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Fabrication and Functionality Integration Technologies for Small-Scale Soft Robots

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Small-scale soft robots are attracting increasing interest for visible and potential applications owing to their safety and tolerance resulting from their intrinsic soft bodies or compliant structures. However, it is not sufficient that the soft bodies merely provide support or system protection. More importantly, to meet the increasing demands of controllable operation and real-time feedback in unstructured/complicated scenarios, these robots are required to perform simplex and multimodal functionalities for sensing, communicating, and interacting with external environments during large or dynamic deformation with the risk of mismatch or delamination. Challenges are encountered during fabrication and integration, including the selection and fabrication of composite/materials and structures, integration of active/passive functional modules with robust interfaces, particularly with highly deformable soft/stretchable bodies. Here, methods and strategies of fabricating structural soft bodies and integrating them with functional modules for developing small-scale soft robots are investigated. Utilizing templating, 3D printing, transfer printing, and swelling, small-scale soft robots can be endowed with several perceptual capabilities corresponding to diverse stimulus, such as light, heat, magnetism, and force. The integration of sensing and functionalities effectively enhances the agility, adaptability, and universality of soft robots when applied in various fields, including smart manufacturing, medical surgery, biomimetics, and other interdisciplinary sciences.

1. Introduction

With soft bodies and compliant structures, soft robots have been widely utilized in various fields, including industrial manufacturing, for applications such as medical surgery and uncharted territory exploration, and a new interdisciplinary area has been conceived accordingly.[1–4] Over the last few decades, from simple pneumatic grippers to complex robotic systems, soft robots have been evolved through several generations along with the development of soft materials (simple/composites), compliant structures, and the corresponding fabrication methodologies.[1,5–7] Comparing to other soft robots, small-scale soft robot that range from millimeter to centimeter, is the most effective for limited space assignments or difficult/risky accessible scenarios such as surgery in biologic body cavities, rescue in messy closed territory, on-site turbine blade crack examination, battle field on-site spying/navigation, and bionic investigation and concealing, because its miniaturized soft body yet compliant structure offers adjustable bulk that can be effectively actuated at a certain power level.[8,9] However, accounting for very limited volume bulk, it is technically challenging to simultaneously achieve robust power actuation modules onto small-scale soft bodies without affecting their functional structures. Therefore, it is necessary though challenging to codesign structures along with actuations[10] for following implementation/fabrication in confined intrinsically soft and stretchable bodies, particularly in continuum large deformations[1,11]

The presented implementation approaches enable novel composite synthesis, soft bulk modular shaping, and compliant mechanism morphing that offer numerous design principles for fundamental fabrication and integration technologies for small-scale soft robots. Nevertheless, based on these materials and structural foundations, enhancing the effectiveness of the soft robots is a crucial issue that must be addressed by researchers.[12–14] By enhancing the diverse features of the electrical, optical, magnetic, mechanical, and thermal-response units/modules, small-scale soft robots can be endowed with more functionalities, for example, bionic functions of color change, interface adhesion, and object grasping/releasing. However, it is challenging to integrate more active and passive functional modules into small-scale soft robots for enhancing their capabilities and improving their intelligence level, because it is unsubstantial to integrate considerably more functional chips in the confined bulk, compared with large-scale soft robots. Therefore, technological advances in fabrication and integration strategies are highly demanded. Recently, an emerging concept of subtle mechanical construction is the enablement of passive response via mechanism morphing computation/physical encoded bodies,[15–17] so-called mechanical/physical intelligence. This

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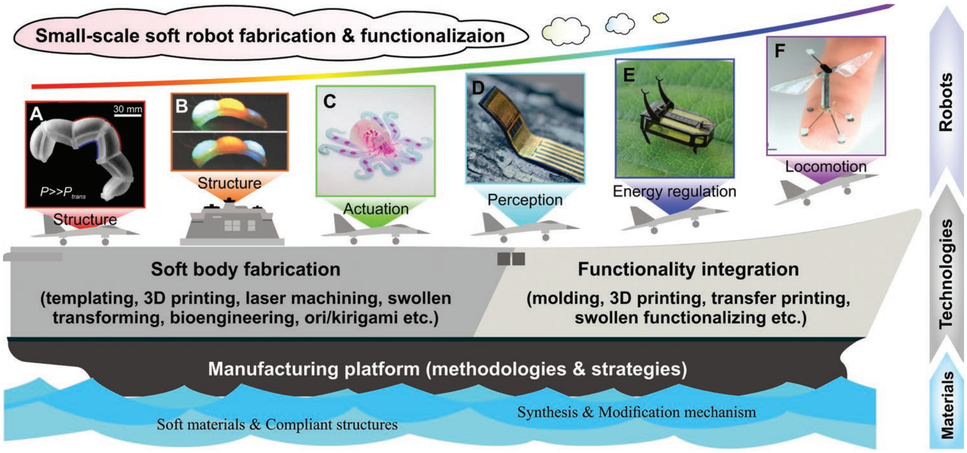

Figure 1. Typical small-scale soft robots on the basis of soft actuation body fabrication and functionality integration. A) A bioinspired dual-morphing stretchable origami robot. B) Highly stretchable electroluminescent robots with optical signaling and tactile sensing. C) An entirely soft, autonomous octopus-like robot. D) A soft ultrathin electronic innervated adaptive fully soft robot. E) An insect-scale autonomous crawling robot driven by catalytic artificial muscle. F) An 80 mg flyable RoboBee tethered with an external power source. Image in (A): Reproduced with permission.[20] Copyright 2019, The Authors, published by American Association for the Advancement of Science (AAAS). Image in (B): Reproduced with permission.[21] Copyright 2016, AAAS. Image in (C): Reproduced with permission.[22] Copyright 2016, Springer Nature. Image in (D): Reproduced with permission.[23] Copyright 2018, Wiley-VCH. Image in (E): Reproduced with permission.[24] Copyright 2020, The Authors, published by AAAS. Image in (F): Reproduced with permission.[25] Copyright 2015, Springer Nature.

strategy can partly simplify the diversity of employed materials, yet is still limited in various active functionalities. Therefore, being fundamental enabling technologies, fabrication and integration strategies pertaining to soft bodies cooperated with functional modules, are of immense importance for achieving multifunction and of practical value for the development of small-scale soft robots.[18,19]

In this work, we review the fabrication and integration technologies of the soft bodies and functional modules of small-scale soft robots. As shown in **Figure 1**, based on various manufacturing techniques, not only actuation structures have been developed with increasing structural complexity, but also increasing functionalities are integrated on the surfaces or into soft bulks. However, there are critical factors in designing and fabricating small-scale soft robots, and we categorize and discuss them in five parts: materials, structure, actuation, function, and intelligence. Moreover, based on such five factors, common and potential fabrication methodologies and strategies for soft bodies together with actuation will be reviewed and discussed. We further highlight a few integration fabrication approaches of structure, actuation, and sensing parts that are effective for integrating the functionalities and thus improving the intelligence of small-scale soft robots. Finally, perspectives on future small-scale soft robots and their application in the potential working fields are briefly discussed.

2. Critical Design Factors of Small-Scale Soft Robots

To construct a sophisticated small-scale soft robot system, a number of critical factors should be considered. After a systematical literature survey of the major design factors on small-scale soft robots, we categorized them into five aspects: material, structure, actuation, function, and intelligence (**Figure 2**), and each aspect further comprises several critical factors. These factors should be carefully considered during the design and subsequent fabrication and integration processes.

i) Material—Material is the fundamental factor in soft robot fabrication. Not only the widely used commercial and natural soft materials, such as silicone/natural rubber, hydrogel, liquid crystal polymers, shape-memory polymer/alloy, dielectric elastomer, ionic polymer metal composite (IPMC), and their composites, but the amorphous liquid matter, including liquid metal, ferrofluid, even biological tissue fluid, can be used to construct behavior-controllable small-scale soft robots.[26–31] During material preparation, modification and synthesis mechanism are often required for improving and developing innovative materials with new features and functionalities, to enhance soft materials' processability and enrich assembled soft bodies' capability. For the general soft robots that equip with large even giant body, subtle and robust stiff–soft composite and compliant mechanisms are more reliable to hold the construction than the purely soft materials. By contrast, small-scale soft robots prefer all-soft or flexible materials because of less loading of tiny scale than that of giant ones.
ii) Structure—To develop a stiffness well-matched body of small-scale soft robots based on actuation mechanism and structural optimization, the following must be considered: varying stiffnesses,[32–36] hierarchical structures,[37] heterogeneous components,[38] compliant mechanism,[39–41] and origami/kirigami.[42–51] Hence, it requires more precise and subtler structural design due to limited operation space on small soft/flexible structures. Meanwhile for general sized robots, structure configuring is much easier to manipulate because of sufficient space than that of the small-scale ones.
iii) Actuation—Actuation is critical for the basic motion of small-scale soft robots, directly determining its mobility and action behaviors. To assure its excellent kinematic

Figure 2. Critical design factors of small-scale soft robots: material, structure, actuation, function, and intelligence.

performance, a few essential characteristics are discussed here: first, to enable its motion, the robot should be preferably designed as untethered;[52,53] second, to guarantee its performance, high energy density and high-efficiency actuators are required;[54] third, to adapt to unstructured environments, the actuators should preferably have multiple motion modes,[55,56] multifield response,[57] and addressable actuation capabilities.[58] Small-scale soft robots possess lightweight than general ones, which results in the former being actuated with less power density to overcome resistance that originated from gravity and friction, than that of the latter. Such a difference brings more mechanism investigation on actuation fabrication and more options on effectively power small-scale soft robots.

iv) Function—In addition to basic and effective motion capabilities, diverse functions need to be integrated into small-scale robots to meet various demands in different scenarios. First, the robots should be preferably equipped with multimode-sensing capability that includes somatosensitive body and environment perception skins.[59–61] Second, the stiffness of the small-scale robots could be tuned in situ according to the specific conditions.[62–68] Third, reconfiguration, self-healing mechanism, and mutual communication are alternative options for small-scale robots.[65,69–75] Finally, system-level control is urgently required and is critical for practical applications. However, in current stage, it is difficult for small-scale soft robots to incorporate all the functional modules mentioned above because of size limitation. Consequently, the functionalities of small-scale soft robots are also limited, and they need to be tailored for each specific application.

v) Intelligence—To realize advanced intelligence, simple function integration may not be sufficient to meet the increasing requirements for complex dynamic environments and highly interactive/dynamic scenarios. There are still many aspects that should be considered, for example, cooperativity,[76,77] swarm,[53,56,78,79] and cognitive capability. For instance, robot swarms allow simpler, less expensive daughter/modular robotic units to be flexibly reconfigured into different forms of team depending on specific aims of the task while being as effective as a larger, task-specific monolithic robot that may be comparatively more expensive and have to be rebuilt depending on the specific aims. Due to the size limitation and constraints on individual robot's function, intelligence, such as cooperativity and swarm, is more important for small-scale soft robots in that the collective behavior might supplement the functional incapability of individual robots. These intelligences can empower them with highly powerful capabilities and may significantly promote the development of the small-scale soft robots.[80]

Overall, the above five aspects are critical for the design and fabrication of small-scale soft robots. However, the current studies have only realized some of them, without fully leveraging their potentials, that would make them comparable to their biological counterparts.[12,13] Hence, it is necessary to comprehensively codesign all aspects according to the targeted demands. Meanwhile, the codesigning of robots necessitates simultaneously consideration of fabrication processes as well, and more advanced fabrication and integration methods need to be developed for realizing the above factors. The following two sections will discuss the typical fabrication and functionalized integration technologies in detail.

3. Fabrication Methodologies of Soft and Compliant Bodies

Different from conventional rigid robots, soft/extensive body is the most prominent yet the most challenging factor for the fabrication of soft robots.[1,7] To effectively manufacture soft bodies and compliant structures for soft robots in small-scale ranging from millimeter to centimeter, materials' synthesis and its coordination with fabrication process have been extensively utilized. In this section, we summarize the key approaches, challenges, and opportunities of fabricating small-scale soft robots. Over the past few decades, numerous fabrication methods have been proposed to achieve subtle structures and mechanisms. We roughly classify such methods into the following eight categories: templating, 3D/4D printing, laser machining, swelling, bonding, bioengineering, and origami and kirigami strategies (see **Figure 3**).

3.1. Templating

Templating, probably the most widespread fabrication method, uses templates for the prototyping of soft robots. It is applicable to various types of materials (silicones, liquid crystal polymers, and magnetic-particle-modified polymers[100]), and it satisfies a wide range of dimensional requirements (from hundreds of micrometers to dozens of centimeters[101]). The most distinguishable characteristic of templating is to utilize templates for a specific shape formation of inner/outer or both surfaces of soft robots. According to the fabrication procedure and templated surfaces, we further categorize templating into three distinct techniques: casting, lithography, and coating (see Figure 3A).

3.1.1. Casting

Casting usually uses a mold that templates the outer (or both inner and outer) surfaces of the desired structure, to prototype the soft robots. During a mold-based fabrication, liquid prepolymers are poured into the prepared mold and cured for later demolding. As the molded materials replicate the shape of mold, the fabrication resolution of profile is determined by the precision of molds that are manufactured by 3D printing in most cases. Therefore, in most cases, the resolution of 3D printer directly determines the resolution of molded materials. Depending on the working principle of 3D printer and its raw materials, the resolution of printed mold ranges from 100 nm to several hundred micrometers. Often, the molds can be used repeatedly though high resolution will increase the expense of fabrication. Therefore, it can be readily adopted for the mass production of soft robots. Moreover, the structure of molds and the sequential use of molds can be flexibly designed on demand for the ease of fabrication.

