microcatheter with a diameter of 0.1 mm carrying magnetic sensor and electrically actuated gripper was developed by Rivkin et al. via the self-rolling method [90]. The fabricated microcatheter exhibited the locomotion capability in a thin curved channel (only 0.2 mm diameter), and the fluid delivery function in the stomach and esophagus of mouse. The end of the catheter is integrated with a conductive polymer film actuated microgripper, which could capture 0.1 mm particles in a tube. In addition, the magnetic sensor based on the anisotropic magnetoresistive effect in the microcatheter could execute *in vivo* localization and navigation with a resolution of 0.1 mm. Han et al. proposed the integration strategy of multilayer configurations of soft electronic arrays and actuators on commercialized endocardial balloon catheters [89]. The integrated flexible electronic arrays include a pressure sensor array, a temperature sensor array, and an electrode array with electrical stimulation and electrophysiology measurement functions, and are capable of withstanding 10 000 cycles of uniaxial stretching, the deflation and inflation of the balloon on the catheter. Irreversible electroporation and programmable radiofrequency ablation for the treatment of arrhythmias could be achieved by the selective powering of electrode arrays. Moreover, ventricular action can be simultaneously monitored by the integrated pressure sensors for surgical improvement.

Wirelessly actuated microrobots have been widely adopted for minimally invasive surgery, e.g. targeted drug and cell delivery. To execute the delivery function, therapeutic units need to be integrated into the robotic system. For instance, Zhang et al. proposed a magnetic anchoring device with a 3D lattice shape equipped with TPP printed cell cages [24]. The fabricated anchoring device could shrink and restore its radial dimension upon magnetic stimulation and stem cells can be carried by the cell cage as a cell scaffold. After reaching the targeted position, the proliferation, migration, and differentiation of stem cells would be performed to achieve treatment functions such as vascular regeneration. The separation and retrieval of the robotic body from the therapeutic units is a key issue for the practical application of miniature robots to avoid the adverse impact of the robotic body. In this respect, a multifunctional magnetic soft robot was developed by Dong et al. (Figure 1.3a) [25]. Magnetic components with 3D heterogeneous magnetization profiles and a therapy patch for gastric ulcer treatment were integrated into the robotic system by an adhesive sticker network. The connection between the therapy patch and the robotic body was realized by a soluble tape. The robot body wrapped the therapy patch to avoid contact with gastric fluids during the movement. After reaching a gastric ulcer position, the release of the therapy patch was performed by the dissolution of the soluble tape in the gastric mucosa.

1.4.2 Environmental and Proprioceptive Sensing

Natural organisms could exhibit sensing and adaption functions to the physical environment with developed intelligence. To mimic the intelligence of biological systems, various robotic systems with embedded perception and sensing capabilities have been developed, enabling the closed-loop control of deformation and locomotion (Figure 1.3b). For example, a magnetic soft robotic system with

