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REVIEW

Light-based 3D printing of stimulus-responsive hydrogels for miniature devices: recent progress and perspective

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Abstract

Miniature devices comprising stimulus-responsive hydrogels with high environmental adaptability are now considered competitive candidates in the fields of biomedicine, precise sensors, and tunable optics. Reliable and advanced fabrication methods are critical for maximizing the application capabilities of miniature devices. Light-based three-dimensional (3D) printing technology offers the advantages of a wide range of applicable materials, high processing accuracy, and strong 3D fabrication capability, which is suitable for the development of miniature devices with various functions. This paper summarizes and highlights the recent advances in light-based 3D-printed miniaturized devices, with a focus on the latest breakthroughs in light-based fabrication technologies, smart stimulus-responsive hydrogels, and tunable miniature devices for the fields of miniature cargo manipulation, targeted drug and cell delivery, active scaffolds, environmental sensing, and optical imaging. Finally, the challenges in the transition of tunable miniaturized devices from the laboratory to practical engineering applications are presented. Future opportunities that will promote the development of tunable microdevices are elaborated, contributing to their improved understanding of these miniature devices and further realizing their practical applications in various fields.

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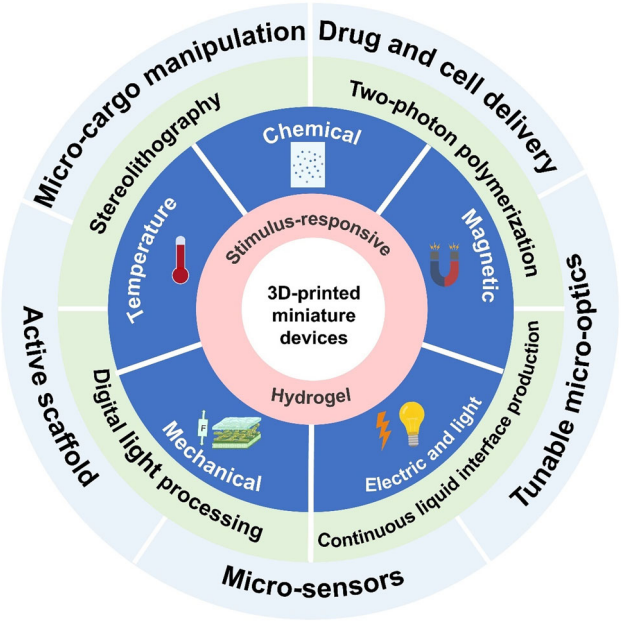
Graphic abstract



Keywords 3D printing · Stimulus-responsive hydrogels · Miniature devices · Shape-morphing

Introduction

Three-dimensional (3D) printing as an emerging process manufacturing method has been widely used in circuit manufacturing [1–3], robotics [4–6], food [7], and art business [8]. Currently, the International Organization for Standardization classifies 3D printing technologies into vat photopolymerization, material jetting, binder jetting, powder bed fusion, material extrusion, directed energy deposition, and sheet lamination [9]. Photopolymerization-based 3D-printing technologies exhibit high resolution and wide material selectivity; they have become powerful tools for the processing of complex miniature 3D structures (nanometer scale to centimeter scale) [10, 11]. Typically, light-based 3D printing technology involves the conversion of a liquid or low-viscosity photosensitive monomer into a solid 3D object under light irradiation [12]. Covalent bond crosslinking during the printing process provides the printed structures with excellent mechanical, thermal, and chemical stability [13–15]. Thus, light-based 3D printing offers a promising technological method for the development of multifunctional miniaturized devices for the fields of science and engineering.

Although light-based 3D printing technology has achieved great progress in terms of the complexity and accuracy of 3D structures, the creation of devices with smart adjustability and strong environmental adaptability remains challenging. Over the past 10 years, smart stimulus-responsive hydrogels have been widely studied and used; these materials can change their properties, such as shape, motion, or function, in a controllable manner in response to different external stimuli [16, 17]. In addition, compared with liquid–crystal elastomers [18, 19] and shape-memory polymers [20, 21], up to 90% of hydrogel matrix consists of water [22, 23], which makes hydrogels suitable for a wide range of biomedical applications. The miniaturized devices obtained through the combination of light-based 3D printing technology with stimulus-responsive materials can cope with complex applications. Currently, the most widely studied stimulus-responsive hydrogels mainly include the chemical [24, 25], temperature [26, 27], light [28–30], and magneto-responsive ones [31, 32]. In the past decade, the number of studies focusing on light-based 3D-printed hydrogels has increased considerably (Fig. 1) [33, 34]. Therefore, a comprehensive review is needed to determine the recent research advances in the area of 3D-printed stimulus-responsive hydrogels to guide the community in the development of next-generation smart miniaturized devices.