Apart from the simple molding of a monolithic structure,[102] several molded parts can be bonded together for a programmed actuation of robots.[35,103,104] Inextensible parts (papers or fibers) are also frequently adopted in casting to restrain extension in certain directions, thereby leading to the stretching, bending, and curling of soft robots.[43,105–107] For soft robots that have complex inner structures, detachable modular molds are suggested for the convenience of demolding.[108] With supplementary techniques such as lamination casting, retractable pin casting, and lost wax casting,[109] casting enables the fabricating of most of soft robots. However, due to the relatively weak connection between two sequentially molded parts, those conventional casting techniques might cause mechanical failure in bonding interfaces. To avoid such mechanical failure, a simultaneous molding technique might be an effective solution.[34] By placing a spacer between two molding areas and removing it for curing, materials with different moduli can be fused and cured together for a seamless connection of two parts. Alternatively, Brun and co-workers recently reported a bubble casting technique that harnesses interfacial flow in elastomers and progressive curation, for the production of monolithic pneumatic actuators with tailored shapes.[81]

3.1.2. Lithography

Compared with casting that uses a 3D mold for templating, lithography, in general, is a 2D template method, and it usually have a micro- or nanoscale resolution that makes it an intrinsically suitable fabrication technique for small-scale soft robots. In our review, we mainly discuss two subcategories of lithography that are photolithography and soft lithography, that are common in the soft robotics field.

For small-scale soft robots, photolithography often involves many other fabrication techniques, such as etching, atomic layer deposition, and electrodeposition.[49,110] Using these techniques in a photolithography process, conductive layers, adhesive layers, and responsive layers are patterned layer by layer with a thickness that range from several nanometers to tens of micrometers. Because all the procedures are conducted under a stringent condition, small-scale soft robots can be fabricated

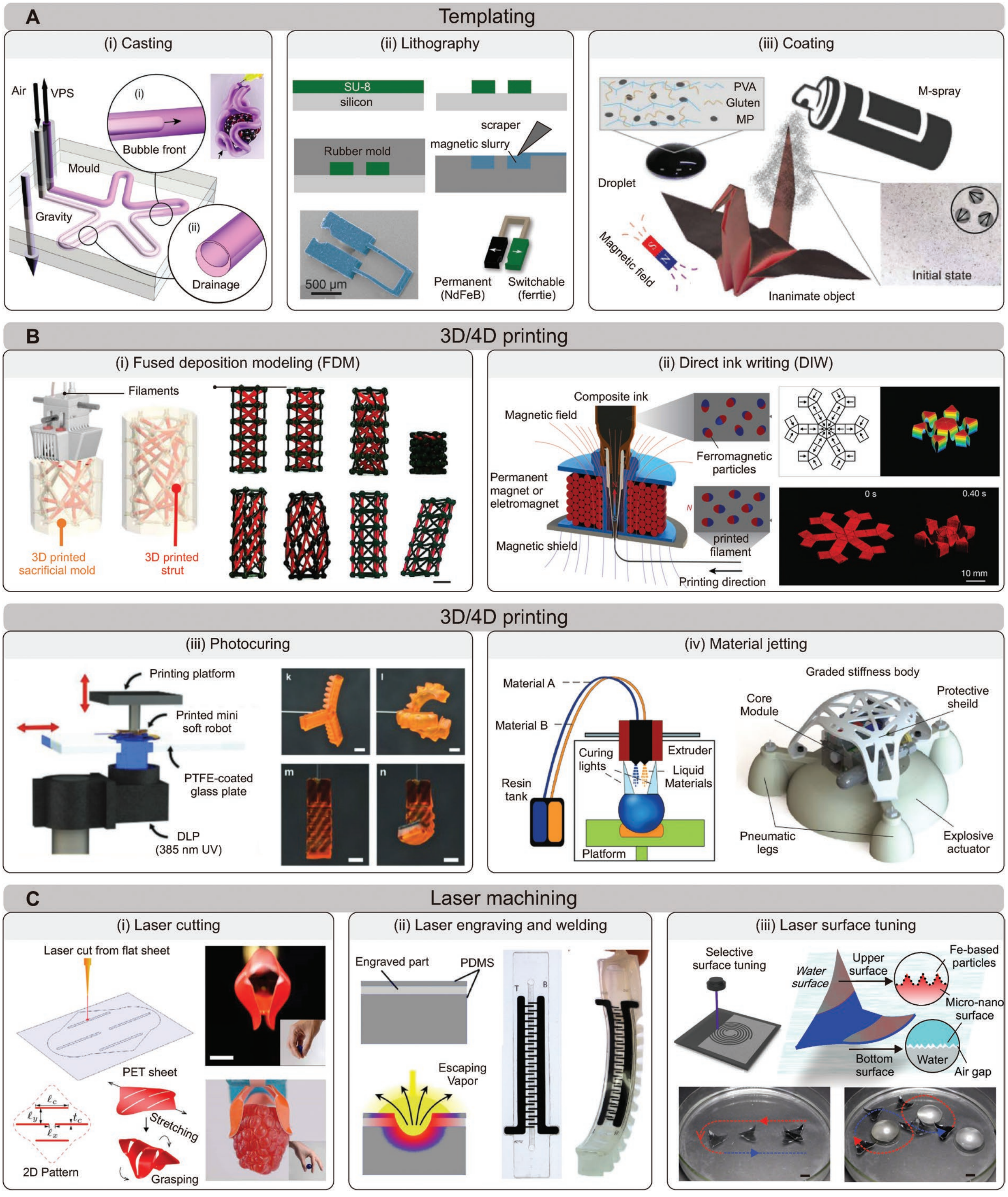

Figure 3. Fabrication techniques for structures in small-scale soft robots. A) Fabricating the structure of soft robots by bubble casting, soft lithography, and spray coating. B) Two materials fused deposition modeling (FDM), direct ink writing (DIW) with ferromagnetic-particle-doped ink, Digital Light Processing (DLP)-based multimaterial printing and multimaterial ink-jetting are used for the 3D/4D printing of soft robots. C) Depending on the laser parameters, different techniques such as laser cutting, laser engraving and welding, and laser surface tuning are utilized in the fabrication of small-scale soft robots. D) A swelling-based multistable configuration of soft structures. E) Glue bonding, thermal bonding, self-healing, and surface modification are frequently used bonding techniques that bind various parts together. F) Typical levels of biological structures, including bacteria and motile cells, living muscle tissues, and insects, are reported to fabricate soft robots. G) Small-scale robots are created by the means of origami and kirigami. A) i) Reproduced with permission.[81] Copyright 2021, The Authors, published by Springer Nature. ii) Reproduced with permission.[82] Copyright 2014, Wiley-VCH. iii) Reproduced with permission.[83] Copyright 2020, The Authors, published by AAAS. B) i) Reproduced with permission.[85] Copyright 2020, The Authors, published by AAAS. ii) Reproduced with permission.[54] Copyright 2018, Springer Nature. iii) Reproduced with permission.[84] Copyright 2019, Wiley VCH. iv) Left: Reproduced with permission.[87] Copyright 2014, Aerosint SA. Right: Reproduced with permission.[86] Copyright 2015, AAAS. C) i) Reproduced with permission.[88] Copyright

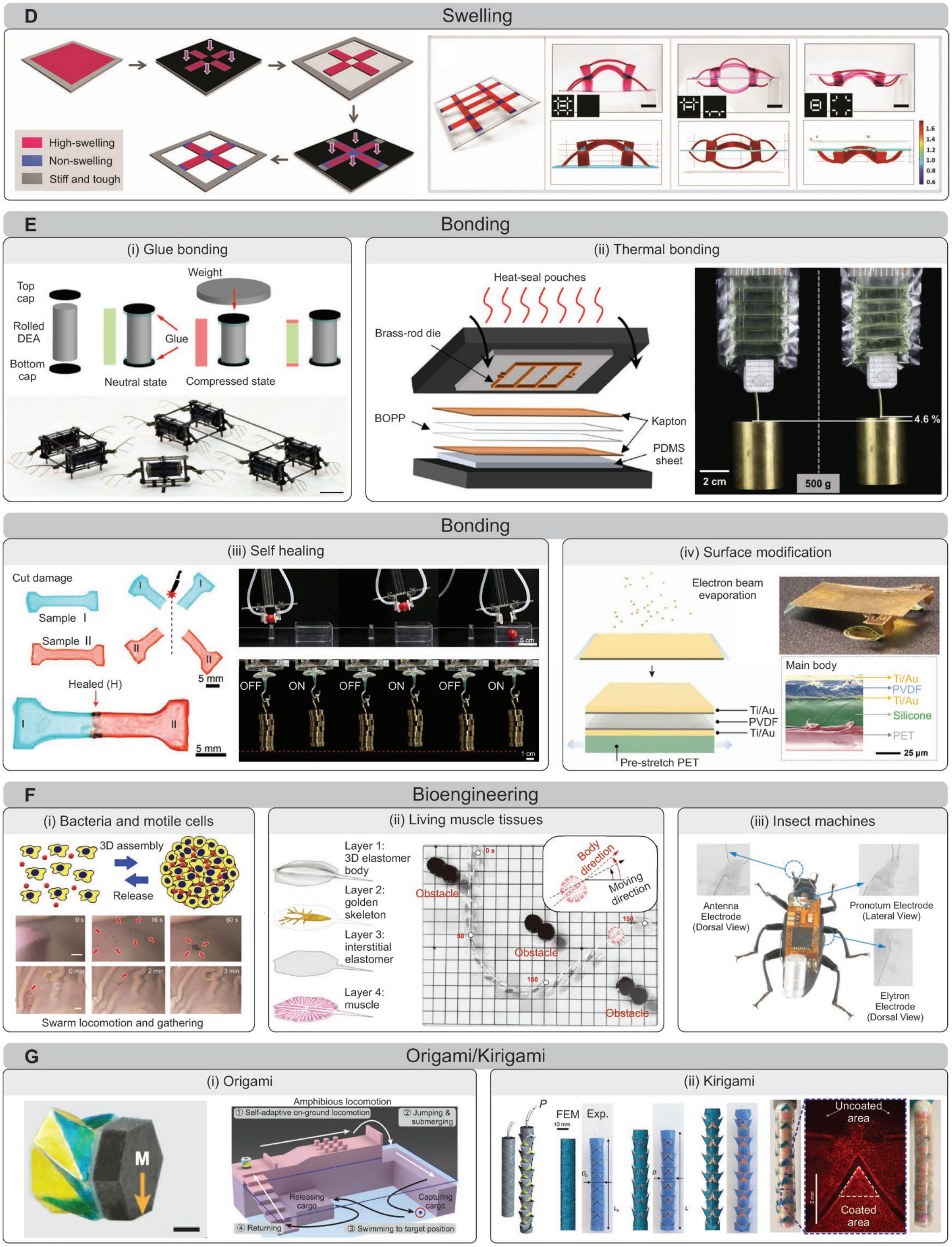

Figure 3. Continued.
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with a considerably high precision. Because of its compatibility with other techniques, photolithography is potentially a versatile fabrication technique for various materials of soft robots. However, the fabrication process of photolithography is sophisticated and time-consuming. Owing to the unbendable photomask, the inability to fabricate nonplanar microstructure further hinders the broader application of photolithography.

Soft lithography that was initiated in the 1990s, uses soft materials for the lithography of materials and has been adopted as a vital technique for micro- or nanoengineering.[111] Furthermore, it also has a high fabrication precision of several nanometers. There are many useful techniques based on soft lithography,[112] among which replica molding (REM) is the most frequently used method employed for the fabrication of soft robots. REM is analogous to the abovementioned casting. The molds, however, are made of soft materials that are replicated from different microstructured objects. Ubiquitous polymers, such as poly(dimethylsiloxane) (PDMS), polyurethanes (PUs), and polyimides, are widely used materials for the molds. Owing to the flexibility of polymers, REM is capable of replicating not only soft robots with flat surfaces,[113,114] but also structures with curved surfaces.[115] Although flexible REM molds can be fabricated from available relief structures (for example, diffraction gratings, transmission electron microscope grids, and assembled polymer beads),[111,116] photolithography is still the primary technique employed to fabricate REM molds for a predesigned robotic actuation.[82,117] Therefore, cheap and rapid techniques are required to be an alternative to high-precision master fabrications.

3.1.3. Coating

Distinguished from casting and lithography, coating can be used to fabricate both 2D and 3D soft robots with fine structures. During a coating process, liquid prepolymers conformally cover the surfaces of a templating object and finally form the shape that is identical to the contour of templating surface. Thickness of the coated materials is one of key parameters that should be precisely controlled during the processing. The coated thickness is strongly related to the rheological properties of materials, and can be tuned on demand by adjusting relevant technical parameters of fabrication. Based on the formation technique of the coated layer, direct coating, blading coating, spinning coating, spray coating, and dip coating are discussed for their applications in small-scale soft robots.

As the simplest coating technique, direct coating templates a thin film of substance by removing the solvent in a composite solution. For instance, by evaporating organic solvent in the solution, a thin layer of freestanding porous membrane is fabricated.[118] Furthermore, by filtering the nanosheets in water solution with a filter paper, a bilayer structure is formed.[119] In case of the direct coating technique, a specific treatment method should be determined by the physicochemical properties (such as the boiling point and solubility in different solvents) of the coating materials. In blade coating, a scraper is used to blade the prepolymers into a thin film that covers the substrate. Technically, a flat polymer sheet can be bladed by any objects that might serve as scraper. Blade coating is influenced by many factors, such as blade velocity, blade parameter, and viscosity of fluid,[120,121] that hinder accurate prediction. Hence, preinvestigation of blading thickness before coating is necessary. Since the viscous force does not need to counter the large force that is generated from accelerations during film forming (for example, gravity and centripetal force), relatively thick films can be fabricated by blade coating. High viscosity liquid, such as particle-functionalized polymers, can reach a thickness of 800 μm or more.[122] By contrast, spinning coating is more suitable for thin films, of which the thickness ranges from several micrometers to tens of micrometers. In case of thin films, by directly applying liquid prepolymers/solutions onto a rotating substrate and curing, spinning coating has demonstrated its applicability for the fabrication of diverse materials. Examples such as fluidic-pressure-driven polymers,[123] magnetic-actuated composites,[75] humidity-responsive materials,[124] and photosensitive elastomers[125] have also been verified. In addition to these flat films, thin films with relief structures are also realized through additional photolithography steps.[126] Actuation of these microstructured thin films will yield a relatively complex motion of soft robots.[123]

Different from the aforementioned 2D coating technique, spray coating is targeted for both 2D and 3D coating; in spray coating, coated objects are printed using atomized ink through a nozzle.[127] Atomized ink merges on the surface of coated objects and eventually forms a continuous film on the surface. Overall coating and selective coating (coating using a mask) can both be realized by spray coating.[83] However, nonuniform distribution of sprayed droplets often results in an uneven surface, which makes it imprecise for the coating of small features or the coating of sub-centimeter robots. Dip coating that usually produces evenly coated surfaces, therefore, is a suitable supplementary method for spray coating. In dip coating, the coated objects need to be immersed into coating materials and thereafter removed to allow the coating materials to drip.[128] The thickness of coated layer is dependent on the viscosity of coating materials; higher viscosity will eventually result in a thicker coated layer. If the thickness is not satisfactory, additional dip coating steps are suggested to thicken the layer. In case of certain dip coating processes, the coated objects need not be removed after immersion; instead, the objects are directly immersed in materials for continuous coating.[129] This new concept of dip coating shortens the time required for liquid dripping and broadens the technical applicability of dip coating for small-scale soft robots.

