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Review

Review of the Research Progress in Soft Robots

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Abstract: The soft robot is a new type of robot with strong adaptability, good pliability, and high flexibility. Today, it is widely used in the fields of bioengineering, disaster rescue, industrial production, medical services, exploration, and surveying. In this paper, the typical driven methods, 3D printing technologies, applications, the existed problems, and the development prospects for soft robots are summarized comprehensively. Firstly, the driven methods and materials of the soft robot are introduced, including fluid driven, smart materials driven, chemical reaction driven, a twisted and coiled polymer actuator, and so on. Secondly, the basic principles and characteristics of mainstream 3D printing technologies for soft materials are introduced, including FDM, DIW, IP, SLA, SLS, and so on. Then, current applications of soft robots, such as bionic structures, gripping operations, and medical rehabilitation are described. Finally, the problems existing in the development of soft robots, such as the shortage of 3D printable soft materials, efficient and effective manufacturing of soft robots, shortage of smart soft materials, efficient use of energy, the realization of complex motion forms of soft robot, control action accuracy and actual kinematic modeling are summarized. Based on the above, some suggestions are put forward pertinently, and the future development and applications of the soft robot are prospected.

Keywords: driven method; manufacturing process; smart material; soft actuator; soft robot

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1. Introduction

Due to the disadvantages of traditional robots, such as large rigidity, complex structure, and poor flexibility [1], the researchers are prompted to draw inspiration from nature and conduct in-depth research on the bionic mechanism, and develop different types of soft robots [2]. The soft robot is a new type of robot made of flexible materials, which can adapt to various unstructured environments and can also form any desired shape by bending, twisting, and stretching to a certain extent [3]. This makes up for the shortcomings of traditional robots in terms of freedom and flexibility. The use of flexible materials also makes soft robots lighter than ever. The application of soft robots also provides a good foundation for maintaining security and flexibility in the current human–computer interaction and complex situations. Today, soft robots are used in a wide range of applications in bioengineering, disaster relief and rescue, industrial production, medical services, exploration, and surveying. For example, Fan et al. from the University of Science and Technology of China [4] designed a frog swimming, which was soft driven with the pneumatic articulated soft driven for joints based on the motion of the frog jumping, thus miniaturizing the frog swimming robot and effectively reducing the mass and volume of the underwater soft robot, enabling it to travel freely between multiple obstacles in the underwater environment. Deng Tao et al. [5] from Shanghai Jiaotong University designed a soft robot for minimally invasive cardiac surgery, which was inspired by the physiological structure of an elephant's trunk and made of a non-toxic and non-polluting medical silicone material that can be safely integrated into the patient's body. The reference [6] presents a scalable continuum of robots inspired by natural lianas, whose ability to bend significantly allows them to adapt to environmental features by curling around them to facilitate navigation and manipulation. Research on digital models based on the principles of bionic motion for soft robots is also underway [7–9]. In addition, due to the advantages of 3D printing with methods and materials, 3D printing is playing an important role in the field of soft robots [10–12]. Soft robot 3D printing manufacturing technology avoids manual errors, simplifies manufacturing steps, and achieves low-cost personalized manufacturing of soft robots. Currently, 3D printing processes that can be used for soft robots include fused deposition modelling (FDM), direct ink writing (DIW), inkjet printing (IP), stereo lithography (SLA), digital light processing (DLP), selective laser sintering (SLS), and other technologies. In the future, with the continuous development of the 3D printing process, high-quality integrated manufacturing of soft robots becomes possible [13,14]. In this article, firstly, the principles, characteristics, materials, and research results of several typical driven methods for soft robots are described. Secondly, the process, practical applications, and advantages and disadvantages of the different technologies in 3D printing for soft robots are dedicated. Thirdly, the application status and latest progress for soft robots in the fields of bionic structure, grasping operation, and medical rehabilitation are expounded. Finally, the problems and difficulties in the research of soft robot technology are discussed.

2. Driven Methods and Materials for Soft Robots

The movement of the traditional rigid robot is mainly realized by the traditional motor-driven mode; but, it is not suitable for the movement of soft robots [15]. In order to enable soft robots to adapt more quickly to transformations in a variety of special environments, the driven methods should not only be considered in terms of environmental adaptation, flexibility of movement, energy, and power consumption, but also the selection of suitable materials in terms of flexibility, deformability, and stretch rate. Common driven methods include the fluid driven, smart materials driven, and chemical reaction driven [16]. A twisted and coiled polymer actuator is also developing [17].

2.1. Fluid-Driven Methods and Their Materials

The fluid-driven soft robots are mainly to control the change of the fluid volume in each channel and produce the change of pressure intensity under the pressure force and constraint, thereby driving the transformation of different parts for soft robots such as contraction, expansion, and bending, which helps the soft robots to interact with the external environment [18].

Gas media is widely used in soft robots because of its light weight, being widely available, and not having pollution. Under the inspiration of the elephant trunk, Professor Leng's team investigated the deformation parameters of pneumatic artificial muscles (PAMs) in axial, bending, and helical muscles and used PAMs to compose a soft tandem manipulator with high flexibility and adaptability [19]. Shown in Figure 1a, Dong Yi University in Korea proposed the wearable rehabilitation robot, DULEX. The pneumatic artificial muscle was fixed at DULEX's elbow, by the length of maximum contraction and relaxed to complete the movement [20]. Shown in Figure 1b, D Drotman has designed a soft-legged untethered quadruped robot that requires only simple pneumatic circuitry to control the robot's movement [21]. Although there are a lot of research achievements on pneumatic-driven soft robots at present, the gas pressure and flow rate of the gas change non-linearly with time, which makes it impossible for the pneumatic soft robot to be accurately controlled [22].

Liquid medium is also used in soft robots because of its high power density and fast reaction. Shown in Figure 1c, Zhang designed a bionic jellyfish robot that was fluid-driven and verified the reasons for this new structure and dynamical model [23]. Harvard University invented smart thermally actuating textiles (STATs). STATs could be de-tethered from pneumatic tethers by internally engineered fluid to change in different environments, contributing to the development of compact wearable devices [24]. So far, there are relatively few studies on fluid-driven soft robots using liquid as the medium. The main reason is that liquid medium is incompressible, so the design process is relatively complicated due to the need for auxiliary devices. Liquid is also greatly affected by temperature, so the liquid-driven soft robots may not be able to be applied in high or low temperature environments. However, with the development of production technology, the liquid-driven method can be combined with other driven methods in the future design of soft robots to overcome the shortcomings of the liquid driven and amplify its advantages.

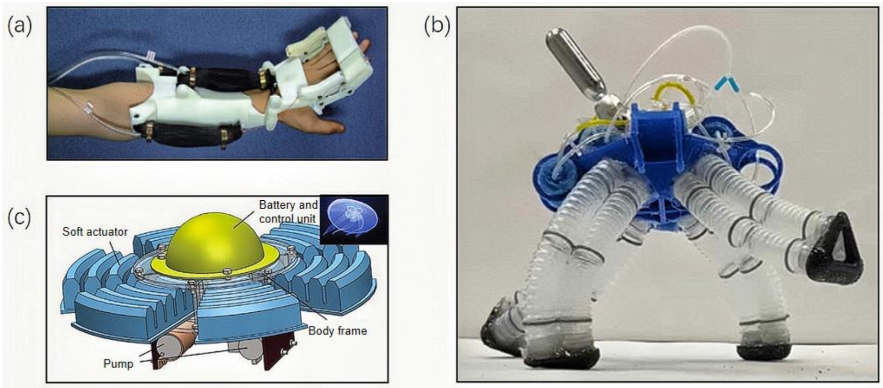

Figure 1. (**a**) DULEX [20]; (**b**) A soft-legged untethered quadruped robot [21]; (**c**) A bionic jellyfish [23].

In order to make fluid-driven soft robots move more flexibly than before, most of their substrates are made of soft, super-elastomeric materials such as silicone rubber. Silicone rubber was widely used in the early use of soft robots because it does not react with anything except strong alkali and hydrofluoric acid, as well as being insoluble in any solvent, and has non-toxic tasteless, stable chemical properties [25]. Shown in Figure 2a, Jiang et al. designed a biomimetic earthworm crawling robot with self-recuperating capability based on Ecoflex00-30 silicone, which can move on various angular planes, the robot achieves the self-recuperating function by inserting the self-recuperating silicone elastomer at key parts [26]. Shown in Figure 2b, Kazuyuki Ito et al. developed a soft robot that was made of silicone and driven by strings. It could grasp various objects by utilizing octopus-like behavior and climbing various columnar objects [27]. Shown in Figure 2c, inspired by the structure of a deep-sea snailfish, Zhejiang University has designed an untethered soft-bodied robot for deep-sea exploration by integrating electronic devices into silicone; the robot can be successfully launched at the deepest depth of 10,900 m, and can swim freely at 3224 m [28].