Miniature devices, including but not limited to miniature robots [35–41], actuators [42, 43], sensors [44–46], and optical devices [47–49], are less than 1 cm in size. Owing to their small size and high precision, they show broad potential for applications in the biomedical [50, 51], precise sensing [52], and microscopic imaging [53, 54] fields. Various microrobots

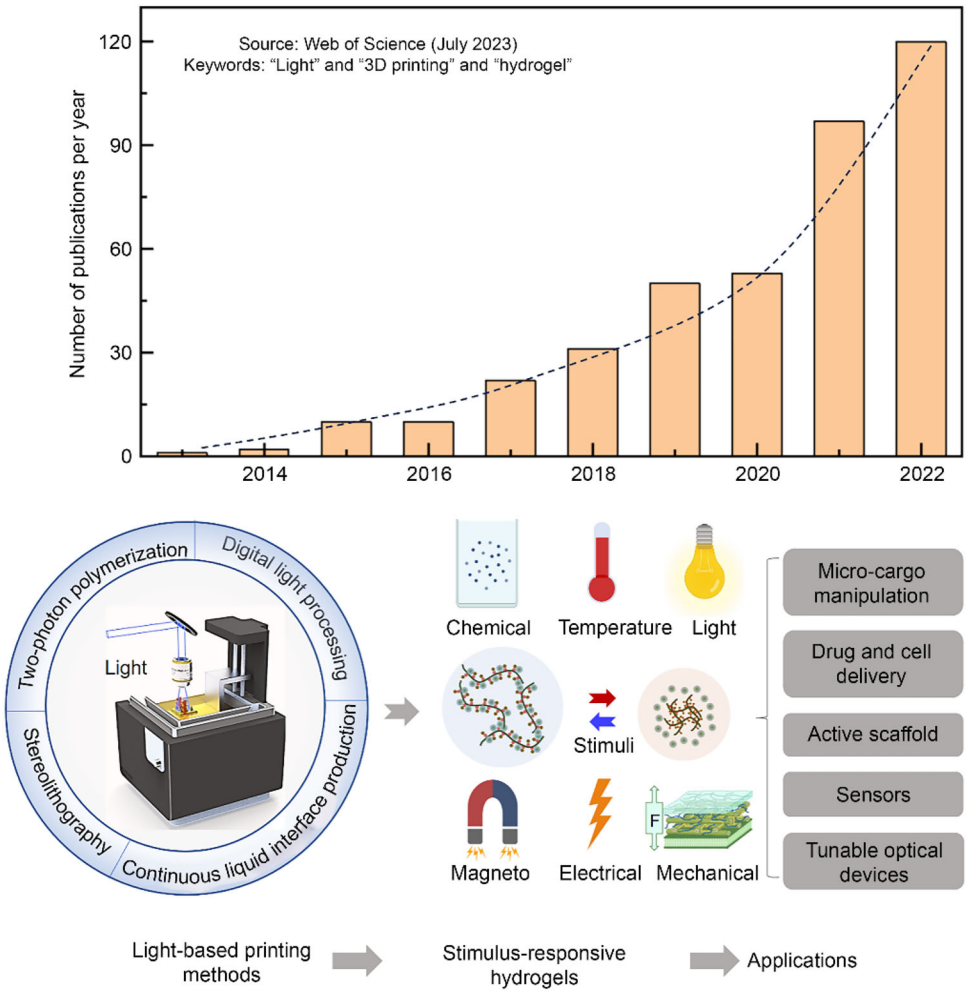


Fig. 1 During the past decade, exciting studies on light-based 3D printing of hydrogels have been published (top). Schematic of light-based 3D-printed miniature devices composed of stimulus-responsive hydrogels (bottom)

and actuators can be adapted to fit into narrow and tortuous tubes in the human body, such as the digestive [55–57] and vascular systems [58, 59]. In addition, various functionalized microsensors with a highly sensitive sensing capability and high accuracy are widely used in the detection of physiological and biochemical signals of the human body. Furthermore, miniature devices with a high depth of field and field of view (FOV) are utilized in light modulation and submicron microimaging [60–62]. Thus, the extended miniaturization, intelligence, and functionality of these microdevices will be the keys to their practical applications.

This review concludes the recent advances regarding the use of light-based 3D-printed hydrogels in microdevices, highlighting the efforts and achievements of researchers over the past decade in light-based 3D printing technology, smart stimulus-responsive materials, and functionalized microdevices (Fig. 1). Smart stimulus-responsive materials include chemical-, temperature-, light-, magnetic-, electrical-, and mechanical-triggered modes that enable the operation of microdevices, which allow them to respond to environmental changes, such as deformation and motion. These smart devices with enhanced tunability and environmental adaptability meet expectations, and they are widely used in various areas, such as micro- and nanomanipulation, targeted drug and cell delivery, environmental sensing, tunable optics, and active scaffolds. We also discuss the major challenges faced by the current research community and future research directions to further advance the real-world applications of these microdevices.