3.1.4. Challenges and Opportunities

Templating incorporates techniques based on traditional molding, microengineering, and surface coating. Additionally, new features for these techniques are being developed for the fabrication of small-scale soft robots. Instead of pure structures, the actuation of these structures is the fundamental requirement in soft robots. Consequently, templating technique must advance toward the compatible fabrication of microchannels for pressure-driven robots and of functionalized materials for various field-actuated robots (such as magnetic, electrical, and optical fields). For example, bubble casting proposed by Brun and co-workers internalized the characteristics of blow molding that is a mature technique in industrial plastic manufacturing.[81] It not only monolithically fabricates the structure of soft robots as blow molding does in plastic manufacturing, but also comprehensively utilizes the timespan of polymer curation to achieve a programmable behavior of soft robots. Continuous dip coating by Zhang and co-workers is another example that modifies the conventional intermittent coating to uninterrupted coating.[129] Leveraging the surface charges on both coated objects and coating materials, functional particles continuously aggregate on the surface and form a membrane. This coating technique that is similar to electroplating, enriches the fabrication technique of soft robots and might inspire further interdisciplinary innovations for templating.

Nevertheless, templating still is limited by a characteristic problem in that small structures need to be molded by small-structured templates. Of particular, for small soft robots with exquisite features, high resolution templates are necessary to ensure the shape fidelity of molded materials. In terms of achievable resolution, templating provides a set of techniques that supplement one with another for covering a wide resolution range. Specifically, casting is probably the most suitable templating technique for centimeter scale robot that is tens of or enough hundreds of the size of its resolution. Lithography improves the resolution to sub-micrometers, which makes it an attractive technique to fabricate millimeter and micrometer soft robots. Coating is a technical-parameter-dependent technique for the 3D realization of micrometer scale thickness. Given a satisfactory resolution has been achieved by templating, two possible advancements are proposed for the templates. On the one hand, versatile or modular templates that are compatible with diverse structures enhance the adaptability of templating. On the other hand, cheap and high-precision microscale or even nanoscale templates are highly demanded for the future application of small-sized soft robots.

3.2. 3D Printing

The next-generation fabrication technology of soft robots will be a simple one-step process, excluding the complex preprocessing and assembly of various parts. Using a coupled processing technique, the entire soft robot with different modules (such as power sources, actuators, and sensors) can be strongly integrated. Although this aim is ambitious and challenging, a soft and integrated robot, Octobot, has been demonstrated for the first time, using 3D printing.[22] Standard 3D printing techniques mainly include fused deposition modeling (FDM), direct ink writing (DIW), photocuring, and material jetting, Figure 3B. In all these techniques, the starting materials (filament, ink, powder, or resin) transform from a mobile state to a solid object. Furthermore, based on 3D-printed smart materials/structures, so-called 4D printing technology has been widely exploited that can respond to the external stimuli (such as, light, temperature, magnetic field, pH, and humidity) and change their shapes. Overall, the 3D/4D printing techniques provide promising and systematic tools for directly fabricating soft robots.

3.2.1. Fused Deposition Modeling

FDM is a widely used and proven 3D printing technology. In this direct-writing process, a heated extrusion nozzle extrudes molten thermoplastic polymers on the substrate, followed by solidification upon cooling to form an additive solid 2D layer. This technique provides a convenient and affordable strategy for directly fabricating soft robots with complex structures. With the aid of the supporting structure, hollow structures and chambers can also be printed. Using FDM printing, soft grippers have been fabricated and can be actuated by high-pressure pneumatic.[130,131] This printing technology is restricted by the performance of thermoplastic polymers. Thermoplastic polyurethanes (TPUs) are widely used, yet the low flexibility (tensile strength $E > 26$ MPa) and stretchability (strain rate < 660%) restrict its application in ultrasoft robots. Moreover, the resolution (100–400 μm) of FDM is highly limited by the aperture of the nozzle (>0.1 mm) that hinders its application in printing for small-scale soft robots.

3.2.2. Direct Ink Writing

DIW uses viscoelastic liquid ink (for example, silicone rubber (PDMS/Ecoflex) liquid polymer resin, and hydrogels) as the structure material, with suitable flexibility and stretchability. An external pressure source (for example, plunger, peristaltic, and air pressure pumps) extrudes the liquid ink from a nozzle, and the corresponding extrusion speed can be regulated by changing the pressure. Liquid ink is deposited on the substrate layer by layer into a specific shape, and the solidification process (heating or photoexposure) ensures its shape retention and interlayer adherence simultaneously.

Furthermore, composting functional materials (for example, magnetic particles and silicone–ethanol emulsions) into the ink can afford 4D printing structures responding to external stimuli, for example, magnetic field,[54] light,[132–134] temperature,[135,136] humidity,[137,138] electrical field (current/voltage),[139,140] and pH,[141,142] to deform or actuate. Kim et al. adopted the DIW technique to print the self-folding microstructures that enable rapidly actuation by the magnetic field.[54] The magnetic ink was prepared by embedding the ferromagnetic particles into the elastomer matrix. During the fabrication, the magnetic polarities of the printed ink can be controlled by the magnetic field's direction around the nozzle. The phase-change materials, particularly liquid–vapor change, can also be used in DIW fabrication. Mixing the volatile liquid (such as ethanol and fluorine-based liquid) into the elastomer matrix allows the soft structures to generate significant deformation and output stress owing to the high-pressure gas by heating.[143,144] Gladman et al. printed composite hydrogel architectures encoded with localized, anisotropic swelling behavior controlled by the alignment of cellulose fibrils along prescribed printing pathways.[138]

Although DIW is compatible with most soft materials, there are still some challenges. The printing quality is restricted by the rheology of the fluidic ink (for example, viscosity, surface tension, and evaporation rate), causing the printing resolution to be relatively large (>0.1 mm) and the rough texture.

Moreover, investigation of the fabrication of hollow structures is challenging owing to the lack of appropriate materials for supporting structures.

3.2.3. Photocuring

Photocuring 3D printing adopts photosensitive liquid resin as base material (PU-based, PDMS-based, and hydrogel) that can be cured under light irradiation and still has suitable flexibility and stretchability. Owing to its high printing resolution (0.1–100 μm), rapid polymerization speed, and smooth printing surface, photocuring 3D printing, particularly complex microstructure printing, can be comprehensively utilized in the fabrication of small-scaled soft robots. Various types of photocuring 3D printing techniques have been demonstrated, including stereolithography (SLA), Digital Light Processing (DLP), light crystal display (LCD), and two-photon polymerization (2PP). SLA is the first generation of photocuring printing technology that uses the plane moving ultraviolet (UV) laser beam to cure the resin, adopting the "dot-line-surface" printing strategy. Influenced by the printing strategy, SLA features a low printing speed, and its printing resolution is limited to 100 μm. DLP and LCD printing exhibit speedier printing speeds and higher resolutions (≈10 μm) because the entire layer cross-section is printed simultaneously. Unlike the aforementioned "layer by layer" fabrication strategies, 2PP is unique owing to the absence of this path limitation.[145] By utilizing the two-photon absorption of near-infrared light to cure the resin, the 2PP can print complex microstructures floating within the photopolymer and currently achieve the highest printing resolution (≈100 nm).

Due to high printing resolution and suitable material compatibility, photocuring 3D printing techniques allow the internal microchannel and cavities to be easily printed and integrated into soft robots. Recently, Zhang et al. reported miniature grippers (sized 2–15 mm) with microscale channels that can grip small objects actuated by pneumatic.[84] Some research groups have fabricated self-healing soft robots using hydrogel materials that demonstrate significant elongation (over 1000%) and can rebound after breaking.[146–148] The structures of these modular soft robots can be repaired and assembled by various parts.

4D printing can also be achieved based on photocuring 3D printing. Several studies have reported the stimuli-response structures and actuators responding to ions,[149] temperature,[150] humidity,[151] and light.[152] Compared with those pneumatic and electric tethered actuators, these stimuli-responded actuators are effective in open, environmentally responsive soft robotic systems.

3.2.4. Material Jetting

Material jetting uses inkjet print heads to jet the liquid resin onto the platform layer by layer under UV light irradiation, to cure the resin to hold its shape. This technology is highly effective for 3D multimaterial printing because an array of print heads can be used on demand. The major commercial material jetting 3D printers are the PolyJet (resolution from 10 to 100 μm) from Stratasys and MultiJet from 3D systems Inc. Using this multimaterial printing technology, many research groups designed soft robotic systems using different materials by assembling. For example, Bartlett et al. directly printed a combustion-powered soft robot, the body of which transitioned from a rigid core to a soft exterior.[86] The stiffness gradients of this robot range over three orders of magnitude (1 MPa to 1 GPa) that can minimize the stress concentration at the surface of the two materials. For instance, Phamduy et al. fabricated a robotic fish composed of rigid and flexible materials.[154] Recently, Hubbard et al. reported fully 3D-printed soft robots integrated with soft actuators, fluidic circuitry, and body features using the PolyJet 3D printer.[155a] This innovative design achieves various fluidic logical elements (such as transistors and diodes) that can be directly embedded into the soft robots. This incorporation of a multimaterial printing strategy enhances the properties of specific features. For example, features designed to deform during operation, such as diaphragms and O-rings, can be constructed using a compliant material. By contrast, those designed to be functionally static (for example, fluidic channels, access ports, and structural casings) can be developed using a rigid material.

3.2.5. Challenges and Opportunities

Despite 3D/4D printing technologies affording speed and efficiency to soft robots, considerable investigations still remain to be conducted. On the one hand, material research is fundamental to 3D/4D printing. In current stage, suitable 3D/4D printing materials for soft robots are limited, and even fewer functional materials (such as conductive materials, stimuli materials, and biodegradable materials) have been presented. On the other hand, the long fabrication process time (from several hours to days) is still a significant hurdle for the mass manufacturing of soft robots. Overall, 3D printing technologies are convenient for digital manufacturing that can directly connect with computer design with reality structures, especially for prototype fabrication. Meanwhile, 3D printing technologies can provide wide range of fabrication resolution (from 10 to 400 μm) to suit various small-scale robots' fabrication. Thus, we expect further research to focus on gradually forming design paradigms to regulate and derive the small-scale soft robots' fabrication.

3.3. Laser Machining

Laser machining is a mode-free fabrication approach that can be widely used for rapid direct fabrication of soft robots or indirect auxiliary methods. Leveraging laser manufacturing, a series of facile and effective methodologies and techniques were developed and proposed for obtaining a soft actuation body recently.[88,156–158] The rich programmability and adjustability of laser with high resolution and output power affords the universality of treating almost all types of materials, including elastomers, plastics, and metals. Generally, by programming different lasers with different power densities, it can be utilized for various processing effects, such as high-energy laser for cutting, middle-energy laser for engraving, hardening, and sealing, and low-energy laser for surface tuning, Figure 3C. These varying processing strategies can provide a universal platform technique for rapidly developing a soft actuation body.

3.3.1. Laser Cutting

Utilizing the relatively high-energy laser to process materials, it is widely used for cutting the substrate materials into preferable arbitrary patterns. It can serve as a general 2D fabrication method, rapidly forming soft actuation structure/body. Utilizing this technique, many small-scale robots are enabled, such as origami/kirigami soft structures/robots, soft magnetic robots, and dielectric elastomer actuators. For instance, Sitti and co-workers used the laser micromachining technique to cut the protein motors into the specified design shape in order to obtain the multifunctional and biodegradable self-propelled protein motors.[157] It demonstrates immense potential for the fabrication of such scaled robots.

3.3.2. Laser Engraving and Welding

In an attempt to develop soft system/body at a small scale with more sophisticated structures such as gradient mechanical structures and multiple pneumatic chambers, some of the aforementioned methods or laser cutting become costly and limiting alternatives. Favorably, due to its excellent programmability, it can also be used to realize various types of fabrication processes such as engraving, stiffening, and welding, by utilizing it with an appropriate laser parameter. Utilizing laser engraving, it can selectively ablate the materials from the original substrate to form a gap, and to weaken its local mechanical stiffness. This is usually used for serving as a hinge. Many elegant studies were conducted based on such technique; for example, Shea and co-workers used laser engraving technique to define the interdigitated pattern to construct stretchable pumps for soft machines.[89] Leveraging the thermal effect of laser, it can also be used to weld or seal different parts or multilayers. For instance, Mosadegh and co-workers used the laser machining to weld the polyurethane to bond the edges of the actuator, and they also proposed a laser cutting and welding-based rapid method for fabricating thin pneumatic actuators and robots.[156]

3.3.3. Laser Surface Tuning

In addition, using a relatively low energy-density mode, laser can also be utilized for processing surface, to realize subtler microstructures. Wu and co-workers used the laser to scan the surface of the soft origami swimming robot to obtain a micro-nanosurface, enhancing its effectiveness using superhydrophobic skin, thus affording higher kinematic performance in water. Additionally, using the laser to tune the surface morphologies of the elastomeric sheets, Wu and co-workers also proposed a laser selective surface-tuning-based swelling method to construct soft origami robot.[46]

3.3.4. Challenges and Opportunities

Despite the intensive progress in the laser techniques for the fabrication of soft robots, there are still some challenges that may limit its further applications: a) most of the current laser methods are limited in 2D fabrication, and direct 3D laser fabrication of complex 3D structures/robots is rare; b) compared with other integrated fabrication methods, laser machining often needs to be supplemented by other methods; c) owing to unignorable heat effect of widely used laser, some machining error results in some sensitive materials; d) it necessitates optimization matching of laser parameters and different materials when processing heterogeneous materials. Owing to these potential challenges, the research community must further develop the corresponding mechanisms, enabling the effective and elegant utilization of laser for developing more sophisticated robots.