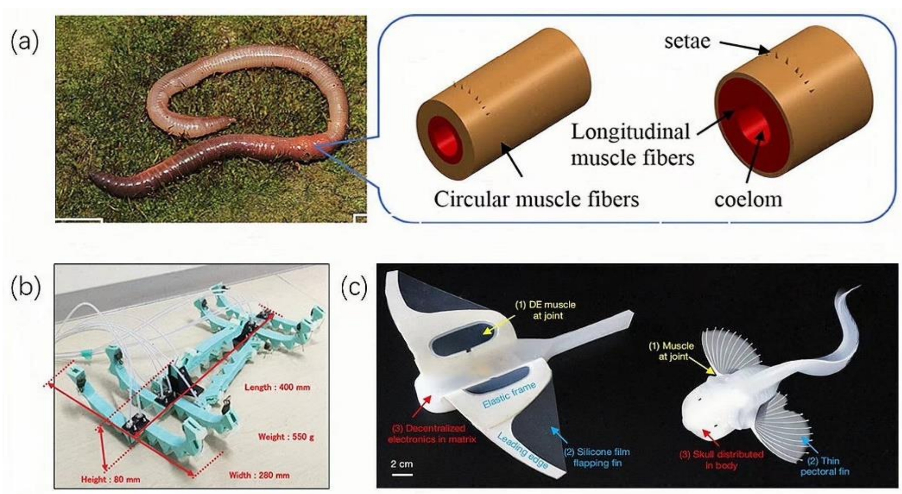

Figure 2. (**a**) The diagram of earthworm body structure [26]. (**b**) TAOYAKA-S II [27]. (**c**) An un-tethered soft robot [28].

2.2. Smart Materials and Their Driven Methods

Smart materials are new functional materials that have been developing rapidly since the 1990s, and combine bionic, nanometer, and new materials science. Smart materials such as shape memory materials, electroactive polymer materials, and piezoelectric materials are currently used in the process of manufacturing soft robots. They can combine a variety of materials into composite materials, which have more advantages than those of traditional materials, and then meet the three functions of sensing, driving, and control, and show superior flexibility in the application.

2.2.1. Shape Memory Material (SMM)

SMM is a kind of smart material with good development prospects. It can sense and respond to external stimuli [29], while it can adjust its mechanical properties to return to the initial state. Typical SMM is mainly Shape Memory Alloy (SMA) and Shape Memory Polymer (SMP).

SMA is an intelligent material with a shape memory effect, super elasticity, and high damping; it can experience reversible martensitic transformation due to the applied thermo mechanical load, and can recover permanent strain when heated to a certain transformation temperature [30]. It can sense temperature changes and convert thermal energy into mechanical energy, as well as it can output force and displacement, or store and release energy [31]. At present, the advantages of SMA are simple fabrication, low cost, and light weight, high power density, high driving force, and large driving displacement; the disadvantages of SMA are easy aging of material, difficult to accurately control the accuracy of the driven temperature, and low driven frequency. Shown in Figure 3a, inspired by the inchworm, Liang invented a soft crawling robot whose motion is based on the interaction between SMA driven and continuous elastomers [32]. Liu et al. created a new class of fast, high-curvature, low-voltage, reconfigurable, micron-scale shape memory actuators. Shown in Figure 3b, they made the world's smallest self-folding paper bird [33]. Shown in Figure 3c, Wang and Hu used the SMA spring to simulate the structure of the trunk corresponding to the muscle of the inchworm. The new type of microrobot's body structure, which could realize the bending deformation by simulating the body structure of the inchworm, was designed [34]. Shown in Figure 3d, IIT Indore developed a soft robot jellyfish based on SMA polymer. It could expand and contract the tentacles by heating and cooling, thereby generating propulsion to move through the water [35]. Liu et al. invented a variable stiffness lower limb exoskeleton robot based on SMA. The variable stiffness exoskeleton knee joint could effectively assist the wearer to walk. It had a good actuation effect, light weight, and high strength, so it could protect the wearer well [36]. Professor Ge fabricated soft composite actuators by embedding SMA wires into soft polymer matrices. The actuator could deform in large bends, retain its deformed shape, and regain its original shape by changing temperature only [37].

SMP is a kind of material that can fix in a temporary shape. It can also revert from the temporary shape to the initial shape under external stimulation such as light, electric field, magnetic field, heat, acid, and base [38]. SMP has the advantages of large deformation, light weight, simple structure, etc. Compared with SMA, SMP has more forms of stimulation, including heat, light, electric field, magnetic field, humidity, chemical stimulation, etc. The rich forms of stimulation make the design of the SMP driven more diversified and the application range is wider. However, the driving force of the SMP driven is smaller, less stable with less precise control, and more demanding on the working environment. In order to solve the problem of variable stiffness in soft robots, Zhang et al. processed the SMP into a thin sample strip embedded in the bottom layer of the flexible sensor [39]. Inspired by a multi-bit screwdriver, Liu et al. created a self-healing, light-driven SMP called "five-petal flower", which enabled soft robots to adapt quickly to changes in their environments [40]. Professor Song's team proposed a universal gripping strategy that used SMP smart plastic as the material. The gripper could be scaled according to different sizes, arbitrary shapes, and different quantities of objects [41]. Lin et al. combined programmable

SMP with 3D printing technology and designed a shape memory occlusion that was biodegradable, remotely controlled, and personalized. The occlusion could promote cell adhesion, proliferation, and tissue growth, facilitating rapid endothelialization. In the future, it could replace metal occlusion devices [42].

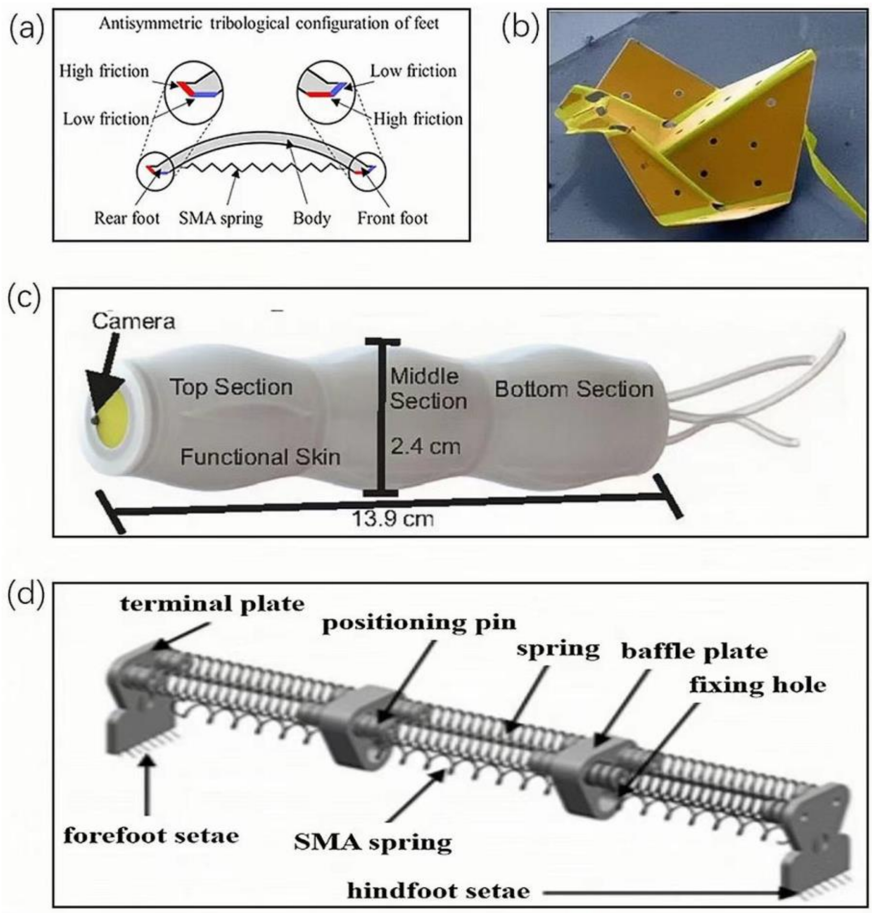

Figure 3. (**a**) Concept prototype of the bionic robot [31]. (**b**) Self-folding paper bird [33]. (**c**) Bionic-inchworm micro-robot [34]. (**d**) A soft robotic jellyfish [35].