Light-based 3D printing

Compared with extrusion and inkjet 3D printing techniques, photopolymerization-based–3D-printing technology offers high-precision and complex structural modeling capabilities. To date, light-based 3D printing methods are mainly divided into stereolithography (SLA) [63, 64], digital light processing (DLP) [33, 65–67], continuous liquid interface production (CLIP) [68, 69], two-photon polymerization (TPP) [70], and volumetric additive manufacturing (VAM) [71]. A portion of the research on extrusion 3D printing is

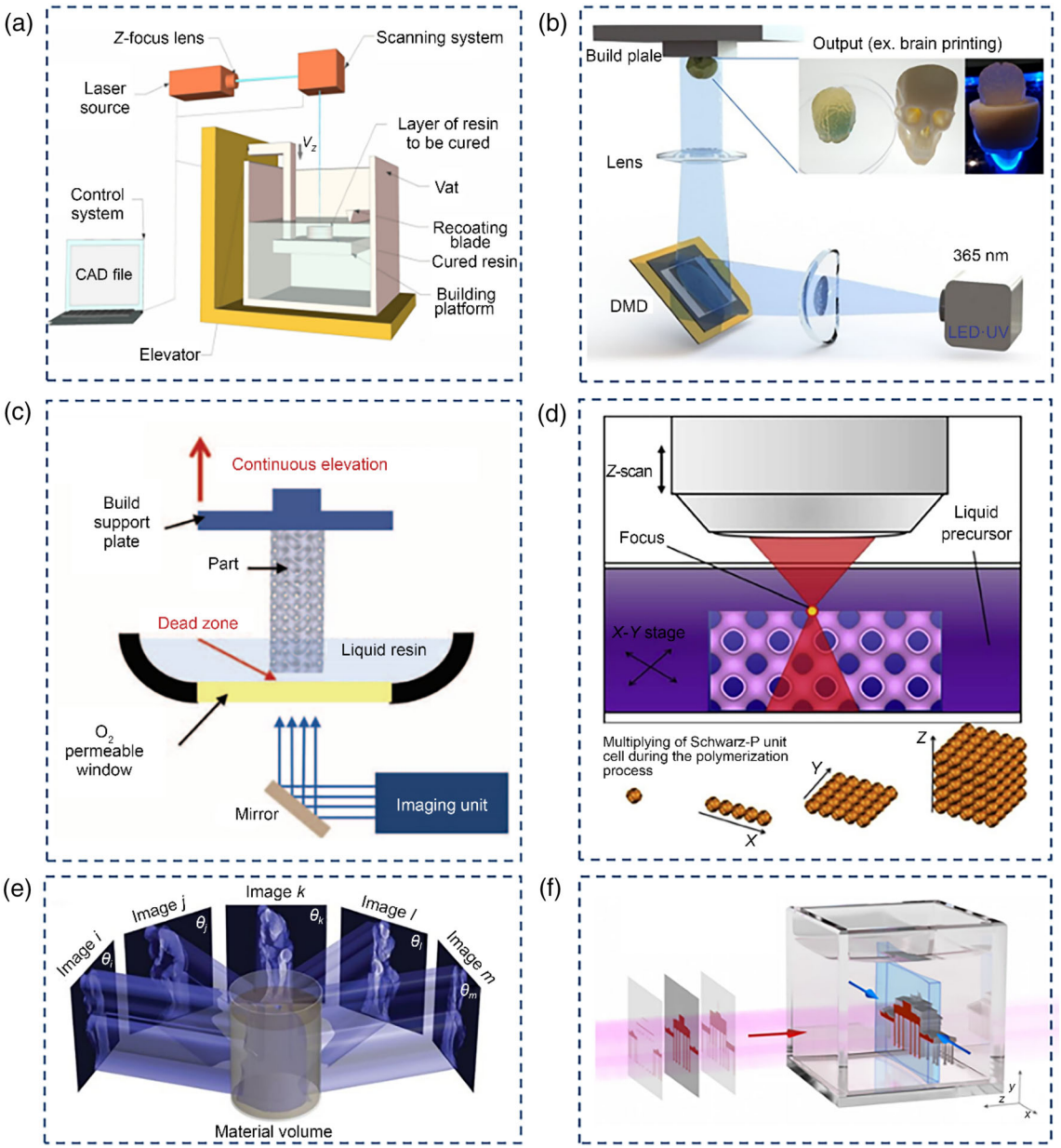


Fig. 2 Schematic of light-based 3D printing technology. **a** Schematic of stereolithography (reproduced from Ref. [72], Copyright 2020, with permission from the authors, licensed under CC BY 4.0). **b** Schematic of digital light processing (reproduced from Ref. [73], Copyright 2018, with permission from the authors, licensed under CC BY 4.0). **c** Schematic of continuous liquid interface production technology (reproduced from Ref. [68], Copyright 2015, with permission from AAAS). **d** Schematic of direct laser writing (reproduced from Ref. [76], Copyright 2018, with permission from the authors, licensed under CC BY 4.0). **e** Schematic of rotating volume printing of 3D structures via a computed axial lithography (CAL) system (reproduced from Ref. [71], Copyright 2019, with permission from AAAS). **f** Schematic of xolography for linear volumetric 3D printing using two intersecting light beams of different wavelengths to solidify localized regions (reproduced from Ref. [84], Copyright 2020, with permission from the authors, under exclusive licence to Springer Nature Limited)