Overall, laser machining is an effective technique for the fabrication of small-scale soft robots, and is also suitable for the fabrication of relative larger scaled soft/rigid/compliant robots. The laser machining resolution of the commonly used materials for soft robots (e.g., functional-particle-doped PDMS or Ecoflex, TPU[55,89,156]) can reach ≈10–20 µm. With more advanced laser equipment and proper selection of materials, the fabrication resolution will probably be improved to sub-micrometer scale,[159] which can satisfy most fabrication requirements for constructing exquisite structure. There are many opportunities for robotic communities to develop more elegant small-scale robots, for example, using dynamic laser equipment with multiaxial degree of freedom can enable the direct processing of the structure on 3D substrates that can significantly improve the complexity of constructed structures. This technology can be harnessed to realize more sophisticated structures/robots by flexibly programming various laser operational parameters.

3.4. Swollen Transforming

Here, swelling refers to a volume enlargement phenomenon resulting from the diffusion effect, when a high-molecular polymer is immersed into a specific solvent. Based on the numerous types of polymers, such as such as silicone rubber, hydrogel, liquid crystal elastomer, and dielectric elastomer, this mechanism can be utilized to conduct the buckling process. During the swelling process, on the one hand, the self-morphing exhibits a predictable, controllable, and reversible shape-shifting behavior that can be further programmed and regulated by various polymer–solvent systems. On the other hand, the diffused solvent or solution carried with the functional particle and polymer solute can endow the entire structure bulk with integratable and accessible functionalities.

3.4.1. Hydrogel-Based Robotic Bulk

Hydrogel, a typically swellable polymer, has been thoroughly investigated as a compliant material for soft robots owing to its outstanding features, such as tunable stiffness and stretchability, high transparency, ion conductivity, biodegradability, and stable biocompatibility.[160] When employing such a solvent-absorbable material, anisotropic swelling behavior on the heterogeneous structure can be observed in an appropriate solvent environment that induces a stress/strain difference between the localized components, resulting in complete anisotropic deformation.[161–163] For instance, Wu and co-workers have presented many findings on programmable multimorphing 3D configurations with composite hydrogel sheets that have potential for the soft robotic bulk, Figure 3D.[51,164,165] In addition, on the condition of responding to an electric field, the 3D-printed electroactive hydrogel model offers a controllable soft robotic manipulation and locomotion.[140,166] Alternatively, encoding composite hydrogel architecture with localized materials affords anisotropic swelling behavior, for example, cellulose fibrils, thus, a novel method for biomimetic soft robots 4D printing is realized.[138] Other researchers have proposed transformable hydrogel composites that can be manipulated based on thermal, optical, magnetic, electrical, chemical, and hydraulic stimuli, for use in bilayer hybrid soft robotics through layer-by-layer polymerization,[167,168] in gradient hydrogel-based robots with complex shape deformations through 3D/4D printing,[169–171] and in various actuators and universal robotic "skins" via photolithography and mask printing.[172–176]

3.4.2. Silicone Rubber Robotic Bulk

Silicone rubber is a widely used elastomer in flexible electronics, soft robotics, and microfluidics, owing to its stretchability, formability, and ease of fabrication and shaping. This silicone-composed elastomer maintains nonpolar high-molecular chains that are compatible with nonpolar organic solvent, such as, acetone, isopropanol, hexanes, pentane, and benzene,[177,178] that allows the elastomer to be swollen and expanded based on solvent penetrating and diffusion.[179,180] Based on this phenomenon, researchers have proposed a 3D shape programming and reconfiguring approach on PDMS sheets via surface topography modification.[46] The planar elastomeric sheets can be swollen into the desired spatial constructions by means of bending and twisting deformation according to the surface microgrooves orientation. This paves the way to precisely fabricate customized small-scale soft robotic bulk with silicone rubber.

3.4.3. Other Active Swellable Materials

For developing swelling-responsive soft robotic bulks, researchers have investigated various polymers, gels, and composites that possess the ability of specific solvent absorption, for example, porous polymer capable of exhibiting the anisotropic swelling effect,[118] IPMC with cation and anion migration caused differential swelling under electric field,[181] liquid crystal elastomer/polymer,[182] and moisture-responsive bioinspired soft robots based on graphene oxide.[183] These stimuli-active materials provide interactive buckling and deswelling behavior that can be coupled and combined to accomplish complex soft bodies that can be actuated.

3.4.4. Challenges and Opportunities

Swelling not only enables the development of 3D morphing structures with precise manipulation and programmability, but also bridges the solvent competition mechanism, soft matter material design, and fabrication. However, some challenges are still encountered during swelling. First, due to the physical or chemical reaction induced by continuous solvent diffusing, ion migration, and bond breaking and formation, the swelling process may continuously proceed for a considerably long time, resulting in an unstable and inconsistent ultimate deformation state. Thus, improving the repeatability and controllability of swelling by precisely adjusting the usage amount of solvent and designing interlocking constructions is challenging. Consequently, for a certain polymer or a new synthetic composite, the swollen system requires compatible solvent for effective penetration, diffusion, swelling, and deforming. Therefore, developing on-demand and suitable polymer/composite–solvent systems for multiple 3D configuration morphing is challenging yet urgent.

The swelling methodology provides a programmable self-morphing process of configuring 3D soft robotic bodies. The cooperation and competition between swelling and deswelling can be harnessed to realize sequential actions for the autonomous locomotion of soft robots. Such a relationship induces an anisotropic deformation that enables a feasible reconfigurability of soft robot body. Moreover, inspired by natural living beings, particularly the ones living in a liquid environment, the swelling effect can be used for mimicking the liquid-responsive robotic bulk that is of immense potential for fabricating solution-triggered transformable robot, to accomplish deployment in uncharted liquid environment, such as medical robots in human internal fluid environment.

3.5. Bonding

As most of the fabrication techniques are unable to directly integrate all parts of the soft robots, bonding is a classic fabrication technique used to bind parts together, and widely used in the process of fabricating soft robots. Methods to enable firm bonding are diverse. Chemical cross-linking of polymers, intermolecular forces between long molecules, or even strong field forces (for example, magnetic forces) are possible mechanisms that enable the creation of connections between two neighboring parts. Depending on the principles of connection formation, the strength of bonds formed by different bonding techniques varies. According to the demand of connection strength, appropriate selection of bonding techniques is important. Here, we mainly discuss three frequently used bonding techniques that are glue bonding, thermal bonding, self-healing, and surface modification, Figure 3E.

3.5.1. Glue Bonding

With a relatively low technical threshold, glue bonding is widely applied in the fabrication of soft robots to form strong bonds. Typical materials for this technique are prepolymers and commercial glues. Prepolymer glues usually require additional auxiliary methods (for example, heating or ultraviolet light treatment) for speedy and complete curations. Precursors of silicones, such as PDMS Sylgard 184, dragon skin, and Ecoflex are commonly used.[104,184] Because these silicones are easily accessible and chemically compatible with each other, different parts can be firmly bonded together ensuring strong connections; these parts can withstand large deformations without delamination.[185] However, contaminated interfaces between two connecting parts easily cause delamination. Clean interface is an indispensable factor for this technique. As for the fabrication resolution, Zhang et al. have achieved the bonding of millimeter scale and sub-millimeter scale parts for small soft robots under the assistance of jigs, which is a stable and reliable technique for 3D structured soft robots.[104]

By contrast, the curing of commercial glue bonding is more robust to contaminations and do not require additional heating or ultraviolet light treatment. After all the parts are assembled appropriately, glue is dropped on the connecting interfaces to ensure firm connection.[91,122] Because these glues are generally instant adhesives (that cure rapidly), evenly dispersing them on a surface as well as precisely controlling the dosage, particularly for extremely small robots, is problematic.

3.5.2. Thermal Bonding

As a mature technique to fuse homogeneous or heterogeneous materials together, thermal bonding is promising for facile fabrication of soft robots. During a thermal bonding process, thermoplastic materials are partly melted and reshaped into a predesigned structure. After the heat is removed, thermoplastic materials solidify again to form an integral part. Considering feasibility in regular laboratory environments, these thermoplastic materials are mostly low-melting-point materials that do not easily react with air. Other materials, such as papers, fabrics, and textiles, are also heat-sealable when they are coated with thermoplastic materials (thermoplastic polyurethane).[186,187] Although some temperature-field-actuated artificial muscles can be fabricated by thermal bonding,[188] many researchers use this technique to fabricate fluid-driven soft robots that are based on thin films which can easily be processed by local heating.[47] In order to customize the hollow structure within the thin film actuators, either patterned heat press[92,186,189] or robotic-assisted heat sealing[190,191] can be utilized to realize various fluid-tight robots with a minimal channel width of around 500 μm. Generally, these fluid-driven robots are based on pneumatic,[47,186,187,190] hydraulically amplified self-healing electrostatic,[92,189,191] or newly reported electropneumatic actuators[] that strongly rely on the hollow structures to generate different motions, including contracting, folding, and curling. By programming the structure parameters of these hollow structures, the complicated shape morphing and sequential control of soft actuators can be further realized, and in fact, researchers have leveraged a software suit for this.[186]

3.5.3. Self-Healing

Soft robots with self-healing property are those in which the materials have the ability to resist damage and still maintain their functionalities. Some soft robots use reinforced materials to prevent further escalation of damages,[193] whereas other soft robots use spontaneously remedial mechanisms to resist damages.[194,195] However, most of the self-healing soft robots leverage intrinsic self-healing materials to recover from damages.[196] These soft robots can reconnect the materials where rupture occur with/without the existence of additionally external energy (heating, for instance).[197–199] From another perspective, the ability to heal the ruptures provides new opportunities to integrate different parts of soft robots together. With the aid of self-healing materials, no additional materials are required for the bonding of different parts. Each part of the soft robots can be fabricated individually and subsequently assembled together for self-healing. The strength of healed interfaces depends on the mechanisms of self-healing materials. Physicochemical interactions, such as hydrogen bonding[200] and metal–ligand coordination,[201] are generally weak bonding interactions.[202] Reversible covalent bonds, in contrast, are strong connections. The formation of the physicochemical interactions, in most cases, is spontaneous in regular laboratory environments, whereas covalent bonds require additional energy input (thermal energy, for example). However, both mechanisms have realized structurally strong robots that can withstand large deformation.[199,203] Furthermore, self-healing methods can also integrate modularized parts together into a complex 3D structure, rendering more fabrication flexibility to the construction of soft robots.[74,203,204]

3.5.4. Surface Modification

Surface modification is an alternative for glue bonding of heterogeneous materials that are chemically incompatible. One of the representative surface modification techniques is to coat a thin layer (several micrometers) of nanoscale adhesive metal particles to the connecting interfaces of two parts. For instance, thin layers of Pd and Ti can be deposited to connect the gold electrode with the piezoelectric polyvinylidene difluoride (PVDF) films.[93,205] Another frequently utilized technique is grafting. Grafting agents should first be utilized for the surface treatment.[206,207] After the surface treatment, partially cured polymers are applied on the surface of grafted materials for total curation, finally leading to a strong bonding interface between the connecting materials. These strong bonds are covalent bonds that require high energy to be broken. Consequently, interfaces fabricated by this technique are capable of enduring high strain. Although the fabrication process of this technique is complicated, it can produce high performance and mechanically stable soft robots.[73]

3.5.5. Challenges and Opportunities

With the gradual evolution of soft robots, the number of multimaterial robots is increasing. The stable and firm connection between two materials becomes problematic. Loose connection is prone to delamination when a large shear force is applied, particularly in those connecting materials that have extremely disparate moduli. Mechanical mismatch of two parts will lead to possible mechanical failure in the interfaces that in turn results in the malfunction of soft robots. Although the existing techniques have achieved a large amount of reliable interfacial bonding of different materials, realizing robust bonding between materials with dramatically different physical and chemical properties is still challenging.[7] Investigation into the crack initiation and bond formation theories might be beneficial for the research of soft material bonding.

However, novel mechanisms also thrive. For instance, the ability to bond living organs with soft elastomer introduces new possibilities for the realization of soft robots actuated by living tissues.[208] Microscale soft robots actuated by magnetic field can be fabricated in a modularized manner and assembled/connected together by self-assembling.[209] Two neighboring parts in this study do not bond directly; rather, they are connected loosely by their attractive magnetic force. Furthermore, this self-assembly technique improves the fabrication resolution to the level of tens of micrometers. This connecting/bonding technique, which actually has been widespread in the molecular scale, may inspire more loosely bonding strategies for all levels of small soft robots. Soft robots are fabricated for achieving specific tasks. As long as the connecting force between two neighboring parts can endure the actuation of soft robots, strong interface bonding may not be necessary; such a field force bonding technique is a simple and effective bonding technique for small-scale robots.

3.6. Bioengineering

Biohybrid soft robots have excellent biocompatibility owing to the integration of artificial devices with living biosystems. It is noted that the application of bioengineering technologies is the reason behind this. In order to fully realize the potential of living beings, various bioengineered technologies have been utilized, including microscaled bacteria, living muscle tissues, and small-scaled living insects, Figure 3F.