2.2.2. Electroactive Polymer (EAP)

EAP is a new type of polymeric flexible smart material that can change in a large scale or shape under the excitation of an electric field [43]. According to its actuation mechanism, it can be divided into electronic and ionic EAP. The advantages of EAP materials are fast response, lighter material mass, higher driven efficiency, and stronger impact resistance; the disadvantages of EAP are high driven voltage for electronic EAP, ionic EAP requires a wet environment, and poorer load-bearing capacity and stability.

Electronic EAP is driven by a high voltage electric field to generate electromigration-induced stress, which can convert electrical energy into mechanical energy directly. The dielectric elastomer (DE) is a typical electronic EAP with a high dielectric constant among them. The Maxwell stress will be generated immediately when a voltage is applied to the upper and lower sides of the elastomer film surface. The Maxwell stress compresses and causes the elastomer film to deform, thus converting electrical energy into mechanical energy [44]. Shown in Figure 4a, the National University of Singapore developed a soft planar dielectric elastomer actuator (DEA). This soft freestanding actuator relied on compression springs for independence to enable linear actuation and steering while maintaining the same dimensions, weight, and structural complexity [45]. Shown in Figure 4b, Cab D et al. took advantage of the fact that DEAs did not require additional elastic elements to achieve resonant actuation. They developed a bioinspired flapping wing mechanism (FWM) that used a double cone DEA (DCDEA) with a power density comparable to that of an insect muscle for actuation [46]. Professor Li's team produced a kind of artificial muscle with a dielectric elastomer spring structure by using the process of the spring structure forming the structural support layer, pre-stretching dielectric elastomer film forming the driving layer, and carbon paste forming the conductive layer [47]. Shown in Figure 4c, Professor Chen's team aligned the direction of DEA in extension with the robot motion movement and developed a soft robot consisting of a unidirectional DEA, a compliant arched robot body, and one-way bearing wheels, which enabled efficient energy conversion [48].

Ionic EPA is based on electrochemistry, which converts electrical energy to mechanical energy by using chemical energy as a transition. The Ionic Conducting Polymer (ICP) is a typical ionic type of EPA that consists of a high molecular weight polymer matrix, alkali metal salts, and inorganic fillers [49]. Yoshihiro Nakabo et al. of the Intelligent Systems Institute in Japan used Ionic Polymer–Metal Composite (IPMC) as its actuator to make the locomotion of a snake-like underwater robot. The snake-like underwater robot could move by changing the driven voltages of each Ionic Conducting Polymer Film (ICPF) actuator [50]. Shown in Figure 4d, Niu et al. developed a high performance IPMC actuator and combined it with expendable lift-scissor structures to design an earthworm-like soft robot [51]. Liu et al. proposed an ionic electroactive polymer (PAST-iEAPs) with excellent tensile, electrochemical, and electromechanical properties, as well as good self-healing ability, which could be well used in the future for the manufacture of soft robots and soft actuators [52].

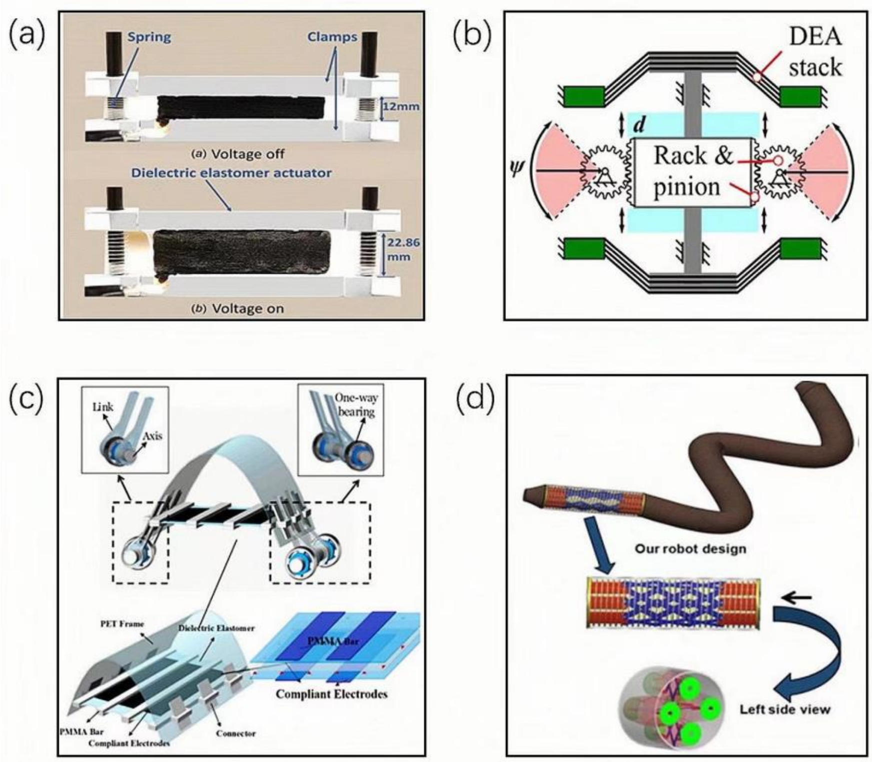

Figure 4. (**a**) DEAs for soft planes [45]. (**b**) Schematic diagram of DCDEA-driven FWM design [46]. (**c**) The design of the soft robot with a unidirectional DEA [48]. (**d**) an earthworm-like soft robot [51].

2.2.3. Piezoelectric Material

Piezoelectric material is a kind of functional material with a piezoelectric effect that can transform mechanical energy into electric energy by generating external action. The advantages of piezoelectric-driven are high response speed, high operating stress and frequency, and large operable bandwidth. The disadvantages of piezoelectric-driven are the high driven voltage required and the small amount of driven displacement produced.

The piezoelectric effect refers to some dielectric in a certain direction by the external force and transformation, and the polarization will be generated internally. At the same time, positive and negative charges appear on two opposite surfaces of the crystal [53]. Shown in Figure 5a, Lim et al. constructed a new soft-bodied mobile robot based on piezoelectric materials with a thin, flexible body and curved tail. The softness of this robot allowed it to move in confined or wet environments. At the same time, its flexibility allowed it to recover quickly after an impact [54]. Shown in Figure 5b, Pan designed a novel piezoelectric-driven self-healing leaf-motion mimic actuator that combined built-in dynamic sensing and room temperature self-healing to simulate the motion of a leaf. The actuator enabled the self-healing of macroscopic damage and restoration of mechanical and dynamic performance at room temperature [55]. The Korean Academy of Science and Technology team created a flexible piezoelectric film that imitated the basement membrane in the human cochlea. Shown in Figure 5c, they used this film to develop a machine learning, self-powered, and highly sensitive acoustic sensor [56].

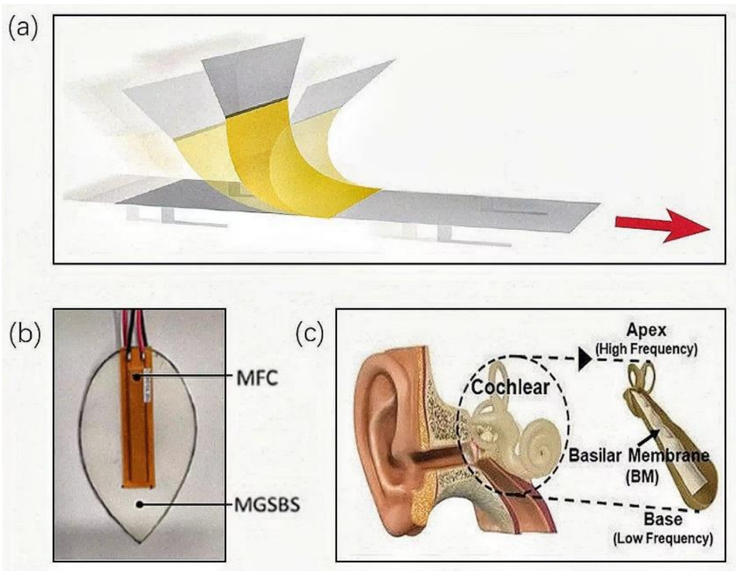

Figure 5. (**a**) Thin piezoelectric mobile robot with a curved tail [54]. (**b**) Piezoelectric-driven self-healing leaf prototype [55]. (**c**) Acoustic sensor [56].