based on photopolymerization processing. However, the 3D-printing accuracy of extruded light curing is limited by the nozzle size and rheological properties of materials, which are difficult to compare with several aforementioned light-based printing techniques. In addition, a considerable number of reviews have summarized extruded light-curing 3D printing. Therefore, this review focuses on SLA, DLP, CLIP, TPP, and VAM technologies. SLA, which was developed in 1984, was the first light-based 3D printing technology, and it is considered one of the most accurate 3D printing processes in the market. In general, SLA uses laser as a light source, where the laser beam sweeps across a resin that can move on a horizontal axis, causing the layer-by-layer curing of the material (Fig. 2a) [72]. SLA printing process requires time to measure and control the resin liquid level and scraping, resulting in a low overall printing speed. For the increased speed of 3D printing, the DLP technology based on digital micromirror device (DMD) as the main beam conditioner has been proposed; this technology uses mask projection to cure one layer of photosensitive resin at a time and accumulate it in layers to obtain 3D structures (Fig. 2b) [73]. DMD features a high switching speed and high resolution, and thus, it can guarantee a high processing accuracy with a high processing speed [74]. DLP technology has shown improved performance and application prospects. It has been used in various fields, such as tissue engineering, biomedicine, metamaterials, microoptical devices, and microelectromechanical systems [73, 75]. In addition, in 2015, Tumbleston et al. [68] of Carbon3D published their work on a disruptive 3D printing technology: CLIP technology (Fig. 2c). CLIP technology not only allows for a stable increase in 3D printing speed but also a notable increase in the printing accuracy. The key to the application of this technology is the achievement of a continuous liquid interface through an oxygen-permeable window below the ultraviolet (UV) image projection plane, which creates a "dead zone" (persistent liquid interface) between the window and the polymerization part, where photopolymerization is inhibited [68]. In this manner, CLIP does not need to consume the time allotted for resin liquid leveling and scraping. Thus, the resin can be used to extract complex structures after printing at a rate of several hundred millimeters per hour. However, ensuring quick printing of highly viscous resin materials is difficult when applying CLIP, and the oxygen permeation membrane is costly. The aforementioned single-photon–absorption-based–3D-printing approach can be used to fabricate structures with micron-level resolution. By contrast, femtosecond laser-based TPP processing can further increase the processing resolution to about 100 nm (Fig. 2d) [76]. Furthermore, some variants of TPP technology, such as stimulated emission depletion (STED) technology [77, 78], can further increase the processing resolution to 40 nm. TPP is initiated by the two-photon absorption of a substance; it refers to the simultaneous absorption of two photons by one molecule of a substance. The laser intensity at other sites on the optical path is insufficient to produce two-photon absorption. Thus, direct laser writing based on TPP presents the advantages of good material penetration and high spatial selectivity. In 2001, Kawata et al. [70] used an ultrashort pulse laser (near-infrared (NIR) femtosecond pulsed laser at 780 nm) to induce TPP of photoresists to produce nano cattle measuring 10 μm in length and 7 μm in height with a resolution of 120 nm, breaking the diffraction limit of conventional optical theory and enabling the fabrication of 3D structures with submicron precision. In addition, some femtosecond laser–two-photon techniques based on beam modulators, such as DMD, prism pair-based spatiotemporal focusing [79, 80], and liquid crystal on silicon spatial light modulator (LCoS-SLM)-based spatial light modulation [81], have been rapidly developed. These studies focused on further improvements of the efficiency, resolution, and cost reduction, which are important for practical commercial applications of direct writing 3D printing based on TPP. In addition to the above forms of point-by-point, layer-by-layer light scanning processing, some VAM methods have been proposed [71, 82–85]. With the use of computed axial lithography (CAL) method, various 3D shapes of microstructures can be printed through polymer rotation in a dynamically changing light field with one complete rotation (Fig. 2e) [71]. This type of volume printing avoids the need for layering and bracing and is orders of magnitude faster than layer-by-layer printing. In addition, localized curing regions can be created within photopolymerized materials using two different wavelengths of dual-color light, and the resulting derived linear reference prints have a processing resolution that is 10 times higher than that of conventional VAM and a volume generation rate that is four to five orders of magnitude higher than that of TPP (Fig. 2f) [84]. Overall, considering the multi-material, high-precision, and complex 3D manufacturing capabilities, light-based 3D printing is a strong candidate for the creation of functionalized miniature devices.