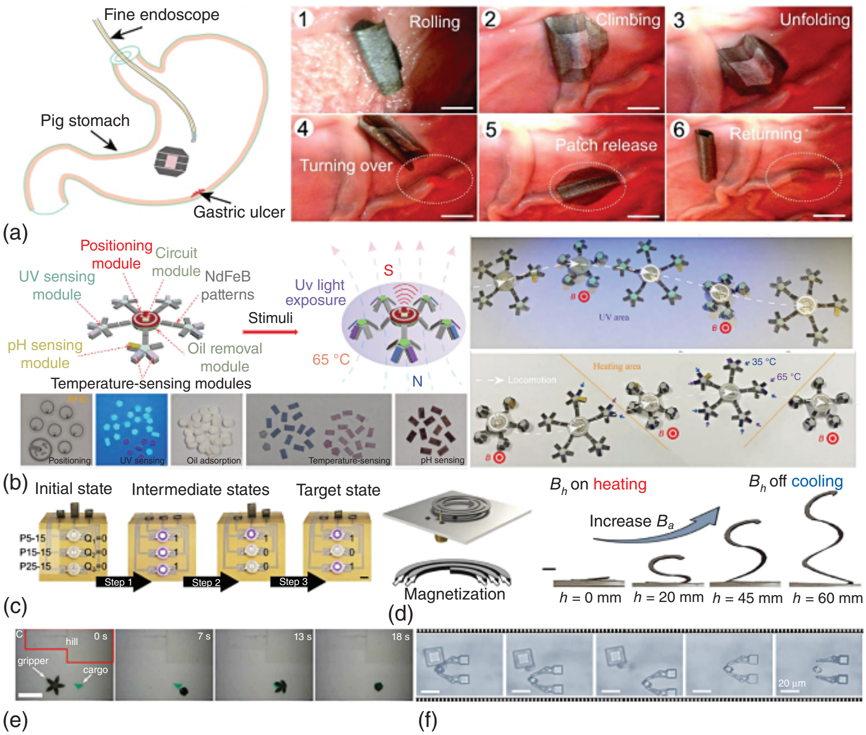

Figure 1.3 Applications of miniature soft robots. (a) Magnetic soft robot actuated in stomach for gastric ulcer treatment. Source: Dong et al. [25], © The Authors, some rights reserved; exclusive licensee AAAS. Distributed under a CC BY-NC 4.0 license http://creativecommons.org/licenses/by-nc/4.0/. (b) Multifunctional multilegged soft robot integrated with environmental sensing modules. Source: Dong et al. [25], © The Authors, some rights reserved; exclusive licensee AAAS. Distributed under a CC BY-NC 4.0 license http://creativecommons.org/licenses/by-nc/4.0/. (c) Magnetic shape memory material applied for logic circuit. Source: Ze et al. [59]/Reproduced from John Wiley & Sons, Inc. (d) Magnetically actuated helical antenna. Source: Ze et al. [59]/Reproduced from John Wiley & Sons, Inc. (e) Magnetic responsive microgripper. Source: Xu et al. [45]/American Association for the Advancement of Science (AAAS). (f) pH-responsive microgripper. Source: Ma et al. [91]/Reproduced from Springer Nature/CC BY 4.0.

seamless integration of multiple functional units was developed by Dong et al. to achieve environmental sensing. Through an adhesive network, pH sensing paper, temperature, and UV sensing particles could be easily loaded by the developed soft robot, and these sensor modules can be replaced after use via the repeatability of the stickers [25]. Recently, Zhang et al. proposed a frog-inspired origami robot made of laser-scanned PDMS sheet which could selectively absorb thermochromic ink, photosensitive ink, and quantum dot solutions [92]. Upon thermal and light stimuli, the origami robot could switch skin color. In addition, to construct a biomimetic intelligent drive system, the integration of the actuation and proprioception units is required. In this respect, somatosensory sensors, e.g. contact sensor, curvature sensor, and inflation sensor, that could monitor the deformation type of the robot body and surface roughness of contacted objects were developed and integrated with a somatosensitive pneumatic actuator via multi-material embedded 3D printing technique [93]. Different types of movements such as flicking, upward bending, and downward bending could induce different resistance changes for the somatosensory feedback. Furthermore, with the variation of contact pressure and local conductivity, the temperature and surface texture of the manipulated object could be monitored by the pneumatic actuator. Different from the multi-material printed robotic structures, an interpenetrating polymer network proposed by Zhao et al. consists of conductive polyaniline and thermally responsive PNIPAAm, which allow the seamless integration of piezoresistive sensing and photothermal actuation [58]. Upon near-infrared light stimulation, the hydrogel soft robot could achieve a series of locomotion, e.g. bending and contraction. Meanwhile, with the intrinsic conductivity, the external force applied to the robot body or structural deformation activated by remote stimulation could induce the variation of resistance. Therefore, the fabricated somatosensory soft robot is capable of executing closed-loop control and recognizing the manipulated unknown object.

1.4.3 Intelligent Electronics

Advances in miniature soft robots promise great potential in reconfigurable electronic devices, e.g. morphable antennas and logic circuits (Figure 1.3c–d). For instance, Kim et al. developed an annular-ring-shaped magnetic film integrated with a soft electronic circuitry [27]. Via magnetic stimulation, the magnetic film exhibits two distinct deformation modes which cause the selective contact of electrodes and light up different micro-LEDs. To realize more complicated shape transformation modes, a magnetic SMP-based robotic structure developed by Ze et al. could present tunable stiffness by magnetothermal effect, resulting in different deformation capabilities under magnetic stimulation [59]. By using an actuation magnetic field and a high-frequency magnetic field as input, and the off or on states of LED as output signal, the developed magnetic SMP-based robots could achieve logical functions such as three-bit memory and D-latch. In addition to the 2D thin-film structure, 3D origami robotic structures are also applied to the logic circuit. Kresling origami robots consisting of conductive components and magnetic discs with different magnetization patterns were fabricated by Novelino et al. [94]. Upon magnetic stimulation, bistable modes including folded and deployed states of robotic structures were exhibited, and results in the connection of different circuits. Moreover, three Kresling origami robots were assembled to demonstrate the function of digital computing of three-bit information. The shape-morphing capabilities of soft robots enable the antennas to exhibit reconfigurable frequency responses. For example, a tapered helical antenna made of magnetic SMP was developed by Ze et al. [59]. Under magnetic stimulation, the morphable antenna could present controllable deformation height, leading to tunable resonant frequency from 2.15 to 3.26 GHz. In addition, Bai et al. utilized a buckling-guided assembly strategy to fabricate a 3D reconfigurable antenna [95]. Nine deformation modes of the morphable structure could be induced by the sequential release of an elastic substrate with pre-strain and endow the antenna with widely tunable radiation directions.