3.6.1. Bacteria and Motile Cell Engineering

In nature, some bacteria (typically sized from 1 to 3 µm) have sustainable and automatic motility with high speed (with speed at least 100 body lengths s^{-1}). Owing to the unique athletic ability of these bacteria (such as *Escherichia coli*, *Serratia marcescens*, and *Salmonella typhimurium*), many research groups have bonded the synthetic cargos (such as imaging agents, genes, and drugs) with the bacteria to form microbacteria-driven microswimmers.[210,211] Various characteristics have been reported to attach the cargo with the bacteria, including hydrophobicity,[212] wettability,[213] bioconjugations (for example, biotin–streptavidin),[214,215] covalent binding (for example, carbodiimide cross-linking reaction),[216] and polyelectrolyte coatings.[217] Furthermore, the cargo can be rebonded or released in response to external environment changes, such as specific chemicals,[212] pH,[214,218] and UV light.[219,220] Actuated by the bacteria's flagella, these bacteria-driven microswimmers can efficiently swim using nutrients of the local microenvironment or inside the bacterial cell. In addition, microswimmers can also be externally guided and selectively delivered/deposited at the target sites via magnetic steering through either magnetic cargo units or natural magnetotactic bacteria.[221] For instance, Alapan et al. reported that bacteria-driven microswimmers used red blood cells rather than synthetic materials as autologous cargo carriers, offering notable advantages in stability, deformability, biocompatibility, and biodegradability.[214] These micro-biohybrid robots can squeeze through microchannels and release the available drugs at the precise location under the magnetic field steering. Sperm cells have also been widely utilized to fabricate biohybrid robots as they can automatically move without cultivation.[222,223] By encapsulating drugs into the head of the sperm, these microrobots can be guided by the external magnetic field to swim against flowing blood and release drugs at the tumor.[224] Furthermore, nanoparticle coating enables the localization of clusters of sperm cells via ultrasound feedback.[225]

Stem cell therapy has emerged as a promising method for restoring damaged tissues, cartilage, and organs. To precisely deliver stem cells at the defect site, magnetically actuated microrobots have been demonstrated. By direct coating of the magnetic nanoparticles on the surface of stem cells, Wang et al. precisely delivered the microrobots into the deep and narrow spaces inside the body with the image assistance of endoscopy.[95] In addition, the stem cells can also be encapsulated into a magnetic microscaffold and carried/fixed by the magnetic field steering at the target area.[226,227] The microscaffold has a biocompatible and biodegradable 3D porous structure, promoting cell penetration and nutrient exchange. Moreover, using 2PP 3D printing technology can fabricate diverse structures of the microscaffold, such as cylindrical, hexahedral, helical, and spherical. Jeon et al. optimized the structure of the microrobots and exhibited suitable rolling and corkscrew motions upon the application of a rotating magnetic field.[228]

3.6.2. Living Muscle Tissue Engineering

Living muscle tissues have many unique characteristics, such as softness, high-power density, and rapid response that are suitable for actuating soft robots. Based on manipulation by the tissue engineering, the living muscles can be integrated into the soft robotic system to achieve biohybrid robots. The most commonly used tissues of this type are cardiac and skeletal muscles.

The primary cardiac muscles can exhibit spontaneous and synchronous beating as long as glucose is available as an energy source.[229] The contractile force of a single cardiomyocyte (dimension of 100 µm × 100 µm × 10 µm) is measured as ≈10 µN,[230] that is higher than the same scale of synthetic actuators. These cardiac muscles are generally isolated from the ventricles of infant rats. Subsequently, they are implanted into artificial materials for 1–3 days of culturing, and generally reach stability.[231,232] In recent decades, many cardiomyocyte-powered soft robots have been demonstrated to achieve deformation,[233,234] walking,[235,236] swimming,[237] pumping,[238] and other operations. For example, Nawroth et al. reported a freely swimming jellyfish robot using the anisotropic tissue-engineered cardiac muscles, generating peak stresses of

10 mN mm^{-2} to actuate the PDMS membrane.[237] Zhao and co-workers assembled the bioengineered cardiomyocyte tissues on synthetic inverse opal hydrogel films. This living structure can change its volume and morphology with the cardiomyocyte contraction, leading to its color change.[231,239,240] Because cardiomyocytes present spontaneous contractions, difficulty in the controllability of soft biohybrid robots is encountered. In this case, optogenetics technology can express light-response proteins in living cardiac cells, controllable by light stimuli.[241] By patterning these optogenetically modified cardiomyocytes on an elastomeric body enclosing a microfabricated golden skeleton, Parker and co-workers reported a biohybrid robotic batoid fish.[96] By controlling the light frequency and position to stimulate the specific contraction of cardiomyocytes, this batoid fish can swim in the water ruling the predetermined trajectory. Moreover, they developed a muscular bilayer structure consisting of two types of tissue-engineered muscles expressing blue-light-sensitive (ChR2)[242] and red-light-sensitive (ChrismsonR)[243] ion channels, respectively. By leveraging the mechanoelectrical signaling of this bilayer construct, they developed an autonomously swimming biohybrid fish with feedback mechanisms for self-sustaining.[244] This self-driven spontaneous contraction enables the biohybrid fish to swim for extended periods (108 days, equivalent to 38 million beats).

Skeleton muscle tissues present suitable adaptability and precise controllability in biohybrid soft robots that can be stimulated by the external electrical or optical signals to switch from a rest state (off) to a contracted state (on). By fixing the engineered skeleton muscles on the flexible scaffold or joint, the biohybrid systems have potential applications in controllable crawling,[245–247] swimming,[248] and pumping.[249] In order to elongate the actuation times of skeleton muscles caused by their spontaneous shrinkage, Morimoto et al. presented a long lifetime (≈1 week) antagonistic structure consisting of a pair of alternate contraction skeleton muscles.[250] Apart from using external synthetic stimulation strategies, neuronal integration with skeletal muscle tissues provides a new synergistic control framework for biosystems. Aydin et al. developed a light-sensitive flagellar swimmer actuated by onboard neuromuscular units.[251] After the skeleton muscles were cultured in the PDMS scaffold, the photosensitive motor neurons (ChR2, derived from optogenetic mouse stems) were cocultured with the skeleton muscles and outgrowth neurite extension.

3.6.3. Insect Machine Engineering

Insects are the largest groups of animals on the planet, whose total number of extant species is estimated between six and ten million.[252] They can be found in nearly all environments, and their locomotion types mainly contain flight, walking, and swimming. Research on insect–machine hybrid robots integrating living insects with artificial devices has recently received widespread attention. By using the insect itself as the robot, researchers bypass the complex process of designing and fabricating various essential parts of robots, fully applying the muscular system and nervous system of the insects. This cyborg system exhibits suitable environmental adaptability and untethered control for locomotion, such as walking[253] and flying.[254] There are various insects suitable for small-scale biohybrid robots, including cockroaches,[253] beetle,[254] locusts,[97b] and moths.[255] In 1997, Holzer and Shimoyama presented the first walking insect–machine hybrid robot, using microelectrodes to directly stimulate the motor nerve of the live cockroach.[256] In order to improve the control precision of the hybrid robots, many researchers have developed various control algorithms to optimize the bioelectrical stimulation strategy.[257–259] As directly using electrodes to provide stimulus to the nerves will cause tissue damage, researchers have also presented a new strategy by applying the electrical signal to the antennae of the live insect for direction steering.[253,254]

3.6.4. Challenges and Opportunities

Bioengineering provides a promising fabrication method for small-scale biohybrid robots, fully reflecting the ingenious features of creatures (structures, nervous systems, and environment sensing). However, there are still some challenges. One is the limited working environment. Bioengineered cells, tissues, and creatures need specific environments to maintain biological activity, for example, temperature, pH, and nutrition. It is of immense significance to enhance the adaptability of biohybrid robots by using synthetic designs (for example, protection structures and materials). Furthermore, these biohybrid robots have low sustained working times (from several hours to days) that need to be integrated with continuous sources of nutrition or power for long-term operation.

Beyond the challenges facing the field, there are several additional promising avenues for the further development in bioengineering. Bioengineering can be combined with other techniques to enhance the functionality of biohybrid robots. Many techniques (such as 3D printing,[228] flexible sensing,[260] and artificial intelligence[259]) have been utilized and have been developed further. In addition, although the unique self-healing ability of biosystems remains to be developed, only few studies have been noted. The development of soft robots with bioengineered components is a growing and exciting area of research.

3.7. Origami/Kirigami

Originating from exquisite paper construction arts, origami and kirigami are conducted for fabricating subtle and complex planar and stereo structures with programmable morphologies and shapes.[261,262] The concept and strategy of origami and kirigami are well-developed for significantly contributing into theoretical geometry, architecture engineering, and folk custom. Inheriting from these traditional paper arts, origami and kirigami have been increasingly utilized for configuring morphological and topological structures of robotic body and bulk.[263–265] Being distinguished from bottom-up manufacturing techniques, origami and kirigami can be considered as top-down approaches that require a dimension-reduction (from 3D structures to 2D precursors) design and fabrication. Therefore, they possess a wide range of morphologies and constructions, along with outstanding mechanical and topological properties (Figure 3G).[266–269]

3.7.1. Origami

The configuring targets of origami are usually derived from biological tissue structures and functional organs,[270] existing architectures,[271] natural animals, and plants that demonstrate unique mechanical, electrical, and even optical properties. By geometric and mathematical computational designs, the complex 3D structures can be mainly reduced into 2D planar precursor with programmable and tunable hinges and joints. Targeting the figurate construction, sequential folding processes along the hinges are conducted for precisely fabricating origami robots via shape transformation.

The most common targeting structure is generally based on the nature-inspired morphologies, including those of crawling creatures such as invertebrates (for example, worms[272] and scolopendra) and vertebrates (for example, snakes) whose locomotion is mainly based on muscle and joint shrinking and mismatching; flying creatures feature with aerodynamic structural wings, such as self-folding earwig wing that is mimicked by synthetic spring origami with pronounced stiffness and fast-morphing programmability.[44] Additionally, the traditional origami works based on the folding of various types of paper, plastic sheets, and thin films inspire the development of high-performance structures with sophisticated mechanical properties,[271] tunable stiffness,[273,274] and transformable and reconfigurable constructions.[275] For fabrication methodologies, apart from directly folding following assembling, rapid fabrication techniques such as multimaterial printing (3D and 4D printing) are employed for fabricating the desired morphologies such as biomimetic constructions,[276] hierarchical structures,[277] and metamaterials.[278,279] Alternatively, laminated manufacturing approaches, such as photolithography, laser machining, transfer printing, pop-up, and other layer by layer assembling provide planar precursors that are synthesized by smart materials for spatially enabled out-of-plane structures. Based on these processing methods, various complex robotic systems have been utilized through structurally intelligent construction.

In tandem with smart functional materials such as dielectric elastomer, shape-memory alloys/polymers, and other stimuli-response materials, small-scale soft origami robots can be actuated by means of several triggers that include electric, magnetic, and thermal stimuli. The responsive or trigger-active materials not only enrich the selection and fabrication of soft bulk, but also provide reliable and effective ways to actuate and control the locomotion of robots. Furthermore, smart materials enabled by compliant intelligent structures also offer a feasible approach for establishing sensing circuits, thereby contributing to improved manipulation of origami robots.

3.7.2. Kirigami

Kirigami is another art of paper cutting that provides a new design strategy for developing deployable structures by programmable cutting notches at the joints. The integration of structures in traditional kirigami works inspires researchers to construct high-performance robotic bodies for shape morphing[174] and adaptive locomotion.[280] This contributes to a crucial and suitable application platform. Being different from the origami strategy, kirigami requires subtractive processing that refers to cutting notches on creased patterns. It not only avoids the disturbances among several intersecting creases, but also provides a novel buckling methodology on the condition of stretching, bending, or twisting.

Kirigami-designed structures show typical out-of-plane designs with a large degree of freedom owing to selective cutting and punching on planar, soft, and flexible sheets.[281] Therefore, the fabrication of kirigami-inspired precursor is diverse and adaptable, including physical engraving by a cutting plotter and chemical ablating via laser patterning. Following the lamination of different material sheets with various properties, the buckling kirigami robot bodies and skins are obtained with spatial mechanisms and preferred locomotion control that are crucial for precise tasks.[45,263,280,282–284] Alternatively, printing methods can also be employed for directly fabricating kirigami structures.[285] This kirigami paper cutting concept and strategy will not only offer new designs of static robotic bodies, but also encourage the investigation of reconfigurable robots with transformable shapes and metastructural and even intelligent mechanisms for medical, biomimetic, and industrial applications.[286]

In brief, kirigami strategy demonstrates suitable compatibility with other fabrication methodologies, and thus can be utilized in functional robotic bulk construction when introducing different functional materials that can be modularly laminated/integrated on planar precursor substrates; the key characteristics include the stiffness gradient, piezoelectricity, shape memory, and self-healing. Moreover, kirigami is also an elegant methodology to develop metastructures that can be optimized for 3D electronics in soft robot applications, such as human–machine interaction and robotic sensing and perception.

3.7.3. Challenges and Opportunities

Origami and kirigami provide a predictable bottom-up methodology for the design and fabrication of sophisticated 2D and 3D structures with compliant mechanism and intelligent engineering, regardless of the interactions among different composites that enable a customized and facile manipulation in a normal environment. These two strategies can guide not only the giant soft robots, but also microscale soft/flexible body fabrication, which is of great potential for making future small-scale soft robot. Nevertheless, challenges still remain pertaining to the exploration of these two strategies. Of particular, the current origami/kirigami-based research on soft robots mostly employs stiff substrate materials such as plastic, paper sheet, and circuit board that can be folded along creases; nonetheless, these materials are not sufficiently soft and stretchable in extreme unstructured environments. Although elastomers have been widely used in soft robotic body construction, it is challenging to fabricate foldable creases and thus conduct feasible origami process on elastomer bulk owing to the elasticity and stretchability of various elastomers. Therefore, it severely restricts the potential of the origami/kirigami elastomer. Moreover, the investigation of foldable soft-material-based creases is crucial for utilizing origami/kirigami with elastomeric materials or composite that may induce new features such as impact adsorption and mechanical adaptability. In addition, it is necessary to investigate and transplant more ingenious mechanics of folding (origami) and out-of-plane prototyping (kirigami) techniques, for example, taking experience on architecture consideration, bioinspired- and metastructures.

Origami is always conducted along with kirigami, an indispensable and effective guiding strategy for curved, complex, topological robotic geometry fabrication. In tandem with elastic and reversible creases, it will encourage the further development of the bistable and multistable mechanism that is of immense potential in diverse fields, including flexible and stretchable electronics, human–machine interaction, compliant mechanism, and soft robotics. In addition, based on physical and chemical interactions between spatial morphologies of different 3D complex structures, it is feasible to achieve high-performance self-locking constructions with customized triggers and thresholds. Origami and kirigami redefine how we design, fabricate, and use small-scale soft robots. These two strategies combine material computing, 2D to 3D mapping, and folding process, that could lead to various potential research directions in mathematics and mechanical and physical science.