Stimulus-responsive hydrogels for miniature devices

Hydrogels are a kind of crosslinked hydrophilic polymer network containing a large number of water molecules [86]. Many smart stimulus-responsive materials have emerged, and most of them, such as hydrogels [87], liquid–crystal elastomers [88, 89], and shape-memory polymers [90, 91], are suitable for light-based 3D printing. Hydrogels exhibit a high environmental adaptability and are widely used in scientific and engineering applications, such as soft robotics [92], flexible electronics [93, 94], and tunable optics [95, 96]. More importantly, through the control of the network

Table 1 Summary of light-printed–stimulus-responsive miniature devices and their applications

Stimuli	Materials	Methods	Applications	Ref
Water	PEGDA, PPGDMA	DLP	Programmable deformation	[106]
Ions	HEA, PCLDA, PSPMA, HEMA	DLP	Programmable deformation	[107]
Organic solvent	$[Cu(TAcO)_2(4,4'\text{-bipy})(H_2O)]_n \cdot 2H_2O$	DLP	Moisture sensing	[108]
pH	AAc	TPP	Microparticle capture, microrobot for drug delivery, tunable structural color, and active micro-stent	[109–113]
	AAc	DLP	pH sensors	[114]
	BSA	TPP	Microgripper, tunable microlens, and compound eyes	[115–117]
	Protin	TPP	Microrobots for targeted drug delivery	[118]
Temperature	NIPAAm	SLA	Smart window	[119]
	MEO_2MA	DLP	Thermoresponsive gripper	[120]
	SA, DMAAm	SLA	Soft robotics	[121]
	NIPAAm	TPP	Programmable deformation	[122]
	NIPAAm	DLP	Actuators with autonomic perspiration	[123]
Light	NIPAAm, carbon nanoparticles	SLA	Hydrogel microrobot	[124]
	NIPAAm, SWCNTs	TPP	Microscale artificial heart	[125]
	NIPAAm, Ag NPs	TPP	Humanoid multijoint microactuator	[126]
Magnetic	UV resin, NdFeB PEGDA, Fe	DLP	Magnetic robot and magnetic mirror, toxin detection	[127, 128]
	GelMA, $CoFe_2O_4$, $BiFeO_3$	TPP	Delivery and differentiation of neuron-like cells	[129]
	PEGDA, GelMA, $Ni_{81}Fe_{19}$ coated silica microparticles	TPP	Microactuator networks and microrobots, and cell transportation	[105, 130, 131]
Electrical	AAc, PEGDA	DLP	Soft robotic manipulation and locomotion	[132]
Mechanical	GelMA	DLP	Active scaffold	[133, 134]
	Agarose, PEGDA	TPP	Cell microscaffold and tunable structure color	[135, 136]

PEGDA: poly(ethylene glycol) diacrylate; AAc: acrylic acid; BSA: bovine serum albumin; NIPAAm: N-isopropyl acrylamide; PPGDMA: poly(propylene glycol) dimethacrylate; HEA: 2-hydroxyethyl acrylate; PCLDA: poly(ε-caprolactone) diacrylate; PSPMA: poly(3-sulfopropyl methacrylate); HEMA: 2-hydroxyethyl methacrylate; MEO_2MA: 2-(2-methoxyethoxy) ethyl methacrylate; SA: stearyl acrylate; DMAAm: N, N-dimethyl acrylamide; GelMA: gelatin methacryloyl; SWCNTs: single-walled carbon nanotubes; NP: nanoparticle; UV: ultraviolet; DLP: digital light processing; TPP: two-photon polymerization; SLA: stereolithography

structure and energy dissipation mechanisms [97], double network, supramolecular, and nanocomposite (NC) hydrogels with strong mechanical properties have been developed [98–103], which further enhances the application potential of hydrogels. In particular, a portion of a hydrogel exhibits good biocompatibility and is suitable for microrobot fabrication with promising applications in targeted drug delivery [104] and stem cell transplantation [105]. Unlike ordinary hydrogels, stimulus-responsive hydrogels are prepared through the incorporation of stimulus-responsive groups or particles into the hydrogel network, which enables them to respond to external stimuli. Therefore, the combination of light-based 3D printing technology in stimulus-responsive hydrogels can be used to create smart miniature devices via the manipulation of microcargos to high-precision sensing. Currently, the stimulus-responsive hydrogels for miniaturized device processing are mainly classified as chemical-, temperature-, light-, magneto-, electrical-, and mechanical-responsive hydrogels, and they have been widely used in microcargo manipulation, targeted drug delivery, environmental sensors, tunable optics, and active scaffolds (Table 1).