2.2.4. Responsive Hydrogel

Responsive hydrogel has a three-dimensional polymer network structure [57]. Due to the presence of a cross-linked network, it can swell rapidly to water and retain a large volume of water in this swollen state without dissolving. It has advantages such as being able to withstand mechanical strains of up to 1000%, biocompatibility, permeability, and responsiveness to external stimuli [58]. It has the disadvantage that the preparation and control process is complex and the driven cannot be precisely controlled. Inspired by the continuous gradient structure of organisms with the dynamic equilibrium mechanism of water, Professor Xu's team designed a temperature-responsive hydrogel actuator with a biomimetic wide-range gradient structure that provided excellent reversibility and rapid recovery in different environments [59]. Professor Mei's team created an active hydrogel with intrinsic capabilities, whose movement depended on the material or geometric design of itself and its surroundings, and which required no external energy. It could move on the water surface for up to 3.5 h without operational stimuli [60]. Yang et al. produced the first hydrogel with the same strength and modulus in compression and tension as human articular cartilage, which could be an excellent material for repairing cartilage damage [61].

2.2.5. Magneto Rheological Fluid (MRF)

MRF is a new kind of functional material, whose physical state and rheological properties can be controlled by an external magnetic field. According to the different magnetic field strengths, MRF shows different properties of the magneto rheological effect [62]. Shown in Figure 6a, Kyushu University developed an intelligent magnetic fluid called MRα fluid, which was used to create a new robot gripper. The gripper could grip non-magnetic objects of various shapes with a maximum force of 50.67 N [63]. Shown in Figure 6b, based on the controllable stiffness characteristics of MRF, Yu et al. designed a new robotic compliant joint. The joint could make the robot with active stiffness characteristics. In addition, a dynamic torque tracking control of MRF compliant joints based on a fractional-order PID control algorithm was proposed [64]. Shown in Figure 6c, Hua et al. designed a spherical magneto-controlled robot for targeted drug delivery to the human stomach. They used MRF as the driving material for a miniature magneto-controlled robot and analyzed the reliability of the robot using simulation [65].

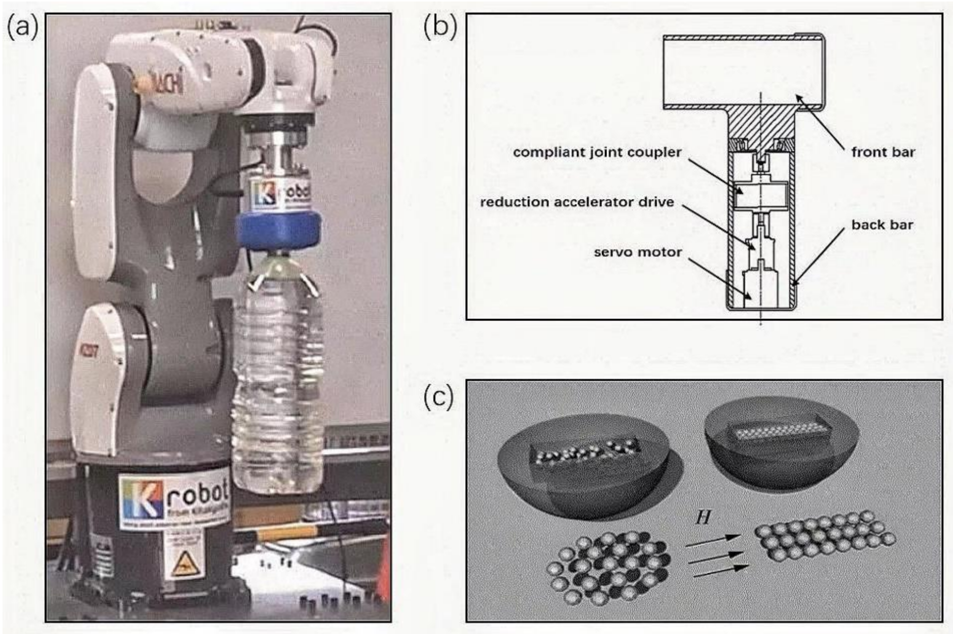

Figure 6. (**a**) Operation of the developed gripper using the MRα fluid [63]. (**b**) A robot flex joint [64]. (**c**) Design scheme of a spherical magnetic robot [65].

2.2.6. Liquid Metal (LM)

LM is a kind of metal that is liquid at room temperature or slightly higher temperature and is mainly used to make flexible sensors. At the normal temperature, it has the advantages of good fluidity, strong electrical conductivity, excellent thermal characteristics, easy to realize solid–liquid conversion, and so on [66]. Its disadvantage is that the manufacturing process is more complicated and there is a risk of leakage of liquid during the working process.

Michael D. Dickey injected LM into the core of hollow and extremely stretchable elastic fibers and then winded the resulting fibers into spirals to create capacitive sensors that could be twisted, touched, and strained [67]. Gao et al. developed a facile Eutectic Galium-Indium (EGaln) liquid-based microfluidic sensor, with high sensitivity at a mass stretch when EGaln was used as a sensing element. Strength support at a mass stretch with EGaln was used as a flexible substrate [68]. Khan H et al. reported single crystal across-the-plane and large-area monolayer single-layer sulfide (SnS) synthesis using a liquid metal-based technique. Large-sized, highly crystalline semiconductor single-molecule layers of SnS were mainly prepared from the -LM surface of tin melts in an H2S atmosphere. SnS had good semiconductor properties and could be applied to piezoelectric nanogenerator devices for flexible, wearable devices [69].

2.2.7. Liquid Crystal Elastomer (LCE)

Liquid crystal elastomer, as a most representative smart material, has both liquid crystal anisotropy and rubber elasticity. Under external stimulation (heat, light, electricity, magnetism, pH, humidity, etc.), its phase state or molecular structure will change, which in turn will change the arrangement order of liquid crystal elements, resulting in macroscopic deformation of the material itself, and when the external stimulation is removed, liquid crystal elastomer can return to its original shape. The advantages of liquid crystal elastomers are unique bi-directional shape memory, large deformation, fast response time, various response mechanisms, and scalability, but the disadvantages are lower mechanical properties and higher preparation cost.

Ware et al. [70] prepared a thermally driven liquid crystal elastomeric soft robot by the 3D printing technique. They first polymerized the liquid crystal monomer RM82 and chain extender to obtain liquid crystal oligomers with acrylate end groups as printing inks, then edited and printed them into the designed shape by the 3D printer, and used UV light to trigger a cross-linking reaction to fix the complex 3D structure of the liquid crystal elastomer to obtain a cylindrical hollow liquid crystal elastomer soft robot, which can achieve radial contraction as well as axial expansion under external temperature stimulation. White et al. [71] successfully prepared a rolling soft robot based on azobenzene liquid crystal elastomer and demonstrated its rolling behavior under continuous UV light irradiation. When the robot was exposed to UV light, the stress generated by the asymmetric strain between the top and bottom overcame the rolling resistance to achieve a rolling motion. In addition, when the robot starts to roll, the film originally at the lower part is displaced to the upper part of the robot, re-generating asymmetric stress to achieve continuous rolling. Yu et al. [72] reported an ultrathin sensing and electronically controlled soft-body robot capable of sensing the environment and performing adaptive soft-body crawling, mimicking an inchworm. These soft-bodied robots consist of ultrathin deformable heated actuators, sensors with single-crystal silicon photodetectors, and liquid crystal elastomer (LCE-CB) nanocomposites doped with carbon black, which can achieve an adaptive crawling motion through a combination of sensing and actuation, where the sensors sense the environment and the actuators respond accordingly and control the motion autonomously by adjusting the deformation of the LCE-CB.

Based on the above description of smart materials and their drivers, the performance of these smart materials is compared in Table 1.

Table 1. Advantages and disadvantages of different smart materials.

	Advantages	Disadvantages
SMA	Simple fabrication, low cost, light weight, high power density, and high driving force	Easy aging of material, difficult to accurately control the accuracy, and low driven frequency
SMP	Large deformation, light weight, and simple structure	Driving force of SMP driven is smaller than SMA, less stable, less precise control
EAP	Fast response, lighter material mass, and higher driven efficiency	high driven voltage for electronic EAP, ionic EAP requires a wet environment, and poorer load-bearing capacity and stability
Piezoelectric material	High response speed, high operating stress and frequency, and large operable bandwidth	The high driven voltage required and the small amount of driven displacement produced.
Responsive hydrogel	Biocompatibility, permeability, and responsiveness to external stimuli	The preparation and control process is complex and the driven cannot be precisely controlled
LM	Good fluidity, strong electrical conductivity, excellent thermal characteristics, and easy to realize solid-liquid conversion	The manufacturing process is more complicated and there is a risk of leakage of liquid during the working process.
LCE	Unique bi-directional shape memory, large deformation, fast response time, and scalability	Lower mechanical properties and higher preparation cost

From the Table 1, it can be observed that most smart materials can meet the requirements of the fast response of drive elements, which can make soft robots respond quickly after being "stimulated" and reduce the reflection lag phenomenon, such as EAP, Piezoelectric material, LCE and other smart materials. At present, "lightweight" has gradually entered the vision of human beings. Soft robots should also pursue lightweight when choosing *smart* materials that are *driven*, such as SMA, SMP, and EAP. In addition, most of the smart materials have the characteristics of a *large* driving force and large deformation, which are beneficial for soft robots to achieve complex motion patterns. LM is suitable for flexible sensors because of its good fluidity and strong conductivity. However, most of the smart materials have problems such as accuracy that is difficult to control and poor stability, which is one of the defects of smart materials as driven materials. Therefore, improving the control accuracy and stability of smart materials will also become the focus of future research on smart materials that are driven.