1.4.4 Micromanipulation

Miniature soft robots have been widely used in micromanipulation to execute the tasks of in situ analysis and active delivery (Figure 1.3e,f). Recently, a micropillar array that could perform reversible bending upon the variation of pH was fabricated by Li et al. using the asymmetric DLW method and adopted as a pH-responsive microgripper [69]. Neural stem cells and microparticles with diameters of 10–15 μm could be in situ captured by the developed microgripper showing great manipulation resolution. A microgripper made of pH-responsive protein and rigid SU-8 resin was developed by Ma et al. using a multi-material TPP printing strategy [91]. Assisted by a microfluidic chip, a photopolymerization chamber was filled with printable polymers that can be replaced by different polymer precursors to achieve the sequential printing of multi-materials in one microstructure. The integration of a 3D moving stage and the adjustment of the pH of surrounding media allow the microgripper with a side length of ∼30 μm to precisely deliver and capture a micro cube (10 μm length). Apart from the pH-responsive behavior, magnetic actuation provides a remotely controlled strategy. For instance, a multi-arm magnetic gripper was developed by Xu et al. through the DLP printing method [45]. The gripper was made of photocurable polymer doped with ferromagnetic particles. With the arrangement of heterogeneous magnetization patterns and external magnetic field stimulation, the gripper could achieve wireless transporting, releasing, and grasping of millimeter-scale cargo with ∼2 mm length in an unstructured environment.

1.5 Scope and Layout of the Book

1.5.1 Scope of the Book

Miniature soft robots refer to controllable soft devices with maximum characteristic sizes in millimeters. Untethered miniature soft robots are able to perform reversible deformations and actively interact with the environment due to their inherent compliance. These robots have attracted great attention because of their broad potential in various fields, including intelligent electronics, smart grippers, biomedicine, and environmental applications. Due to their small-scale sizes, miniature robots may access diverse tortuous and confined spaces such as eustachian tubes and cerebrovascular networks. In addition, due to the ability to conduct micromanipulation with high precision, microactuators have the potential to perform in situ cell analysis. It demonstrates that micro-robots and micro-actuators have great potential on the important research topic of biomedical applications. Other meaningful applications are also explored in previous research. Over 5000 articles related to soft robots and their applications were published in the period from 2017 to 2021, and there has been an exponential growth of published works about small-scale soft robots over the past decades. However, there is a lack of a specialized and dedicated book on this topic. We aim to fill this gap and present the latest achievements in research on untethered miniature soft robots.

This book is focused on the emerging field of untethered miniature soft robots. It introduces fundamental understanding of various small-scale soft robots, including actuation mechanisms, soft matter, fabrication strategies, actuation, and locomotion principles. This book also demonstrates applications of miniature soft robots in different fields, such as intelligent electronics, smart grippers, biomedicine, and environmental applications. The detailed analysis of new materials and fabrication strategies, as well as experimental demonstrations in this book, provide readers ranging from students to researchers from diverse communities of robotics, materials, and biomedical engineering with a realistic understanding of progress achieved recently in the field of miniature soft robots.

1.5.2 Layout of the Book

This book introduces readers to the emerging field of miniature soft robots. From the perspective of fundamental research, we describe different types of functional materials to build miniature soft robots, such as silicone elastomer, carbon-based materials, hydrogels, liquid crystal polymer, flexible ferrofluid, and liquid metal. The material properties, fabrication strategies, and functionalities in soft robots are presented in detail, together with the underlying mechanisms. The description in this book is concise and explicit, which is easy to understand even for readers who have not been exposed to related fields. Due to the limitation of space, we emphatically introduce magnetically, thermal, light, and chemically actuated soft robots in this book. Furthermore, various specific applications of miniature soft robots in biomedical, environmental, and electrical fields are demonstrated. Finally, we summarize the opportunities and challenges faced by miniature soft robots in the future of this field. For researchers in this academic field, this book can serve as a reference for their research on soft robots, which may inspire more excellent ideas. For non-expert readers, such as undergraduate students, the attractive contents presented in this book can intrigue their interest in miniature robotics by showing them the amazing behaviors of tiny robots.