Chemical-responsive hydrogels

Chemical-responsive hydrogels typically introduce ionic groups into the network to accomplish a response stimulated by solvent, ion concentration, and pH [110, 137–141]. When a hydrogel contains hydrophilic and hydrophobic

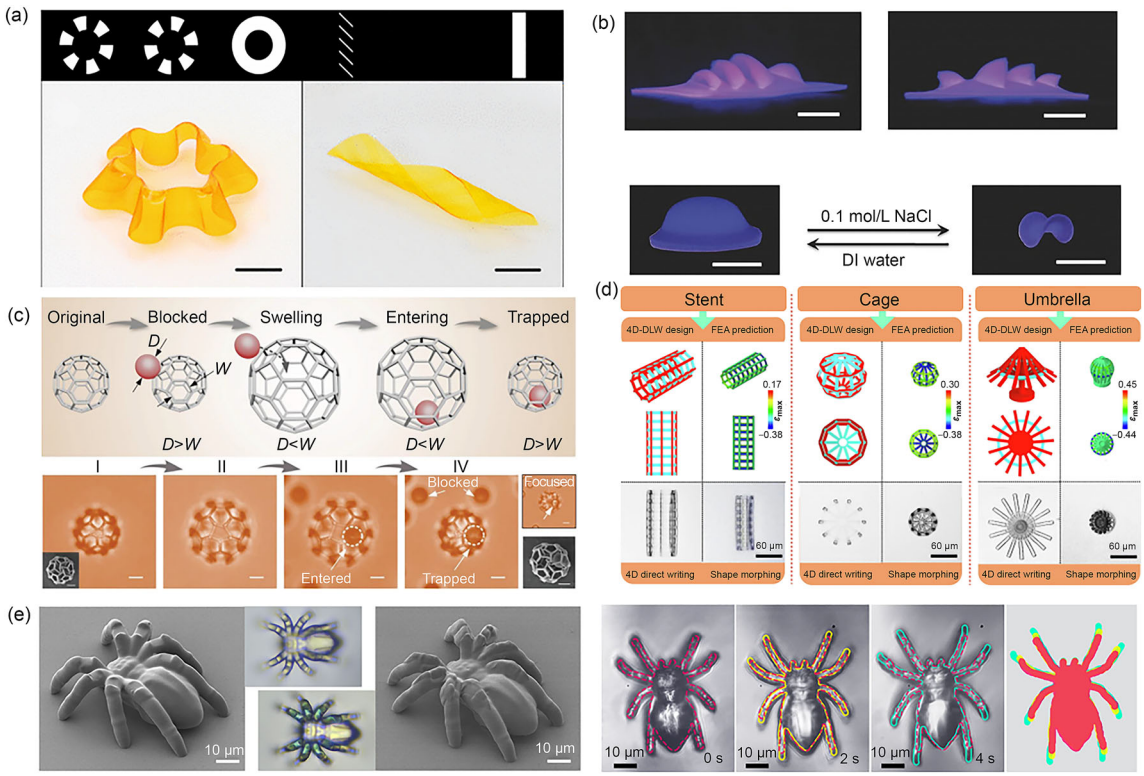


Fig. 3 Light-printed miniature structures based on chemical-responsive hydrogels. **a** 3D hydrophilic and hydrophobic composite shape-shifting structures prepared using a digital light processing (DLP) projector (scale bar: 10 mm). Reproduced from Ref. [106], Copyright 2018, with permission from the American Chemical Society. **b** DLP of ion-responsive hydrogel used to construct a miniature theater (scale bar: 10 mm). Reproduced from Ref. [107], Copyright 2016, with permission from WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim. **c** Two-photon polymerization (TPP) of pH-responsive hydrogel used to fabricate a microcage for microparticle capture (scale bar: 10 μm). Reproduced from Ref. [109], Copyright 2019, with permission from WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim. **d** 4D-TPP of various microstructures realizing 3D-to-3D shape transformation via the change in pH (reproduced from Ref. [110], Copyright 2019, with permission from the authors, licensed under CC BY 4.0). **e** On-chip TPP strategy was proposed to print two photosensitive materials for the development a pH-responsive spider (reproduced from Ref. [115], Copyright 2020, with permission from the authors, licensed under CC BY 4.0)

groups, the hydrophilic portion placed in a liquid absorbs water molecules and is thus in a swollen state, which, in turn, causes the hydrogel to change shape [142, 143]. Zhao et al. [106] reported a type of hydrophilic and hydrophobic composite hydrogel fabricated via a multilayer DLP printing technology, where the structures enable shape-shifting capabilities, including wavy rings, helix ribbons, and curved leaves (Fig. 3a). In addition, the ionic response is a widely used stimulus–response mode, and it relies heavily on the sensitivity of the hydrogel to the concentration of liquid ions. Hydrogel structures based on potassium 3-sulfopropylmethacrylate (PSPMA) can exhibit reversible shape-change properties as the ionic strength changes [107]. A hydrogel structure reversibly switches between two shapes with the changes in ionic concentration (Fig. 3b). Besides, pH-responsive hydrogels are one of the most common types of chemical-responsive hydrogels. The backbone of pH-responsive hydrogel polymers carries ionic (anionic or cationic) groups. In an aqueous medium with an appropriate pH, the ionic groups ionize and generate charges that cause swelling or shrinkage of the hydrogel. Importantly, slight alterations in pH can result in considerable changes in the mesh size of the polymer network. Specifically, in anionic hydrogels, the responsive group ionizes above the acid dissociation constant (pKa) of the hydrogel, which causes swelling of the anionic hydrogel at pH > pKa. Polyacrylic acid hydrogels are the most common anionic hydrogels, and they switch between swelling and shrinking of liquids of different pH via the ionization and unionization of carboxyl groups [144]. The C60 microcages printed using TPP can achieve microparticle capture and release under a switch in the solution pH with a response threshold of pH = 9 (Fig. 3c) [109]. Similarly, four-dimensional (4D) TPP allows the precise control of the exposure dose to produce various 3D-to-3D shape transformations of microstructures, such as microstents, microcages, and microumbrellas (Fig. 3d) [110]. In