3.8. Outlook

Although the above summarized approaches have presented diverse design principles and fabrication strategies on soft bodies along with the actuators of small-scale soft robots, the operating connection between different approaches should be enhanced to improve the versatility and integrity of soft body fabrication.[287] For instance, the origami and kirigami design inspired from natural living structures can be utilized in conjunction with modular assembly to achieve hierarchically heterogeneous biomimetic structures with high performances, in the presence of a robust and stable interface between heterogeneous multimaterials under large deformation.[266,282] In addition, 3D/4D printing was employed to modify the fluidic mixture marbles that facilitated integrating soft body with more features upon tuning the rheological properties of liquids.[288]

It is crucial to render soft robots functional and useful, rather than simply kinetic. Moreover, small-scale soft robots have shown immense potential for various applications, including exploration, medical surgery, and swarm tasks, owing to their miniature bodies. However, it is important yet challenging to integrate considerable functional units on/in limited soft bodies. Therefore, an "all in one" methodology based on the investigation methods of fabricating structures, actuations, and functionalities, has been pursed.

4. Functionalized Integration

Soft and compliant structure body and various actuation mechanisms enable the motion of small-scale robots, allowing them to move in various scenarios and accomplish specific tasks. However, to adapt to more complex environments and interact with highly dynamic scenarios, basic actuation/motion cannot aid in coping with such complex or dynamic situations. Therefore, function integration in small-scale robots is crucial for significantly improving their comprehensive capabilities. To further empower small-scale soft robots with rich function and ability, a plethora of integration techniques for functionalization have been developed during the past decades.[100,289–294] These functionalized integration techniques enable extensive previously inaccessible behaviors, for example, somatosensitive/proprioceptive actuation and environment perception and response (**Figure 4**A), self-control locomotion (Figure 4B), remote communication (Figure 4C), energy harvest/storage/manage and power transferring (Figure 4D), tunable stiffness (Figure 4E), reconfigurable architectures (Figure 4F), self-healing (Figure 4G), and biodegradable body.[59,75,295–298] Owing to the aforementioned properties and merits, functionalized small-scale robots also demonstrate various elegant applications. In this section, we highlight a few key advancements, challenges, and opportunities of functionalized integration techniques for small-scale soft robots. To simplify our discussion, we roughly classify the specific integration techniques into the following subcategories: molding/bonding, 3D printing, transfer printing, and swelling functionalizing (Figure 4H–K).

4.1. Molding/Bonding

Different from that in fabrication techniques, molding and bonding techniques are discussed together in that they are complementary techniques to integrate the functional part of soft robots into/onto different locations. Specifically, molding embeds the functional modules within the body of soft robots, whereas modules integrated by bonding usually adhere to the external surface of soft robots. Molding and bonding are both straightforward techniques to integrate soft robots with various functional modules. Generally, to ensure the stable integration of functional parts, molding is utilized to integrate functional parts. However, bonding ensures fast functionalization of robots. Because molding occasionally only shapes the contour of functional parts, bonding is frequently used as an auxiliary technique for the functionalization.[21,22,114,301]

4.1.1. Proprioception and Active Environment Sensing

Both proprioception and environment perception have been realized by sensing modules fabricated by molding and bonding. The integration position of the sensing parts varies relative to different perceptional targets. In order to maximally record the shape changing of soft robots, proprioceptive sensors are usually integrated within the parts that undergo large deformations when robots are actuated. For example, fluid chambers,[302] expanding surfaces of actuators,[303] are ideal integration positions. Particularly, there are a few occasions that indicate conflict with the principle. Thuruthel et al. have reported an array of proprioceptive strain sensors that are embedded on the upper surface of inextensible layer.[304] Because there are several sensors integrated for the simultaneous perception of deformation and obtained signals that are further analyzed by machine learning, these sensors are tailored into different shapes and embedded at different positions for distinct signals. Similarly, Meerbeek et al. also demonstrated a machine-learning-based optoelectronic sensor to monitor the

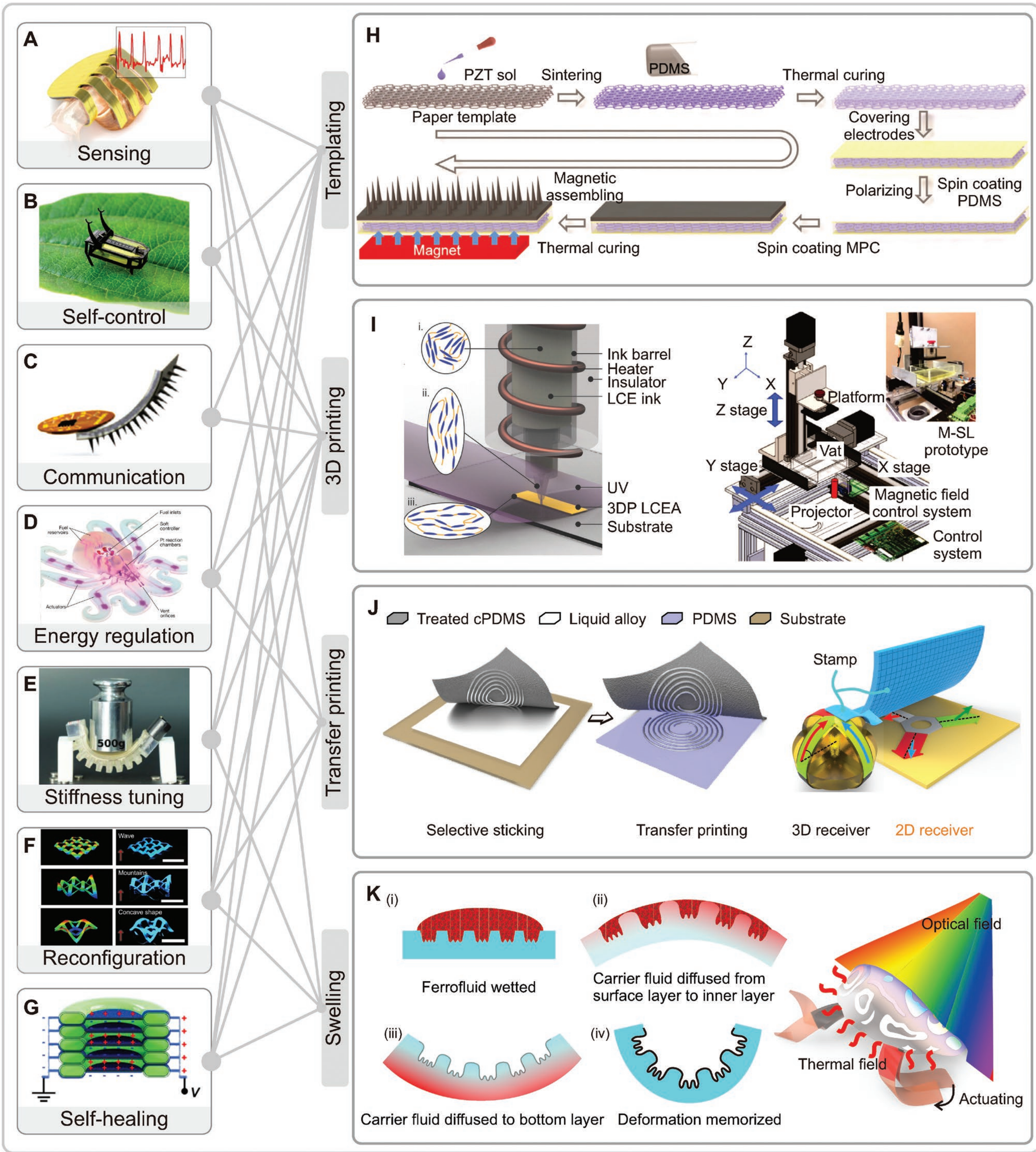

Figure 4. Typical functionalities for small-scale soft robots and corresponding function integration techniques: A) sensing, B) self computing/control, C) communication, D) energy harvesting/storage/regulation, E) stiffness tuning, F) reconfiguration, G) self-healing, H) templating, I) 3D printing, J) transfer printing, and K) swelling. A) Reproduced with permission.[299] Copyright 2021, The Authors, published by AAAS. B) Reproduced with permission.[24] Copyright 2020, The Authors, published by AAAS. C) Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (https://creativecommons.org/licenses/by/4.0).[75] Copyright 2020, The Authors, published by Wiley-VCH. D) Reproduced with permission.[22] Copyright 2016, Springer Nature. E) Reproduced with permission.[10] Copyright 2019, Wiley-VCH. F) Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (https://creativecommons.org/licenses/by/4.0).[69] Copyright 2020, The Authors, published by Springer Nature. G) Reproduced with permission.[73] Copyright 2018, The Authors, published by AAAS. H) Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (https://creativecommons.org/licenses/by/4.0).[75] Copyright 2020, The Authors, published by Wiley-VCH. I) Left: Reproduced with permission.[155b] Copyright 2018, Wiley-VCH. Right: Reproduced with permission.[300] Copyright 2022, Mary Ann Liebert, Inc. J) Left: Reproduced with permission.[349] Copyright 2019, ACS. Right: Reproduced with permission.[122] Copyright 2020, Elsevier. K) Reproduced with permission.[46] Copyright 2021, The Authors, published by AAAS.

deformation of a soft actuator.[305] The optic fibers that comprise the optoelectronic sensor are aligned uniformly as a layer using the soft lithography technique. These finely arranged fibers and the corresponding machine learning method finally result in a sensory system that can detect four deformation modes of soft robots.

Distinguished from proprioceptive sensors, environment sensors need to be exposed to external environments for improved sensory signals, and they tend to be integrated in inextensible parts to minimize the perturbance of deformation. For instance, pressure sensor and thermal-sensitive sensor fabricated by photolithography are integrated on the surface of inactive parts.[60] Active materials of a triboelectric nanogenerator are molded on both sides of a rigid skeleton to minimize the interference caused by the deformation of soft parts.[306] Typically, an actively perceiving and responsive soft robot has been fabricated by the combined technique of mold casting and drop coating.[307] Two sequential molding processes fabricate two soft parts, between which the silver-flake-based electrode is drop coated and encapsulated. This soft robot is able to achieve both proprioception and environment perception. However, because the signals resulted from body deformation and environment stimulation are coupled, it is difficult to practically distinguish them. Localized stiffness tuning technique that is used to template strain-insensitive sensors can be adopted for the integration of these soft robots.[308]

4.1.2. Calculation, Control, and Communications

Active interactive modules, such as signaling module, reconfiguration module, and computing module extend the functionalities of soft robots. The ability of realizing visual communication and disguise has been demonstrated by Morin et al.[114] and Larson et al.[21] The functional layers of these soft robots are first fabricated by soft lithography and then molded/bonded on the actuation part to serve as an active color-tunable skin. In terms of computation, digital logic gates are demonstrated based on conductive materials.[309] The elastic body of materials are first molded with channels to accommodate the conductive materials. Subsequently, the conductive prepolymer is filled within the channel for curation, finally forming a conductive metamaterial. Further, Garrad et al. have embedded logic gates into soft robots, demonstrating electrically reconfigurable soft robot.[301] The so-called soft matter computer is fabricated by successive molding and bonding techniques to ensure the correct positioning of electrodes and a stable connection. Embedded soft matter computer simplifies the structural complexity of reconfigurable soft robots, endowing soft robots with the capability to perform local computing. Without local computing capability, however, a more sophisticated templating process needs to be conducted to fabricate a reconfigurable soft robot.[310]

4.1.3. Energy Regulation

Rational energy regulation is a necessity for long-term and sustainable actuation of untethered robots. Compact energy regulation module for small-scale robots is reported to be fabricated by soft lithography molding and bonding techniques.[22] This entirely soft controller provides continuous energy input for the actuation of the deformation of soft robots for 10 min. Delicate microscale channels regulate the fluid flow accurately, indicating that lithography might be a promising fabrication technique for precise energy control.

4.1.4. Challenges and Opportunities

Although various functional parts integrated by templating have been demonstrated, more functionalities are further required to systematically develop a soft robot. Sensing, signaling, and responding constitute a complete interactive loop for soft robots. However, current templating techniques still fail to integrate all these functionalities together, especially for small-scale soft robots. The fabrication method of a jig-assisted 3D fabricated can be adopted to integrate these functional parts and improve the integration resolution to the level of sub-millimeter scales.[104] Moreover, despite the ability of the structure of soft robots to physically adapt to diverse external stimuli, more interactive responses require active control of the soft robots that pose a high demand for the computation modules. Unfavorably, the existing computation is in a primitive state that is only capable of simple logical computation; scaling down these computing modules is almost impossible at present. Therefore, some soft robots directly bond traditional rigid circuit board for signal processing and wireless communications.[75] However, it is remarkable that traditional photolithography is revolutionizing the field of soft chips. With the edge-cutting technique of soft material photolithography, millimeter-scale complex logic circuits are realized,[311] which might be molded within the soft robots to further advance the computing modules of soft robots.

4.2. 3D Printing

As a convenient, speedy fabrication technology, 3D printing can not only be used for printing soft robotic structures, but also is suitable for functional integration. In the past few years, the printing ability of all-printed robots has been demonstrated through the integration of various functional parts (for example, sensing, computing, and stiffness-tunable) into the soft robots directly.

4.2.1. Sensing

Fabricating flexible embedded sensors without impacting mechanical performance is crucial in soft robotics. Using 3D printing technology, various flexible sensors, including resistive and capacitive sensors,[312–317] pressure sensors,[318–320] and optoelectronic sensors[321–323] can be realized. Among them, resistive and capacitive sensors are the most prevalent that detect the variation of the electrical signals during the strain and deformation of soft conductive structures. Using DLP and DIW printing techniques, flexible conductive electrodes (such as ionic hydrogels,[312] elastomer composites of carbon nanotubes,[304] carbon black,[313] and metal particles[314]) can be fabricated. Furthermore, liquid metal (for example, EGaIn or Galinstan) can be directly deposited or injected into the elastomer by DIW as the embedded circuit for stretchable resistive sensors[315,316] that can reach a significant elongation (over 400% strain).[317] Soft optical sensors leverage high-precision, low-hysteresis flexible waveguides for the reflection of the optical signals internally, demonstrating low hysteresis and high precision. The soft and stretchable elastomer optical fibers can be readily fabricated using FDM printers.[321] Furthermore, the optical fiber and the cladding layer can be simultaneously printed using core–shell DIW.[324] By integrating the optical sensors into the soft robotic systems, various types of deformation (such as bending, stretching, and pressing) can be detected.[325]

4.2.2. Computing

In order to replace the rigid onboard electrical controller, which could influence the deformation of the soft robots, fully soft computing systems are under study. Using 3D printing technology, researchers presented pneumatic/hydraulic logic systems embedded into the soft robots. For example, Drotman et al. used the FDM printer to fabricate the pneumatic circuits consisting of logic components (soft valves and oscillators).[326] Furthermore, Hubbard et al. presented a fully 3D-printed soft robot with integrated fluidic logic controllers.[155a] This innovative design achieves various soft physic logical elements (similar to electronic devices such as transistors, diodes, and one type of the transistors) that can be directly embedded into the soft robot.

