for different operation conditions. Numerous researchers explored stiffness sensing and control for soft robots [134,201–204]. Accordingly, the following subsections will discuss stiffness sensing and control in terms of fluidic stiffness control, pneumatic stiffness control, magnetic stiffness control, and thermal stiffness control.

Fluidic stiffness control: He et al. [205] developed a tunable stiffness sensor that can be directly 3D-printed into a hydraulic soft robot with the intent to control its stiffness. Sozer et al. [206] proposed a novel fluid-driven variable-stiffness revolute joint (VSRJ) based on a hybrid soft-rigid approach to achieving adjustable compliance. The VSRJ is composed of a silicone rubber cylinder as a pressure chamber and two identical rigid links. By applying fluidic pressure, the stiffness of the VSRJ joint can be adjusted with up to 8-fold rotational stiffness enhancement from 0 to 500 KPa input pressure within a rotation angle range between $-30°$ and $+30°$. Although fluid-driven actuators resemble biofluid-driven muscles, they may eventually leak by polluting the environment and degrading the overall performance of actuation.

Pneumatic stiffness control: Best et al. [207] used a linear quadratic regulator (LQR) and model predictive control (MPC) for an inflatable humanoid robot to perform object handling tasks that require stiffness. Crowley et al. [208] have successfully developed a 3D-printed soft robotic gripper with variable stiffness using an innovative positive pressure layer jamming technology.

For increased safety in interventional surgery, stiffness adaptation with concurrent tendon-driven and pneumatic actuation is suggested [54]. In order to temporarily increase the stiffness of a soft robot, Liu et al. [209] presented a tubular stiffening segment based on layer jamming. Wei et al. [59] also looked at a flexible robot that can grip objects and has variable stiffness based on a folding plate mechanism and particle jamming. Micklem et al. [210] proposed and demonstrated a method for tunable stiffness using inflatable rubber tubes to effectively stiffen a soft robot via adjusting the internal pressure of the inflatable tubes from 0 to 80 KPa.

Soft pneumatic actuators (SPAs), which are engineered with 3D-printed conductive polylactic acid (CPLA) materials or bio-inspired lattice chambers and fused deposition modeling (FDM) 3D printing, were able to modulate the soft robot stiffness and shape [175,211]. A stiffness-tunable modular bionic soft robot that can crawl and overcome obstacles consists of a series of inflatable soft modules, whereas each module consists of two parallel inflatable, tunable soft actuators [212].

For high-performance gripping tasks in industrial applications, Aydin et al. [213] demonstrated a novel variable-stiffness soft gripper with an ability to change its stiffness through the use of a proportional air-pressure regulator. Soft robots with stiffness regulated by pneumatic artificial muscles (PAMs) were demonstrated by Pardomuan et al. [214]. Yang et al. [215] also implemented PAMs in a particle robotic arm with stiffness and damping regulation.

When an internal vacuum is produced, fiber jamming modules (FJMs), which are made of axially packed fibers in an airtight container, go from being flexible to rigid. This FJM can offer flexural stiffness that is up to eight times more than that of a particle jamming module [123].

Overall, pneumatics provides enormous possibilities in soft robotics, but leakage and the compressibility of air may degrade the overall performance of pneumatic actuation.

Magnetic stiffness control: Gaeta et al. [107] demonstrated magnetically induced stiffening for soft robotics. Zhao and Dai [113] have successfully implemented the liquid-metal thermotropic phase transition as a method for regulating the stiffness of soft robots. They have developed a liquid metal variable-stiffness material (LMVSM) that can actively and rapidly adjust its stiffness by applying an external magnetic field or temperature modulation. The LMVSM is composed of a nickel-chromium wire layer for Joule heating, a soft heat dissipation layer for rapid cooling, and gallium-iron magnetorheological fluid (Ga-Fe MRF) layers for altering the stiffness. By utilizing a magnetic field, stiffness can be increased by a factor of 4, while the solidification of the Ga-Fe MRF can enhance the stiffness by a factor of 10 [116].

The principles of jamming combined with the use of magnetorheological fluid offer faster stiffness control and portability [107]. To generate strong magnetic fields with lower power consumption for the manipulation of magnetorheological fluid, electro-permanent magnets (EPMs) have been proposed as a potential solution [172]. EPMs can not only generate magnetic fields comparable to permanent magnets in strength but also involve electric pulse control that does not need continuous power input.

In recent developments, Wu et al. [216] demonstrated the effectiveness of magnetic-responsive composites as soft, active metamaterials for fast transforming actuation under external stimuli for tunable mechanical properties. Bartkowski et al. [217] created a compliant soft actuator with variable stiffness using an electromagnetically controlled shape morphing composite (e-morph). Electromagnetism offers various ways of sensing and controlling soft robot motion and stiffness, but such magnetic sensing and control may suffer electromagnetic interference (EMI) generated by external sources.