addition, Sun's group developed a bovine serum albumin (BSA)-based hydrogel (Fig. 3e) that enables the deformation of microspiders under pH 5–13 [115]. Microgrippers prepared through the same method, including grasping, transferring, and releasing, can be used to manipulate micrometer particles. Especially with the rapid development of microfluidic technology, pH-responsive microrobotic systems may play an important role in intelligent microfluidic chip systems and hold great promise for in vitro cell manipulation, cargo handling, precision assembly, device integration, and minimally invasive surgery. By contrast, cationic hydrogels swell at pH < pKa. 2-Hydroxyethyl methacrylate (HEMA) is used as a cationic response group to prepare stimulus-responsive microgrippers, which can be used for targeted drug delivery therapeutics; it can also shrink at high pH to grab drug particles and swell at low pH to open for the targeted release of drug particles [145]. Although miniature devices consisting of chemically responsive hydrogels demonstrate a high environmental adaptability, large variations in solution ions and pH limit their application scenarios.

Temperature-responsive hydrogels

Temperature-responsive monomers can also be added to hydrogels to induce a temperature response. Poly(N-isopropylacrylamide) (PNIPAm), which has a low critical-solution temperature (LCST = 32 °C), is the most common temperature-responsive unit. Its working principle is that when the temperature exceeds the LCST of the hydrogel, the hydrogel exposes hydrophobic groups and squeezes the water molecules inside, producing a strong contraction [146]. Given the proximity of its LCST to the human body temperature and biocompatibility, PNIPAm is suitable for miniaturized devices used for in vitro and in vivo drug delivery and dynamic actuation. Han et al. [119] reported the 3D printing of PNIPAm structures using high-resolution DLP technology. The temperature-responsive deformability of a miniature dumbbell can be flexibly tuned by controlling the 3D printing process parameters and hydrogel composition (Fig. 4a). In addition, Liao et al. [218] constructed a variety of hydrogel structures, including octopus, chameleon, and flower (Fig. 4b). They can change their shapes and colors at different temperatures. Moreover, temperature-responsive hydrogels with shape-memory capabilities, which can change shape within 40 min (Fig. 4c) [121], have been developed to fabricate miniaturized devices. In addition to millimeter- to centimeter-scale structures, TPP-based 4D printing enables the development of micron-scale temperature-responsive microdevices. Hippler et al. [122] reported 3D PNIPAm heterogeneous microstructures and achieved designable and large deformation of complex structures by controlling the local exposure dose during TPP. The microcantilever structure can change from straight to curved at temperatures of 20 to 45 °C (Fig. 4d). The introduction of ionic copolymerization monomers, such as acrylic acid and acryloyl, to temperature-responsive hydrogels can be used to modulate their LCST to suit various applications [147]. Moreover, several strategies, including interpenetrating polymer networks, NCs, and slip-ring hydrogels [148], have been proposed to further increase the mechanical strength of PNIPAm hydrogels to suit various application environments.

Light-responsive hydrogels

Light-responsive hydrogels are also commonly used materials in building miniaturized devices [149]. The light-responsive mechanism of these devices is mainly divided into photoisomerization/ionization and photothermal conversion of nanoparticles. Azobenzene is one of the most common photoisomerization units, and it can switch between trans/cis structures stimulated by light from UV to NIR [150]. Light-responsive hydrogels based on photothermal effect must be added with various photon-absorbing materials, such as gold nanorods [151], graphene [152], and carbon nanotubes [125], to their networks. The photothermal effect is that the photothermal material rapidly changes from the ground state to the excited state when exposed to light radiation and then returns to the ground state, and the energy is dissipated in the form of heat. Miniature light-responsive devices with micrometer to centimeter dimensions have been developed using light-based 3D printing. Based on SLA technology, ultrafast light-responsive shape-memory hydrogel was used to construct microstructures (Fig. 5a). The structure's degree of deformation and angle can be controlled via different printing grayscales [124]. In addition, a light-driven microgel rotor constructed through doping of gold nanorods into the hydrogel was demonstrated [153]. Graphene oxide-doped bilayer hydrogels also quickly respond to near-infrared light. The photothermal mode enabled the rapid heating and distortion of the hydrogel bilayer (Fig. 5b) [154]. In particular, TPP can also be used to build 3D light-responsive structures at the microscale. Compared with larger structures (mm to cm), microstructures reduce their photothermal response time for deformation to <1 s. Deng et al. [125] used a femtosecond laser to directly write a variety of complex 3D structures with uniformly doped single-walled carbon nanotubes (SWCNTs) inside, which can be deformed within 300 ms under NIR (70 mW). For demonstration, a microscale 3D artificial heart was constructed, and the pacing process was verified by light stimulation (Fig. 5c). Furthermore, we have developed a two-in-one TPP method for the precise deposition of photothermal materials in localized regions of multijoint microactuators, which can realize the deformation of localized regions of microactuators by 3D multifocal beams stimuli and exhibit high degrees of freedom and multimodality. Figure 5d shows a humanoid microactuator