Moreover, compliant structures and metamaterials also can be utilized in mechanical computing. For example, the FDM-printed structures with bistable flexure mechanisms can be assembled as the logic systems to achieve the functionality of mechanical computation.[327–329] Some complex metamaterials (2D to 3D) structures can also be fabricated by 3D printing and can respond to the external input.[330–332] In summary, 3D printing provides a promising paradigm for realizing the whole process from design to fabrication and enables topologic optimization.

4.2.3. Stiffness Tuning

Soft robots have the appealing advantage of being highly flexible and compliant to complex environments. However, low-stiffness materials restrict the soft robotics system's application in tasks requiring relatively high load capacity. To realize the stiffness tuning of soft robots in diverse scenarios, many efforts have been made to embed stiffness-tunable materials or structures (such as low-melt-point alloys[10]), thermoplastic polymers,[333,334] and jamming structures[335] in 3D-printed soft robotic systems. Thermoplastic polymers (for example, poly(lactic acid) (PLA)) can be gradually softened during heating. Thus, many researchers reported stiffness-tunable soft grippers embedded with variable stiffness modules, consisting of 3D-printed PLA layers and heating electrodes.[333,334] These soft grippers can achieve variable stiffnesses in whole or in part by controlling the specific heating areas. Although such a design can achieve about 18-fold stiffness tuning, the stiffness of the softened PLA layer after heating is still much high for the soft robots. Low-melt-point alloy, which can be melted to fluid, offers another solution for broad range stiffness tuning of soft robots. Zhang et al. reported a 120 times stiffness-tunable 3D-printed gripper integrated with the low-melt-point alloy, which can rapidly switch the liquid and solid-state under Joule heating and water cooling.[10] Laminar jamming structures can reach rapid stiffness tuning under the vacuum or electric field control. Soft robotic systems can be easily controlled to achieve variable stiffness change by integrating the jamming structures in soft grippers or bodies.[336–338]

4.2.4. Challenges and Opportunities

Despite the promising developments in the fabrication of various function parts, only a few works presented one-step integrated printing. Most of the printed function parts require secondary processing (such as bonding or assembling) to be integrated with soft robots, and it reduces the reliability of robotic systems. In addition, the intelligence level of physical computing is still at the primary stage and remains to be further optimized. Although some challenges exist, the feasibility of fully integrated 3D-printed soft robots is evident. The future goal in this field has the potential to develop all-printed soft robots that can directly integrate multifunction parts, without the need to attach wiring or assemble parts. In that case, every part of the soft robot, including actuators, controls, and power sources, can be printed using a single, on-demand 3D printer.

4.3. Transfer Printing

An increasing number of technologies require large-scale integration of disparate classes of separately fabricated objects into spatially organized, functional systems. Transfer printing is a set of techniques for 2D and 3D spatial rearrangement of various material or functional parts from a donor to a receiver. As a versatile platform technology, it offers a useful, yet flexible tool for fabricating a high-performance, heterogeneously integrated functional system at a relatively low cost.

During the transfer process, the energy release rate tuning between different interfaces (stamp and transferred objects, transferred objects and donor, and transferred objects and receiver) is critical for successful implementation. To address this, various approaches were proposed.[339,340] Presently, the utilization of transfer printing techniques for small-scale soft robot function integration is relatively uncommon, but it is a potential function integration technique. To systematically discuss this technique, in this section, the methods have been classified according to their fundamental principles.

4.3.1. Kinetical Controlled Transfer Printing

Based on kinetically controlled switching between adhesion and release of transferred objects to and from an elastomeric stamp, some facile transfer printing methods have been proposed. Typically, Rogers and co-workers developed a transfer printing technique based on the kinetic control of adhesion to an elastomeric stamp.[341] Contacting a soft elastomeric stamp against these transferred objects leads to conformal contact, driven by generalized adhesion forces that are typically dominated by van der Waals interactions. The adhesion between the transferred objects and the stamp is rate-sensitive (that is, kinetically controllable) owing to the viscoelastic behavior of the elastomer. In this case, pulling the stamp away from the donor substrate with sufficiently high peel velocity leads to adhesion that is sufficiently strong to adhere, preferentially the transferred objects to the surface of the stamp, lifting them away from the substrate. The stamp, "inked" with these transferred objects, is brought into contact with a receiving (device/robot) substrate. Removing the stamp with sufficiently low peel velocity causes these transferred objects to adhere preferentially to the device/robot substrate and to separate from the stamp. The transfer can be performed uniformly with a flat stamp or with a structured element that contacts and transfers only a particular set of transferred objects from the donor substrate. The physics that governs the kinetic dependence of the adhesion process has its origin in the viscoelastic response of the elastomeric stamp.

4.3.2. Microstructure-Based Transfer Printing

To guarantee the successful implementation of the transfer printing, various microstructure-based approaches were developed. Several modalities of transfer printing can improve the ability to modulate the adhesion through the use of microstructured stamps,[342] enhanced adhesion with pedestal-shaped elastomeric stamps,[343] pressure-controlled contact area,[344] and angled relief structures.[345] In each case, to guarantee the transfer printing process, the key goals include strong adhesion when the stamp retrieves an ink from a donor substrate and weak adhesion when it releases the ink onto a target substrate. To achieve this goal, these transfer printing methods will also synergistically couple with other strategies, such as the aforementioned kinematic dominated methods and the shear-assisted methods.[346]

4.3.3. Triggered Transfer Printing

To achieve on-demand picking up and printing, several triggered transfer printing methods were developed by introducing laser, magnetic field, and vacuum. The adhesion between the stamps and transferred objects can be controlled on demand by the trigger of the external stimulus. Ferreira and co-workers reported on a laser-driven micro-transfer-placement process that leverages, instead of ablation, the mismatch in thermomechanical response at the interface of a transferable microstructure and a transfer tool to a laser pulse to drive the release of the microstructure from the transfer tool and its transportation to a receiving substrate.[347] In addition, Song and co-workers developed a simple yet robust magnetically actuated, aphid-inspired design of an elastomeric surface that provides rapid tunable and high reversible adhesion strength.[348] The magnetically actuated adhesive features open reservoirs filled with magnetic particles and encapsulated by a thin surface membrane that can be deformed in a controlled manner via the magnetic field, thus, to tune the adhesion. The combination of the rate dependent effect and magnetic actuation of the thin surface membrane offers continuously tunable adhesion with an effective switchability and a swift response. By introducing various trigger mechanisms to tune the adhesion of stamps on demand enables broader operation windows for transfer printing different transferred objects.

4.3.4. Laser-Tuned Selective Transfer Printing

In addition to the aforementioned methods, by introducing laser selective surface morphology tuning, various facile and elegant selective transfer printing techniques were developed for liquid alloy printing or heterogenous cell transfer printing. For example, by tuning the wettability of liquid alloy on a soft substrate through a selective surface morphology modification, Wu and co-workers presented a flexography printing technique of liquid alloy circuits on both planar and 3D complex surfaces. This technique was enabled by the systematical investigation of the tuning mechanism and the relation between liquid alloy wettability and surface morphology modification.[349] Recently, a more precise selective heterogeneous integrated transfer printing technique was developed. By introducing the influence of the laser to the surface morphologies and its adhesion of the stamp and transferred objects, Ke et al. proposed a laser tuning selective-transfer-printing-based heterogeneous integration technique.[122] This method enables selective adhesive transfer printing of modularized heterogeneous cells (for example, preanisotropic magnetized ferromagnetic and other functional cells). Leveraging this method, the researchers realized various types of soft magnetic robots, including 2D/3D-shaped, 2D/3D-magnetized, heterogeneous responsive, multifield responsive, environmentally perceptive, and multifunction integrated robots, and even those with functional updating, repairing, and recombination of daughter robots enabled. Compared with width-based selective transfer printing method,[350] this method provides a broader operational window for the heterogeneous integration of various functional parts.

4.3.5. Hydroprinting

A gentle fabrication process is critical to enable the adaption of compliant electronic systems to the highly dynamic situation. A hydroprinting technique was developed by Jiang et al. to address the challenge of integration of compliant electronic systems on an unstructured object.[351] Specifically, a prepatterned liquid alloy circuit on a water-soluble poly(vinyl alcohol) (PVA) film is placed on the surface of water and subsequently swollen to obtain a layer of soft and viscous PVA gel. Thereafter, by hydroprinting, such a prepatterned liquid alloy allow can be transfer-printed on arbitrary objects (even for gentle plants). Such a hydroprinting technique enables various previously inaccessible liquid alloy integrations on various complex objects.

4.3.6. Challenges and Opportunities

Despite the intensive progress in transfer printing and its influence on the function integration of small-scale soft robots, there are still some challenges, for example, the transfer printing technique is a skin empowerment technique that enables the integration of the functional part on the surface of the soft actuation body in most cases. In addition, the transferred ink/objects depend on the transfer methods, and transfer printing techniques are not applicable for all the ink/objects. These constraints limit its universality.

The advances of transfer printing enable relatively broad applications; the ease with which most of these techniques can be implemented with high throughput and engineering control suggests their applicability not only in basic scientific studies and engineering prototyping, but also in volume manufacturing. From the results of current transfer printing technologies, the size of transferred objects can cover from sub-micrometers to centimeters. This technique is more suitable and effective for the integration of small-scale soft robots. Although not many transfer printing techniques have been utilized in function integration of small-scale robots, it is still a potential and promising technique. With the introduction of such a technique, it can realize the integration of mass function by the deterministic assembly of micro- and nanomaterials into organized, functional arrangements with 2D and 3D layouts.

4.4. Swelling Functionalizing

As stated in Section 3, swelling is a potential approach for the development of soft and compliant bulk for soft robots via programmable and localized buckling. During solvent penetration and diffusion, it is possible to infuse active particles and molecules into the expanded bulk. Therefore, this process provides effective functionality endowment during shape morphing. Current works have presented various soft and compliant structures for multilocomotion, including crawling, rolling, turning, and jumping, that act as the actuated bulk in soft robots.

4.4.1. Perceptibility Integration

Active and passive sensibility is of immense importance nowadays for advanced and intelligent robots because it can offer timely response and feedback that can enable the precise operation and control of soft robots. Swelling is a potential approach to introducing additional stimuli-responsive materials into the soft matter bulk. By combining the selective surface morphology tuning and active-particle-infused solvent swelling, Zhang et al. proposed a programmable and reprocessable method to seamlessly integrate reconfigurable passive-sensing layers on the surface using ferromagnetic, photochromic, or thermochromic nanopowders.[46] Such a swelling method endows the soft robot with not only switchable actuation locomotion, but also environmental stimuli passive-sensing abilities that enhances the multifunctionality of the robot and inspires biomimetic feature designing. Alternatively, anisotropic swelling behavior of hydrogel–carbon nanotube composites contributes to a flexible liquid sensor, enabling bidirectional monitor and detection of the liquid leakage.[352] This swelling liquid sensor design offers a distinctive perspective on the accurate position and direction of soft robots in diverse liquid environments. Swelling can be used to integrate tactile sensing layer as well. Benefiting from being swollen in organic solvents, the buckled carbon-nanotube-embedded elastomeric substrate provides an out-of-plane serpentine surface for configuring the strain-sensitive sensor[353] for detecting deformation, induced by interaction with the external environment. In addition, the sensing and reaction to the external temperature, pH, and chemical substances are realized based on the corresponding swelling-integrated stimulus-sensitive materials.

4.4.2. Computing and Communication Ability Integration

Because the mismatched stiffness causes unstable interface under deformation, it is still a significant challenge to the integration of logic-based rigid electronic chips on the soft bodies of soft robots. To address this, researchers used various stimuli-responsive hydrogels as building blocks to configure the diverse logic gates, including YES, NOT, XOR, AND, OR, NOR, and NAND, realizing a conventional size change.[354] Such a design strategy paves a new approach toward the integration of on-board computing and communication capabilities into small-scale soft robots and machines. Favorably, swelling is an effective approach for the construction of shape-controllable and material-integratable structures based on the bistable and multistable compliant mechanism that affords potential application in transformable logic modules.

4.4.3. Energy Regulation

Energy and power source is crucial for the actuation, locomotion, and task assignment of soft robots. Benefiting from the shape change induced by swelling, it causes a snap-through buckling behavior. Transient shape changes during drying induce a mechanism constraint and an internal diving force for snap-through buckling that has been utilized for developing autonomous snapping and jumping polymer gels.[102] This swelling design mechanism inspires researchers to integrate high power density output into jumping organisms and soft engineered robots.

4.4.4. Challenges and Opportunities

Although it is common to apply shape change and morphing during swelling, there still remain challenges. First, the swelling process is continuous and isotropic that may result in a random functional particle infusion and an uncontrollable doping and function integration. Such a result is insufficient for high-precision and accurate robot sensing and feedback. Second, a suitable and effective swelling process requires suitable and compatible soft-material–solvent system involving material characterization, chemical mechanism, and mechanics. There is scope for further investigation in this regard. Nonetheless, this swelling fabrication scheme provides a platform for producing soft robots with programmable and reprocessable shapes, actuation, and sensing. This scheme offers a rapid, flexible tool for seamless integrating of multiple materials simultaneously into soft robots, thereby laying a solid foundation for the development of multifunctional/high-intelligence robots.