The layout of this book is briefly introduced as follows:

Chapter 1 Introduction to untethered miniature soft robots

This chapter introduces different kinds of miniature soft robots and provides a brief description of their development history and recent progress of miniature soft robots in terms of actuation strategies, materials, fabrication, control, and applications.

Chapter 2 Silicone elastomers-based miniature soft robots

This chapter presents the recent research outcome of silicone elastomers-based untethered miniature robots. Silicone elastomers have good biocompatibility and mechanical properties. They are widely used in forming soft robots, especially magnetic-responsive robots. By using 3D printing techniques, mold-assisted fabrication, or bottom-up assembly strategy, silicone elastomers-based miniature robots with 3D programmable magnetization profiles have been developed and exhibited fast shape-morphing and multimode locomotion capabilities.

Chapter 3 Carbon-based miniature soft robots with rolled-up concept

This chapter describes botanical-inspired strategies for constructing multi-stimuli-responsive robots. Some plants adopt rolled-up strategies (e.g. bending and curling) by sensing surrounding environmental changes. By learning from them, a series of carbon-based robots are fabricated to display dexterous structural changes once activated by external stimuli. Among these robots, graphene oxide (GO)-based films have been widely adopted. The programmable deformation of GO film is achieved by precisely patterned oriented wax or polymers on the GO film. The fabricated GO-based robots exhibit responses to light, humidity, and temperature, and are applied as shape-adaptation grippers and autonomous crawling robots.

Chapter 4 Hydrogels-based miniature soft robots

This chapter presents 3D-printed environmentally responsive hydrogels for constructing programmable miniature robots. Stimuli-responsive hydrogels feature broadly tunable chemical and mechanical properties and have shape-morphing capability in response to diverse environmental stimuli such as pH, temperature, and ion concentration. By using direct laser writing or digital light processing printing strategies, the hydrogel-based robots exhibit revisable and programmable 2D-to-3D or 3D-to-3D shape transformation by applying external stimuli.

Chapter 5 Liquid crystal network and elastomer-based miniature soft robots

This chapter discusses the application of liquid crystal networks and liquid crystal elastomers (LCNs and LCEs) to fabricate monolithic or bimorph material based robots with programmable shape-morphing and self-adaptation capability. By embedding magnetic particles into LCN or LCE films or integrating LCN or LCE and magnetic-responsive elastomers, the fabricated materials could integrate magnetic responsiveness with environmental awareness by responding to environmental cues like light and temperature, while simultaneously being remotely steered by the external magnetic field.

Chapter 6 Flexible ferrofluid as soft robotic agents

This chapter reports ferrofluid droplets used to form miniature soft robots. By the integration of elastomeric structures with ferrofluids, such as selective modification of elastomeric surfaces with laser scanning method or the injection of droplets into polymer structure with internal channels, the fabricated robots could exhibit diverse complex and controllable deformation and are applied as soft robots with multimode locomotion and multi-functionality.

Chapter 7 Conclusions and future prospects

This chapter summarizes the recent key progress made by researchers in the investigation of miniature soft robots and discusses the prospects and challenges of intelligent and autonomous soft robots. Section 7.1 introduces other functional materials including shape memory materials and bio-hybrid materials and discusses the comparison between these functional materials regarding their properties and applications. Section 7.2 introduces the integration of different types of functional materials. Multi-material integration strategies could build miniature soft robots with different functional modules, enabling them to respond to different external stimuli or execute multiple tasks. Sectionr 7.3 discusses multifunctional integration strategies used to fabricate soft robots with powerful perception capabilities that enable the feedback and adaptive control of the miniature soft robots. Section 7.4 discusses the development and challenges of miniature soft robots with intelligence and autonomy. The development of functional materials continuously improves the performance of miniature soft robots. The envisioned positive influences of these intelligent miniature robots in different aspects of our real world and perspectives for future miniature soft robots will be discussed.

Abbreviations

CAL	computed axial lithography
CLIP	continuous liquid interface production
DIW	direct ink writing
DLP	digital light processing
DMD	digital micromirror device
FDM	fused deposition modeling
FFF	fused filament fabrication
GelMA	gelatin methacryloyl
LCE	liquid crystal elastomer
NFC	near-field communication
PNIPAAm	poly(*N*-isopropylacrylamide)
SLA	stereolithography
SLS	selective laser sintering
SMP	shape memory polymer
TPP	two-photon polymerization

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