2.3. Chemical Reaction Driven

A chemical reaction is a process in which molecules break into atoms and the atoms rearrange themselves to form new molecules. Chemical reactions can be divided into compound reactions, decomposition reactions, displacement reactions, and metathesis reactions according to the types of reactants and products. Chemical reactions are usually accompanied by changes in energy, so they are chemical reaction-driven soft robots that convert chemical energy into mechanical or kinetic energy by means of combustion, expansion, or catalytic reactions [73].

Shown in Figure 7a, Harvard University printed the functional body of a robot directly on a multi-material three-dimensional (3D) printer, by filling it with butane and oxygen, which expanded on the ignition to provide power for cordless jumping [74]. This driving method is similar to pneumatic driving, but the source of the gas medium is different. Due to the effect of the gas production efficiency of the chemical reaction, this kind of driving mode is mostly used for small tethered soft robots. The repetitive use of a chemical reaction that is driven is still a technical challenge for soft robots [75]. Shown in Figure 7b, M. Wehner's group developed the world's first fully soft-bodied autonomous micro-bionic robot, Octobot. The robot moved by embedding the components required for fuel storage, catalytic decomposition, and actuation. This allowed it to move by expanding the fluid network downstream of the reaction site through the gases generated by the decomposition of the fuel [76]. He et al. designed a chemical reaction self-driven rolling robot. The reaction liquid and catalyst were placed inside the robot. The gas generated by the chemical reaction pushed the reaction liquid to circulate in the multiple cavities of the robot, changing the center of gravity of the robot to achieve rolling [77].

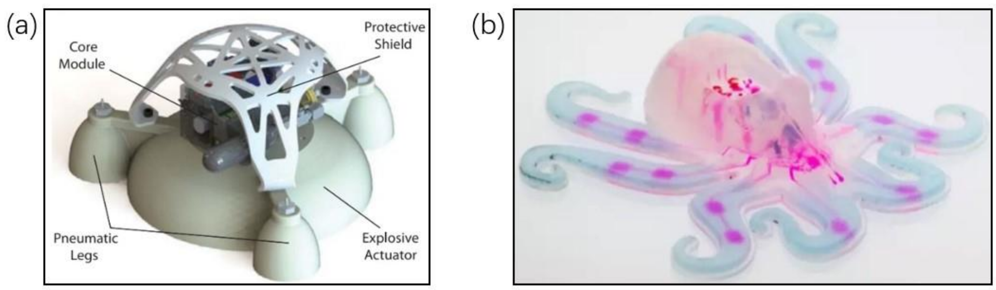

Figure 7. (**a**) Computer-aided design model of the entire robot [74]. (**b**) Fully soft, autonomous robot, Octobot [76].

2.4. Twisted and Coiled Polymer Actuator (TCPA)

TCPA is a novel soft actuator. It is fabricated by twisting nylon thread or fishing line. It can be thermally activated and has remarkable properties such as a high power/mass ratio and large deformation. By applying conductive nylon fibers to the actuator, it can be electrically driven by Joule heating. IPMC can achieve a large deformation with low voltage (1–3 V) and high speed motion, but the manufacturing cost is relatively high. DEA can achieve a large strain (<400%), but DEA requires a high driven voltage [78]. Conductive polymer actuators can achieve large deformations at low voltages (1–4 V), but the response is slow [79]. In contrast, TCPA has the following remarkable properties.

- Its fabrication cost is extremely low since it is easily fabricated by commercially available nylon fibers.
- It realizes large deformation over 20%.
- It is flexible and lightweight.
- Its motion is silent.
- The actuation environment is unbounded, such as in water, in wet conditions, or in a magnetic field.
- Compared to the shape memory alloy actuators, a hysteresis property of TCPA is small.

TCPA has been developed for various applications in robotic systems, such as robotic hands [80], power assist systems [81], mobile robots [82], deformation mechanisms for flying robots [83], and bionic robots [84]. Therefore, TCPA has good prospects for soft robots.

Due to the wide range of smart materials and the obvious differences in performance between the different smart materials, as shown in Table 2, only the performance of the fluid driven and chemical reaction driven were comprehensively compared.

Table 2. Performance comparison of fluid driven and chemical reaction driven.

		Advantages	**Disadvantages**
Fluid driven	Pneumatic driven	Good safety, low production cost, large deformation, and light weight	Low output force, hysteresis, and external air supply required
	Hydraulic driven	Fast response speed, large output force, circular loop, and lower working noise	Heavy weight, external hydraulic pump, and high energy consumption
Chemical reaction driven		Fast response and large output force	Low energy utilization, poor stability, poor controllability, and short service life

Gas media are widely used in soft robots because of their light weight, a wide range of sources, lack of pollution, and good safety. The pneumatic-driven requires an external compressed air pump to store the gas, which is bulky and consumes a lot of gas, greatly limiting the application of soft robots in non-structural environments. In addition, air pressure and flow rate vary nonlinearly with time, which makes it difficult to control the robot accurately in real time, and the control has hysteresis. Liquids have good incompressibility, high response frequency, can withstand high loads, and can be used with specific pumps to build a recirculation loop, which in turn can supply energy to the soft robot for a long time. However, the hydraulic-driven requires an external hydraulic pump to provide power, and the hydraulic system is generally larger and more energy-consuming.

Due to the different types of chemical reactions, the performance of the chemical reaction driven varies greatly. The chemical reaction speed inside the actuator is generally difficult to accurately control; thus, the controllability of the chemical actuator is poor [73]. Although the chemical reaction driven has fast response, it has low energy utilization, poor stability, and short life.

3. 3D Printing Manufacturing Process

Most of the existing soft robots are made of soft materials that are easily deformed. These materials can not only maintain the initial state of motion while being stretched, bent, and twisted, but also have good softness and flexibility. They can be well compatible with 3D printing technology. As the traditional manufacturing method is mainly based on mold casting, the form is too single and the printing efficiency is low, which is gradually replaced by the continuous development of the 3D printing technology.

3.1. Stereolithography (SLA)

SLA is one of the laser rapid prototyping technologies and belongs to the additive manufacturing method. The process of SLA printing technology mainly uses the laser beam through a scanner controlled by a numerical control device [85]. The scanning path designs by the laser illuminate the liquid photosensitive resin surface so that a layer of resin in a specific area on the surface is solidified. Finally, the layers are superposed to form a three-dimensional entity [86]. The factors that affect the printing results of SLA technology include the resolution of the light source, exposure time, light power, type of resin in the print paste, the size and shape of ceramic powder, solid content, type and amount of dispersant, and so on [87].

Ge et al. developed the Projection Micro Stereolithography (PμSL), which was a high-resolution 3D printing technology based on the principle of surface projection lithography. The technology can be used to create high-precision complex 3D structures with cross-scale and multi-material properties and has promising applications in the fields of mechanical metamaterials, optical devices, 4D printing, bionic materials, and biomedicine [88]. Hunan University proposed a method for the fabrication of bionic mushroom-like functional surfaces with continuous controlled wettability and adhesion. They were inspired by the elastic tail cuticle and fabricated by using a 3D printing technique based on projection PμSL [89]. Inspired by the interlocked structure between the epidermal layer and the dermis layer of human skin, Cai et al. used an SLA 3D printer to fabricate a bioinspired ionic skin (BIS) with high transparency, compressibility, and inherent electrical conductivity [90].

3.2. Digital Light Processing (DLP)

DLP 3D printing technology is formed by using a high-resolution DLP projector to solidify a liquid photopolymer layer by layer [91]. The speed is faster than the same type of SLA printing technology because each layer is cured in a slide like a sheet.