4.5. Challenges and Opportunities

Despite the extensive research on techniques for functionalized integration in small-scale soft robots, it is still at an early stage, and the existing challenges and opportunities still remain to be investigated further. Functionalized integration in the current stage is relatively simple and only a few of small-scale robots are at the system-level. Consequently, its performance is far comparable with their biological counterparts and further practical applications are difficult. Therefore, further efforts should be made to develop more advanced integration techniques for highly integrated, function synergistic, system-level small-scale robots, particularly the all-in-one techniques. It is also expected that biological intelligence can be realized by sophisticatedly codesigned structures and functions of robots.

5. Discussion and Perspectives

As summarized in **Table 1**, we contrast different techniques from aspects of approximate resolution, fabrication dimension, materials, material stiffness, processing efficiency, cost, and learning curve. Such a quantitative result not only clearly suggests the advantages and shortcoming of discussed methodologies or strategies, but also holds the direction of small-scale soft robot fabrication and functional integration. During the past few years, to realize various behaviors, different fabrication and integration methods have been proposed and developed for small-scale soft robots in the millimeter to centimeter scale.[262,289] However, there remains numerous challenges ahead for these small-scale robots to be widely adopted as valuable commercial products, and further recognized as powerful tools in practical applications. Of particular, the materials introduced in small-scale robot are not smart like the biological "cell or tissue," which limits their function and potential in terms of microscale. Apart of this, current structures and actuation mechanisms are not optimized for biological equivalence and efficiency, hence leading to a quite ordinary performance and not sufficient to handle a lot of harsh tasks.[12] Moreover, the limited multifunction integration density and system-level integration in small-scale robots are also not sufficient to support the expected elegant behaviors. In addition, at the current stage, physical intelligence and more advanced intelligence are rarely introduced in small-scale robots.[80] These challenges dramatically limit their performances and behaviors in practical applications.

In the near future, advances in the field will begin to yield new consuming, healthcare, environment exploration, and industrial technologies that will have a transformative impact on how we interact with small-scale robots. Such advancements will require continued efforts and progress in the fabrication and integration techniques. For the advances of the small-scale soft robots, future fabrication/integration technologies on small-scale robots need to consider a lot of factors and aspects.

1) All-in-one fabrication and integration technologies are preferable for more stable mechanical interface and lower fabrication cost. For this goal, 3D printing will be a promising fabrication and integration techniques for simultaneously achieving fabrication of main actuation body and function integration. Therefore, it will be significant and meaningful to further develop the all-in-one 3D printing techniques and develop more matched printed inks toward small-scale soft robots.
2) Transfer printing is a set of techniques for 2D and 3D spatial rearrangement of various material or functional parts from a donor to a receiver. As a versatile platform technology, it offers a useful, yet flexible tool for fabricating a high-performance, heterogeneously integrated functional system at a relatively low cost. This technology is promising to be employed for constructing both actuation bulk and functional skin of small-scale soft robots in the future, although it is not widely used at the current stage.
3) Swelling is a potential approach for the development of soft and compliant bulk for soft robots via programmable and localized buckling. During solvent penetration and diffusion, it is possible to infuse active particles and molecules into the expanded bulk. By introducing new controllable competition mechanisms, this method may enable a plethora of new elegant and effective fabrication and functionalization strategies for small-scale robots.
4) The rapid development of advanced bioengineering may potentially enable a plethora of biohybrid soft robots by integrating artificial living tissue, to really realize creature-like robots/insect cyborg. Therefore, the development of small-scale soft robots with bioengineered components will be a growing and exciting area of research.
5) To significantly advance this field, for various fabrication and integration technologies, it is critical to codesign every aspect including materials, structure, actuation, function, and intelligence.

Being an interdisciplinary area, in the foreseeable future, the advancements from other fields will also be introduced in this domain. With collaborations of diverse research communities, small-scale robots can be codesigned sophisticatedly and be rapidly implemented with more advanced fabrication and integration techniques. As shown in **Figure 5**, those fabrication and integration techniques can be combined together to empower those small-scale soft robots with bionic-level materials, structures, actuation, function, and even intelligence, hence potentially rendering them biological equivalence and even afford abilities more effective than the typical functionalities in order to deal with complex situations. They can be potentially applied in many important domains; here, we divide them into four typical cases according to the existing literatures: i) biomedical applications, such as minimally invasive robotic surgery in hematologic system and targeted drug delivery in stomach,[369] ii) environment and confined/risky space exploration, such as rescuing, planetary exploration, deep sea exploration, ecological

Table 1. The contrast of different techniques from aspects of approximate resolution, fabrication dimension, materials, materials stiffness, processing efficiency, cost, and learning curve.

Techniques Category	Subcategory	Approximate resolution	Fabrication dimension	Materials	Material stiffness	Processing efficiency	Processing cost	Learning curve
Templating	Casting	<200 μm	3D	Elastomers[35,81,102]	10 kPa–10 MPa[35]	★★★	★	★
	Lithography (P for photolithography, S for soft lithography)	<1 μm[49,110] (P) >1 nm[355–357] (S)	2D (P)/3D (S)	Metals[49,112] (P) and polymers[49,110,355–357] (P and S)	10 kPa–100 GPa	★	★★★	★★★
	Coating	1–100 μm in thickness	3D	Various viscous materials (PDMS,[123] magnetic particle composite,[75] poly(3,4-ethylenedioxythiophene)-polystyrene sulfonate (PEDOT:PSS),[124] liquid crystal elastomer,[125] etc.)	1 MPa–1 GPa	★★	★	★★
3D/4D printing	FDM	100–400 μm[358]	3D	Thermoplastic (filament)[130]	$E > 26$ MPa	★	★★	★
	DIW	1–100 μm[152]	3D	Viscoelastic liquid ink	$E < 1$ MPa[321]	★	★★	★
	Photocuring	100 nm–100 μm[359,360]	3D	Photocuring resin	–	★★★	★★★	★
	Material jetting	10–100 μm[359,360]	3D	Liquid resin	1 MPa–1 GPa[99,361]	★★	★★★	★
Laser machining	Laser cutting	10–100 μm	2D	Polymers (Ecoflex-based material,[55] shape-memory polymer[299])	10 kPa–10 MPa	★★★	★★	★
	Laser engraving and welding	10–100 μm	2D	Laser-absorbable materials (e.g., carbon-doped PDMS[89]), thermoplastic polymers (e.g., thermoplastic polyurethane[156])	1–100 MPa	★★★	★★	★
	Laser surface tuning	10–20 μm	2D	Laser-absorbable materials (e.g., carbon-doped PDMS[46])	1–10 MPa	★★★	★★	★
Swelling	Hydrogel-based robotic bulk	>5 mm[160,362]	3D	Hydrogel	10 kPa–10 MPa[164,165,363]	★★	★★	★
	Silicone rubber robotic bulk	>5 mm	3D	Silicone rubber	10 kPa–1 MPa	★★	★★	★
Bonding	Glue bonding	<100 μm	3D	Polymers[91,185]	20 kPa–200 GPa	★	★	★
	Thermal bonding	<100 μm	2D	Thermal plastic polymers (e.g., thermoplastic polyurethane[186]) or materials modified by thermal plastic polymers[187]	1 MPa–100 GPa	★★	★	★
	Self-healing	<100 nm	3D	Self-healing polymers[196,364]	100 kPa–100 MPa	★	★	★
	Surface modifying	<100 nm	3D	Between hydrogels and elastomers[206] Between hydrogels and metals[207] Between polymers and metals[93,205]	10 kPa–100 GPa	★	★★	★★
Bioengineering	Bacteria and motile cells	1–3 μm[365]	2D/3D	Bacteria and cells	1–20 Pa[366]	★	★★★	★★★
	Living muscle tissues	2–20 mm[248]	2D/3D	Cardiac and skeletal muscles	–	★	★★★	★★★
	Insects–machines	30–50 mm[253,254,260]	3D	Living insect	–	★	★★	★★
Origami/kirigami	Origami	1–100 μm	3D	Hydrogels,[165] elastomers,[46] plastics,[98b] papers,[264] metals[49,112]	1 MPa–100 GPa	★	★	★★★
	Kirigami	1–100 μm	3D	Papers,[264] plastics,[88] liquid crystal elastomers,[367] composites[368]	1 MPa–100 GPa	★	★	★★★
Transfer printing	Kinetical controlled transfer printing	>0.3 μm[341]	2D/3D	Elastomer, copper[350]	–	★★★	★	★
	Laser-tuned selective transfer printing	30–500 μm	2D	Liquid alloy,[12] elastomer[122]	Liquid or 10 kPa–1 MPa elastomer	★★★	★	★
	Hydroprinting	>70 μm	2D	Liquid alloy[351]	Liquid	★★★	★	★

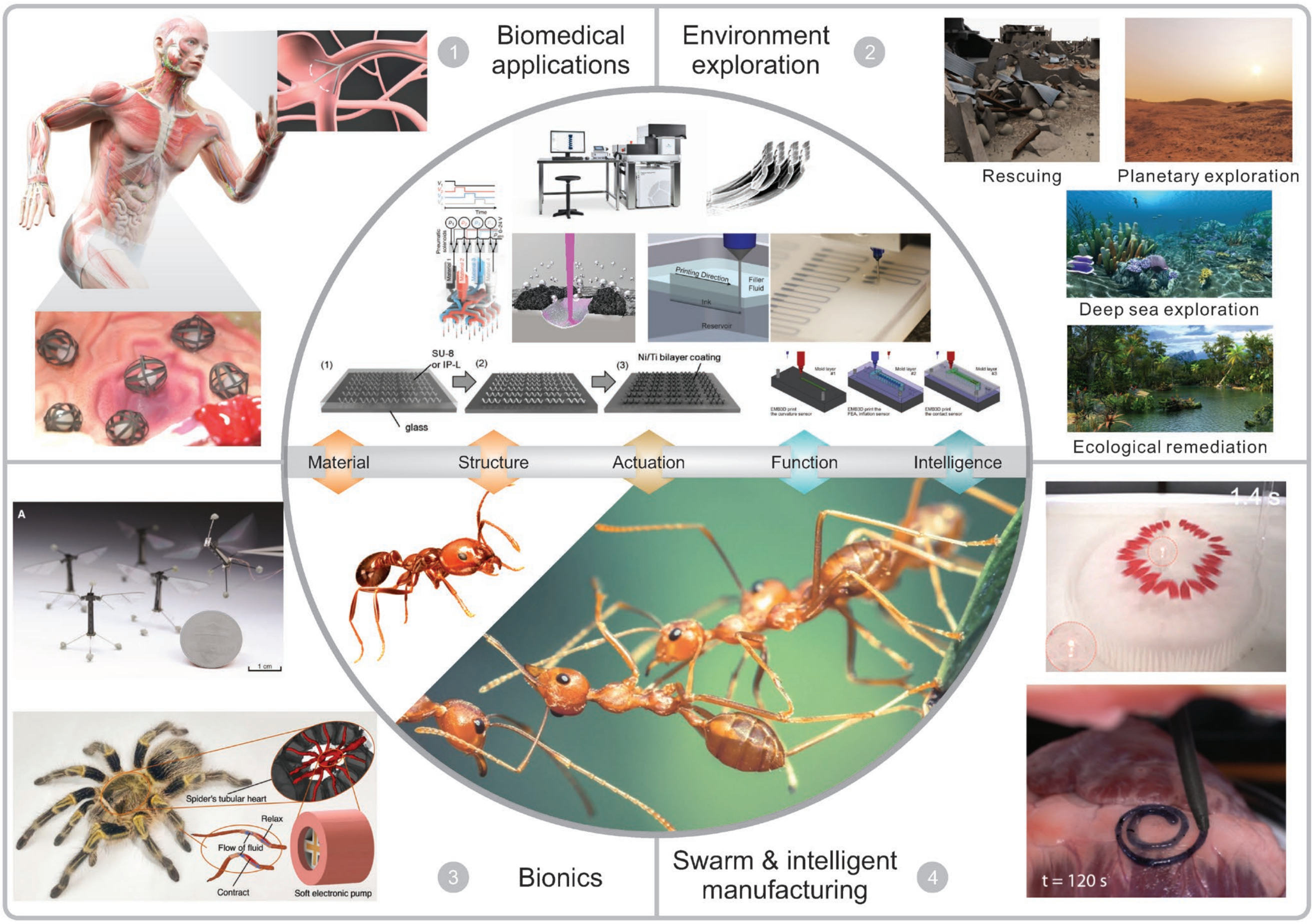

Figure 5. Perspective: Advanced fabrication and integration techniques empower small-scale robots with bionic-level material, structure, actuation, function, and intelligence that enable wide-scale applications in various scenarios, such as medical applications, unstructured environment exploration and rescue, bionic research, and swarm and intelligent manufacturing. Fabrication and integration techniques. Middle figure: second row, first panel: Reproduced with permission.[372] Copyright 2019, The Authors, published by Springer Nature. Second row, second panel: Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (https://creativecommons.org/licenses/by/4.0).[373] Copyright 2020, The Authors, published by MDPI. Second row; third and fourth panels: Reproduced with permission.[374] Copyright 2014, Wiley-VCH. Third row, first panel: Reproduced with permission.[375] Copyright 2012, Wiley-VCH. Third row, second panel: Reproduced with permission.[61] Copyright 2018, Wiley-VCH. Biomedical applications. Top right: Reproduced with permission.[369] Copyright 2019, The Authors, published by AAAS. Bottom: Reproduced with permission.[122] Copyright 2020, Elsevier. Bionics. Top: Reproduced with permission.[376] Copyright 2013, AAAS. Bottom: Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (https://creativecommons.org/licenses/by/4.0).[72] Copyright 2021, The Authors, published by Springer Nature. Swarm and intelligent manufacturing. Top: Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (https://creativecommons.org/licenses/by/4.0).[53] Copyright 2019, The Authors, published by Oxford University Press on behalf of China Science Publishing & Media Ltd. Bottom: Reproduced with permission.[371] Copyright 2021, Springer Nature.

remediation, turbine internal inspection, nearly invisible battle field spying/navigation, and task implementation, iii) bionics, such as, bioinspired design and insect robots,[370] and iv) swarm and intelligent manufacturing, such as in situ multi-machine-cooperated intelligent manufacturing.[76,371] In tandem with feasible fabrication and integration technologies, small-scale soft robots have a significant impact in the field of soft robotics and facilitate various applications.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

all-in-one fabrication strategies, codesign, fabrication/integration technologies, multifunctional soft robots, small-scale soft robots

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