Thermal stiffness control: Ma et al. [218] designed and produced thermally controlled variable-stiffness joints using thermo-rheological fluids (TRF). They employed two phase-changing substances: low-melting point solder (alloy) and hot-melt glue. Both substances are incorporated into a joint fabricated by silicone casting and 3D printing. The findings indicate that the proposed variable-stiffness joint with TRF yields a wide range of load-deflection ratios under temperature manipulation.

The tuning of soft gripper stiffness and adhesion is enabled by thermally induced phase transition of a thermoplastic composite material implanted in a silicone pad [62]. The soft gripper works by putting the pre-heated silicone pad into contact with an object and then allowing it to cool and stiffen to produce a solid adhesive attachment for object handling.

A stiffness-tunable soft-rigid gripper [219] was made of a polylactic acid-based variable-stiffness module (VSM) and a rigid retractable mechanism to achieve hybrid soft-rigid actuation. A heating circuit was designed to divide VSM into three segments, where each segment can be activated separately for varying stiffness to enhance the dexterity of the gripper. Recently, Zhong et al. [220] proposed a discrete variable-stiffness approach to a bio-inspired bistable articulated joint that consists of a rigid joint and bistable structures. The bistable structures are triggered by thermal shape memory alloy springs.

In general, temperature manipulation provides a handle on soft robot stiffness control. However, a possible drawback of thermal control can be the time delay needed for temperature manipulation that may slow down the soft robot reaction.

5.2.2. Opportunities

A soft robot inarguably needs stiffness sensing and control to be able to adjust its stiffness for various mechanical tasks that require compliance as well as stiffness. Scholars have explored different ways of harnessing soft robot stiffness with the use of fluidics, pneumatics, electromagnetism, and thermal control as reviewed in Section 5.2.1. In addition, Xiao et al. [221] developed a tendon-driven concentric tube as a concentric backbone for a stiffening soft robot. Another tendon-based stiffening has been created for soft robotic gripper with a noticeable grasping force using twisted string actuators (TSAs) inspired by the anatomy of the human hand [120]. Even though the recent literature indicates noticeable achievements in the field, soft robots still need to go a long way to reach the level of their biological counterparts in terms of harnessing stiffness.

6. Summary

Advancements in smart manufacturing embrace the adoption of soft robots for improved productivity, flexibility, and automation as well as safety in smart factories. Hence, soft robotics is gaining a significant surge in popularity by garnering considerable attention from researchers and practitioners. Bionic soft robots, which are composed of compliant materials like silicones, offer compelling solutions to manipulating delicate objects, operating in unstructured environments, and facilitating safe human–robot interactions. In this regard, enhancing the operation performance of soft robots necessitates intricate, complex structural designs, compliant multifunctional materials, and proper manufacturing solutions to unleash better soft robots that complement humans in future manufacturing.

By using bionics and digital engineering tools, researchers are able to explore unchartered design principles and new innovative engineering solutions to making better soft robot designs that have the potential to revolutionize the design process, facilitate soft robot manufacturing, and unleash better soft robots that complement humans in future manufacturing. Synthesizing compliant multifunctional materials with distinct sensing and actuation modalities remains a challenge. Combining various materials that can leverage the bionic functionalities of soft robots requires a multifaceted understanding of materials, mechanics, and manufacturability in conjunction with soft robot design principles. Additive manufacturing has emerged as a solution to complementing the limitations of traditional casting and subtractive methods by enabling the fabrication of complex geometries, the integration of in situ sensors, and the use of multiple functional materials to enhance the capabilities of soft robots.

Motion precision and stiffness compliance pose challenges in the areas of soft robot sensing and control. Soft actuators are used for bending, twisting, stretching, shrinking, and other biomotion variants driven by chemical reaction networks, thermal stimuli, pneumatics, electromagnetism, and tendon-based artificial muscles. Adjusting the stiffness of soft robots is also crucial for generating the needed force using certain materials and mechanisms that can be stiffened via fluidics, pneumatics, electromagnetism, thermal stimuli, and artificial muscles. Flexible sensors capable of enduring large deformations play a vital role in achieving these operation objectives. Recent advancements also suggest the development of soft actuators with in situ sensing mechanisms that eliminate the need for external sensors.

Although this literature survey focuses on soft robot design, manufacturing, and operation challenges, it is important to note that the precursors of these challenges are often defined by the applications of soft robots. An important aspect of soft robot applications is the integration of soft robots with existing platforms. Based on applications, a soft robot may need a certain mechanism or method for integration with existing platforms that may consist of either rigid or soft bodies. Such integration efforts need the joining or assembling of dissimilar soft or rigid materials. Soft–rigid material integration is still an open topic for future research.

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