Zhu et al. developed miniature robotic fish using three different functional nanoparticles based on DLP 3D printing technology. It laid the foundation for enabling the customization of nanobots for future use in targeted drug delivery within the human body [92]. Based on DLP 3D printing technology, Professor Chan Hum Park's team successfully constructed an artificial trachea with certain mechanical properties using silk fibroin-glycidyl methacrylate (Silk-GMA) as the material and performed the first in vivo transplantation experiment with satisfactory results [93]. Using DLP 3D bioprinting technology and hyaluronic acid (HA)-derived materials, Tang et al. established a highly reproducible, high-throughput, and controllable 3D in vitro model of the glioblastoma microenvironment by distributing different cells according to the structure of healthy tissue surrounding tumor tissue [94].

3.3. Fused Deposition Modeling (FDM)

FDM technology is a method of heating and melting various filaments without relying on a laser as the energy source for modeling. The principle is that the nozzle moves along the profile of the section and the filling track of the parts under the control of the computer. At the same time, the semi-liquid material is extruded after heating and melting, and was selectively coated on the panel to form a three-dimensional part [95].

Shown in Figure 8, FDM-based digital manufacturing technology for printing foldable paper spring creeping crawling robots are in the reference [96]. The curvilinear deployment of the collapsible paper spring subtlety offers the undulatory movements for the peristaltic crawling robot. This greatly simplifies the structure and control of the creeping robot by comparing with the existing systems. Professor Ruan's team investigated prediction models for interlaminar bond strength and modulus. A temperature-dependent diffusion model was determined from rheological data to predict the diffusion between layers of FDM parts based on a one-dimensional transient thermal analysis. In turn, the load-bearing failure process of the printed part was effectively predicted [97]. Hua et al. combined FDM 3D printing techniques with photoresponsive shape deformation composites to create a flexible and lightweight actuator on paper to study its photoresponsive behavior [98]. Oladapo et al. used the FDM method to make a PEEK-cHAp biocomposite material by combining polyetheretherketone (PEEK) with hydroxyapatite (cHAp). This material could be biodegradable and suitable for bone [99].

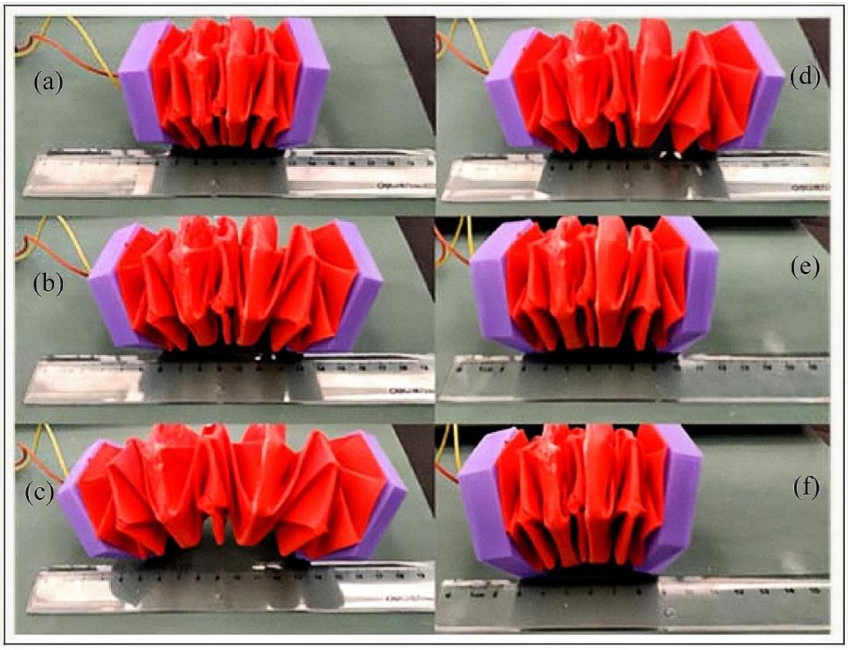

Figure 8. A peristaltic crawling robot with undulatory movements induced by curvilinear deployment [96]. (**a**) Fully compressed state; (**b**) elongating state; (**c**) fully curvilinear deployment; (**d**) starting to compress; (**e**) compressing state; and (**f**) fully compressed state.

3.4. Direct Ink Writing (DIW)

DIW technology is used to generate a variety of complex patterns on the deposition platform by extruding semi-solid ink materials with shear-thinning properties layer by layer through moving nozzles [100]. The factors that affect the printing effect of the DIW technology include solid content, viscosity, the particle size of printing paste, and so on.

Professor Liu's team designed a new 3D printing material based on a strategy of the in situ UV-Vis emission from NIR-excited upconversion particles and established a NIR-assisted DIW 3D technique for multi-color material, cross-scale, unsupported 3D printing [101]. Professor Bai's group developed a range of composite elastomer inks for direct-write 3D printing that could print composite elastomers with excellent elasticity and stable shapes. This material was used as a material to create a high performance frictional electric nanogenerator [102]. Professor Luo's team prepared a new composite ink and obtained CP composite scaffolds with significantly improved hydrophilicity, compression properties, cell affinity, and osteogenic activity by the DIW method. The CP composite scaffold could be used for the repair of bone tissue [103].

3.5. Selective Laser Sintering (SLS)

The process of SLS involves laying a layer of powder material in the powder spraying unit. When the material is preheated to the melting point, the cross-section shape is scanned through laser irradiation and the melted powder is sintered and bonded together. In this way, the powder is deposited layer by layer until it is finally formed [104]. The parameters that affect the printing results of SLS technology include the size and shape of the powder, the power of the laser, the size of the light spot, the duration of the irradiation, and so on.

Hiroshi Sugihara created a series of bionic robots by using SLS 3D printing technology. If they were equipped with a motor drive, they would start crawling like animals [105]. Wei et al. analyzed the mechanical properties and biocompatibility of the porous titanium (Ti) implant fabricated by SLS and investigate the promotion of osseointegration by porous titanium implants combined with a chitosan (CS)/hydroxyapatite (HA) composite coating [106]. Professor Xia's team developed a self-healing and recyclable polyurethane with high mechanical strength and excellent flexibility that could be used for SLS 3D printing. This approach improved the interaction of the printed product between adjacent interfaces and enhanced the mechanical strength in the z-direction [107].

3.6. Shape Deposition Manufacturing (SDM)

SDM is a process in which materials are deposited and then micromachined by numerical control machine tools to create the expected smooth contour surface. During the molding process, prefabricated parts or sensors and actuators are embedded into the parts. This method can embed electronic devices into the structure to realize effective integration with flexible materials, so as to fabricate flexible structures [108].

Mark R. Cutkosky designed a gecko bionic robot, Stickybot, with a simplified hierarchical adsorption system. They were inspired by the toes of the gecko and thus used polyurethane as a material and SDM as a 3D printing method to build the robot's torso, legs, and feet, allowing it to crawl smoothly along the vertical surfaces [109]. Stanford University used SDM technology to create the first bionic claw and thorn wall-climbing robot SpinybotII. The robot could crawl on rough, dusty walls and could be used in disaster rescue situations [110]. Joshua Gafford et al. combined shape SDM and 3D printing to produce a new, deployable, non-invasive grasper for minimally invasive surgical (MIS) procedures that could be used for tissue manipulation and retraction in MIS procedures [111].

3.7. Inkjet Printing (IP)

IP technology is a process that uses inkjet and photosensitive polymer powders to manufacture parts. The photosensitive polymer powder is activated by UV light, and then the curing layer is formed on the construction platform. This is repeated many times to form a three-dimensional structure [112]. In IP, the rheological properties of the ink determine the quality of the print. Among them, if the viscous force of the ink dominates, droplets will not form during printing and printing cannot continue; if the inertia or surface tension of the ink dominates, the droplets ejected during printing will easily splash or disperse into multiple subsidiary droplets and printing accuracy will be reduced.

Based on a new hybrid ink formulation consisting of 1D/2D nanostructures, Professor Zhang's group used a highly scalable 3D conformal aerosol jet printing method to create high-performance and flexible thermoelectric films for energy harvesting and cooling applications in flexible thermoelectric devices [113]. MIT demonstrated a new multi-material 3D IP process that allowed 3D solids and liquids to be printed together to build hydraulically driven machinery. This method allowed complex robots that moved to be printed intact and could also be used for flexible robots [114]. Israeli 3D printing electronics specialist Nano Dimension launched the DragonFly 2020 Pro 3D printer. The printer included precise inkjet deposition systems, advanced radiochemistry, and advanced soft printing technology. It could make the rapid prototyping of multilayer-printed circuit boards cheaper and faster to print than ever [115].

According to Section 3, the advantages and disadvantages of different 3D printing manufacturing processes are listed in Table 3.

Table 3. Materials, advantages, disadvantages, and applications of different 3D printing manufacturing processes.

Classification	Materials	Advantages	Disadvantages	Applications
SLA	Photosensitive modified silicone materials	Accurate control of the shape and size of the part	Cannot achieve multi-material printing	Octopus like robots [76]
	Hydrogel materials	Smooth surface	Materials with generally toxic	Micro soft robot [116]
			Need extra print support and manually remove	Magnetic response octahedron [117]
			Curl or break when cured	Flexible sensor [118]
DLP	Photopolymer	Fast formation	High purity liquid photopolymer	Software gripper
		High precision		
		High surface finish		
		Low cost		
		Safe and reliable		
FDM	TPU, SMP, P2VP, ABS	Low cost	Long molding time	Soft gripper [119]
		Materials with accessibility, compatibility, and usability	Low precision of material extrusion nozzle and molding effect	pH response parts [120]
		Small environmental pollution	Need extra print support and manually remove	
DIW	Silicone rubber	Fast printing speed	Low accuracy	Software gripper [121]
	Silicone, hydrogel	Low cost	Need extra print support	crawling robot [122]
	Liquid metal	Widely used		Magnetic elastomer [123]
	Nano silver	Easy to operate		
SLS	TPU and other thermoplastic materials	Materials with accessibility and usability	Laser radiation	Soft gripper [124]
		High precision	High cost	
		High reducibility	Low efficiency	
		Function test or assembly simulation for sample	Limited by material	
SDM	Active agent mixing material	High manufacturing accuracy	Rough surface	Soft gripper [124]
	Thermoplastic materials	Process complicated equipment	High cost	Crawling robot
			High control requirements	
			Fatigue failure	
IP	Tangoplus materials	Simple molding mechanism	The print head blockage	The print head blockage
	Vero white materials	Fast molding speed	Difficult to control the size of the ink droplets	Hardness gradient distribution software driver [125]
		No internal stress	The printing process accompanied by nozzle offset	
		No additional support	The printed product with serious grain	
		Low cost		

4. Applications of the Soft Robots

4.1. Bionic Structures

Bionic soft robot is a kind of soft robot made of materials with muscle characteristics. It can imitate the movement of various creatures in nature, and actively change its shape, size, and position in a complex environment according to the actual situation. It can adapt to environments that humans cannot reach and expand the scope of human work [126]. Compared with the traditional rigid robot, it has the characteristics of good continuity and strong adaptability.

Currently, bionic robots can already achieve creeping crawling, leg crawling, jet swimming, fish-like swimming, wriggling, and other bionic movements [15]. Shown in Figure 9a, MIT invented a new telescopic drive system and applied it to a hybrid bio-inspired sea urchin robot. The robot was driven by extending and compressing the spine and was able to move over rocks and overcome obstacles [127]. Shown in Figure 9b, Yan et al. created a compact and maneuverable underwater bionic robot fish that combined 3d-printed functional structures with embedded electronics to enable controlled movement underwater by converting electrical energy into mechanical energy in the tail fin [128]. Shown in Figure 9c, Yan et al. designed a bionic jellyfish robot with multiple degrees of freedom. The Robotic Toolbox in Matlab analysis software was used to establish the model of the jellyfish manipulator, performing the motion simulation. The simulation results demonstrated that the motion curves were continuous and smooth without mutation, and could meet the needs of marine exploration and underwater reconnaissance [129]. Shown in Figure 9d, inspired by slender sharksucker, Professor Wen's team created a biologically similar multi-material biomimetic remora disc. The discs could attach to different surfaces and generate 340 times their own weight in tension, allowing the design of an underwater robot that could strongly adhere to a variety of surfaces [130].

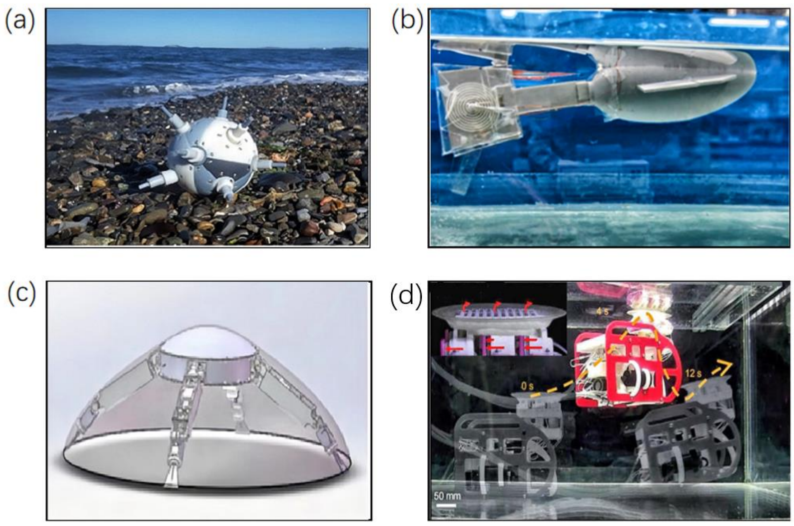

Figure 9. (**a**) Bionic sea urchin robot [127]. (**b**) Schematic diagram of a 3D fish model [128]. (**c**) Bion-ic jellyfish robot [129]. (**d**) The biomimetic remora adhesive disc prototype [130].

The bionic soft robot is made of super elastic silicone material. Thus, it has the advantages of good impact resistance, simple drive, continuous deformation, unlimited freedom, compatibility with obstacles, being non-toxic and harmless, etc. In the future, it has a wide application prospect in many fields such as military, production and living, rehabilitation, and medical treatment [131].

4.2. Gripping Operations

Relying on the unique properties of soft materials, soft robots solve the obstacles that may be encountered in the human–computer interaction. For example, it can reduce the damage in the process of grabbing and passing fragile items, thus deriving the soft manipulator. The soft manipulator overcomes the shortcomings of the traditional rigid manipulator, such as poor flexibility, high cost, and poor adaptability to the environment. Additionally, it can alter its shape depending on the shape and size of the object and cover the object well [132].

Shown in Figure 10a, Professor Wen's team built a tunable four-fingered soft robotic gripper. The gripper approximated a biological finger with infinite degrees of freedom and could grasp objects of different sizes, weights, and shapes, as well as material hardnesses, with a simple actuation [133]. Wang et al. designed a pneumatic three-jaw soft gripper that was different from existing conventional robotic arm end grippers. The gripper allowed for the non-destructive gripping of objects of different shapes and sizes with a simple control [134]. Shown in Figure 10b, Anthony L et designed a novel, tendon-driven soft robotic gripper with active contact force feedback control. It used the passive compliance of the gripper to gently harvest blackberries and could reduce the berry damage caused by the plastic cylindrical force sensor holder attached to the gripper fingertip [135].

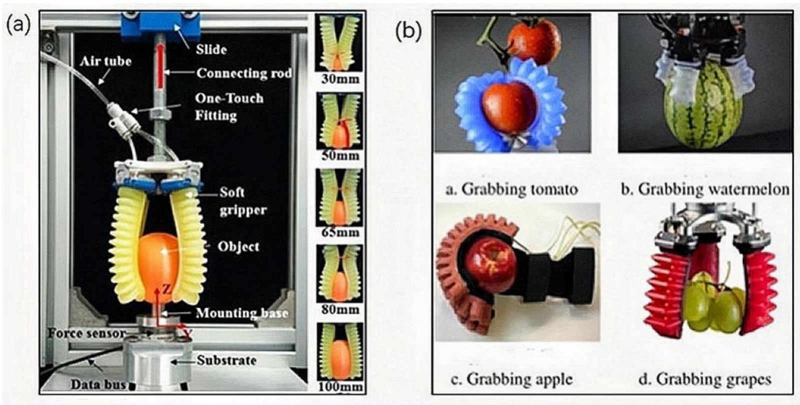

Figure 10. (**a**) Apparatus for measuring the force of the soft gripper under different effective lengths [133]. (**b**) Proposed robotic system for soft gripper-enabled berry harvesting [135].

All in all, the soft gripper has the advantages of high safety, low cost, simple structure, and convenient control. Additionally, it can grasp various shapes and even fragile objects without complex feedback, so it has a better application prospect in object grasping.

4.3. Medical Rehabilitation

The soft robot has been widely used in the field of medical rehabilitation, mainly because of its simple structure, light weight, and convenience for patients to easily achieve free bending and twisting. It also has the advantages of fast response speed, soft touch, good affinity, a high degree of bionics, and can safely carry out human–computer interaction [136].

Shown in Figure 11a, Ploygerinos et al. designed a portable, assistive, soft robotic glove that could assist people with hand disabilities with daily living and at-home rehabilitation activities. The glove used a soft body brake consisting of a molded elastic cavity and fiber-reinforced material that could produce specific bending, twisting, and extending trajectories under fluid pressure [22]. Shown in Figure 11b, Lessard et al. built one such eXosuit: Compliant Robotic Upper-extremity eXosuit (CRUX). The CRUX was compliant, lightweight, multi-degree-of-freedom, and portable. The wearer was able to empower themselves in many unconventional environments [137]. Shown in Figure 11c, Dong et al. designed a soft bionic tongue based on pneumatic actuators that could simulate the functions of swallowing and chewing. They developed a non-linear mathematical model, carried out a simulation study of the soft bionic tongue, and related experimental validation to prove the rationality of the design [138].

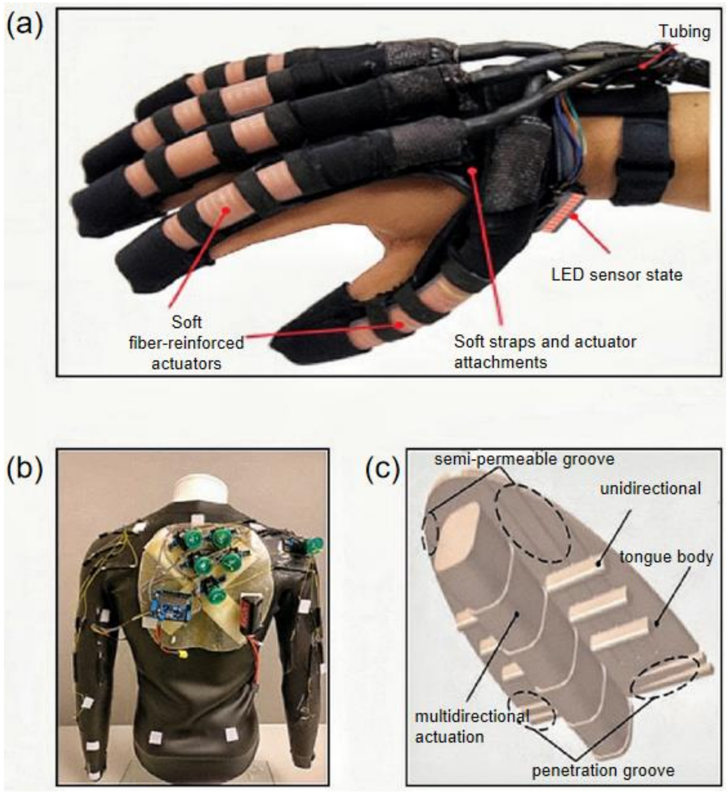

Figure 11. (**a**) The prototyped soft and lightweight robotic hand assistive device [22]. (**b**) CRUX: a soft, lightweight (1.3 kg), robotic eXosuit [137]. (**c**) CRUX: a soft, lightweight (1.3 kg), robotic eXosuit [138].

5. Problems of Current Research

5.1. Problems of 3D Printing in Soft Robot Manufacturing

Soft robots are mainly manufactured using soft elastic materials, and the design structure, size, mechanical properties, and other factors put forward high requirements for printing technology and equipment. Currently, in FDM technology, with a low cost and high popularity, similar to SLS, the printable materials are limited to thermoplastic materials, and the material properties find it difficult to meet the high elasticity needs of soft robots. SLA technology has high molding accuracy and printing speed, but the equipment is more expensive and more difficult to achieve the multi-material 3D printing method. Ink-based DIW and IP are currently the most widely used printing technologies in the field of soft robots. However, IP is more complex and less flexible than DIW technology in terms of ink configuration. DIW is similar to extrusion printing technologies such as FDM, where resolution and speed are traded off against each other, and is less accurate and faster than IP [139]. Traditional 3D printing technologies have their advantages and disadvantages, and new printing technologies that can take into account these issues still need to be explored.

The shortage of 3D printing soft materials, and efficient and effective manufacturing, are the current problems of 3D printing. Current 3D printing technologies for soft materials still face various limitations. The 3D printing technologies based on the heating–melting–cooling–curing principle, such as FDM and SLS, are limited to the use of thermoplastic materials such as polyurethane, making it difficult to meet multifunctional needs. Although SLA and IP technologies can achieve efficient manufacturing, the current printable materials are limited to photopolymer. For the manufacturing of multi-functional soft robots, since various 3D printing methods have their own advantages and disadvantages, such as the balance between the printing speed and printing accuracy of DIW, the use of a single 3D printing technology may not meet the requirements for efficient and effective manufacturing.

5.2. Problems of Soft Robot Research

The key issues of soft robots mainly include the shortage of smart soft materials and the performance of them, efficient energy utilization, the realization of complex motion patterns of soft robots, the accuracy of control movements, and the practical modeling of kinematics. Smart materials still have defects in stability, price, deformation, battery life, and load capacity. At the same time, smart materials with low pollution, low energy consumption, and high toughness also need to be developed. More complex motion patterns often cannot be achieved using a single driven method. In addition, soft robots theoretically have infinite degrees of freedom, but the relationship between degrees of freedom and actuators is not a simple one-to-one linear relationship; thus, it is difficult to achieve accurate modeling and low control accuracy. At present, the control model of the soft robots is relatively simple, which makes it difficult to accurately process the feedback data after the movement, and it is also difficult to ensure the real-time control of the soft robots; thus, sensor control devices for soft robots also need to be further explored. The hardware and software design of the input and feedback devices of soft robots is still inadequate, and the human–robot interaction is poor. The production cost of soft robots needs to be reduced.

6. Conclusions and Prospects

This paper introduces the driven methods and materials of soft robots, and the basic principles and characteristics of mainstream soft materials in 3D printing technology in detail by reviewing the relevant references on soft robots in the past 20 years, aiming to provide readers with some references on the driven principles of soft robots and 3D printing manufacturing. Then, aiming at the current studies, some problems existing in soft robots are summarized, such as the shortage of smart soft materials, the effective use of energy, the realization of the complex motion form of soft robots, the accuracy of the control motion, the actual modeling of the soft robot kinematics, high-efficiency and high-precision manufacturing of soft robots, and so on. Some suggestions are put forward as future research directions.

Several suggestions are made to address the above problems:

(1) Developing new smart materials [140]. It is necessary to conduct in-depth studies on materials, chemistry, machinery, control and other disciplines, and new smart materials that are non-toxic, pollution-free, high stability, low cost, and large deformation for soft robots should be developed, so as to provide a variety of options for the applications of soft robots.

(2) Developing 3D printing soft materials. More soft materials compatible with 3D printing should be developed to solve the limited range of printable soft materials.

(3) Exploring new 3D printing technology. Traditional 3D printing methods restrict each other in manufacturing cost, printable materials, molding accuracy, printing speed, and universality, which poses new challenges to the 3D printing manufacturing technology of soft robots, and new 3D printing technology that can comprehensively take into account the above issues needs to be explored. In recent years, new technologies such as multi material 3D printing [130], embedded 3D printing [76], and 4D printing [141] have been developing.

(4) Exploring the combination of multiple driven methods, the combination of multiple driven methods can make up for the shortcomings of a single driven method, and enable the soft robot to achieve more complex motion patterns.

(5) Optimization of modeling techniques. The modeling needs to consider the multi-coupling problem to ensure the accuracy of the physical model of soft robots; for example, the finite element analysis software can be used to model and analyze the soft robots, and further optimize the design on the basis of ensuring the accuracy [140].

(6) Optimizing sensor control technology. Optimize sensor control technology to obtain accurate data feedback and meet the requirements of infinite degrees of freedom control.

(7) Optimizing human–computer interaction techniques [140]. Optimizing the hardware and software design of the input and feedback equipment of soft robots, so as to better implement human–computer interaction techniques and facilitate people's control.
(8) Reducing the production cost of soft robots. In terms of applications, currently, soft robots have good prospects in the field of medical and human health testing, but their production costs are still high, so the research of soft robots in low-cost and industrial production needs to be further advanced.
(9) High-efficiency and high-precision manufacturing of soft robots. Explore the combination of high-efficiency 3D printing technology and high-precision 3D printing technology to meet the requirements of high-efficiency and high-precision manufacturing of soft robots. Therefore, the combination of multiple 3D printing methods with complementary advantages provides the possibility to realize high-efficiency and high-precision manufacturing of soft robots.

In the future, soft robots will provide great assistance to people in expedition rescue in the hardest-hit areas, medical surgery and human skeletal replenishment, and even outer space exploration. It can even be extended to new areas closer to human life such as education, services, living and entertainment, and become an indispensable part of people's daily life [142]. In soft robot manufacturing, the exploration of high-precision 3D printing technology and high-efficiency 3D printing technology will also be a hot spot for future research.

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