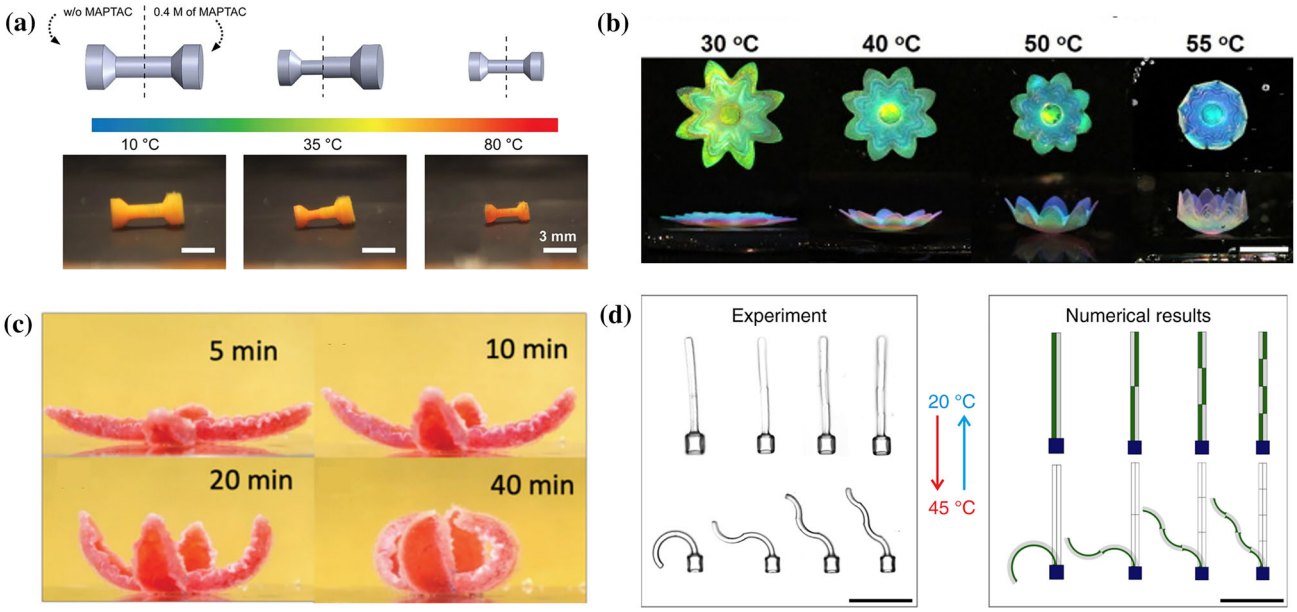


Fig. 4 Light-printed miniature structures based on temperature-responsive hydrogels. **a** Temperature-responsive dumbbell-shaped structure fabricated using micro-stereolithography (μSLA) (reproduced from Ref. [119], Copyright 2018, with permission from the authors, licensed under CC BY 4.0). **b** A 3D-printed flower has different colors under different temperatures (scale bar: 5 mm). Reproduced from Ref. [218], Copyright 2022, with permission from Elsevier Ltd. **c** A 3D-printed temperature-responsive flower for deformation in hot water (reproduced from Ref. [121], Copyright 2019, with permission from WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim). **d** Direct laser writing (DLW) of a temperature-responsive microcantilever, presenting two shapes at 20 and 45 °C (scale bar: 50 μm). Reproduced from Ref. [122], Copyright 2019, with permission from the authors, licensed under CC BY 4.0

presenting two different modalities via two- and four-foci beam stimulations [126]. Light-responsive devices have the advantages of high response speed and local independent control, which are suitable for a wide range of applications.

Magneto-responsive hydrogels

Magnetic field stimuli, which are wireless, accurate, and harmless to the human body [155], can be competitively used in miniature devices [156–159]. Thus, various magneto-responsive devices have been developed for applications in medical robotics [160–165], flexible electronics [166], and biosensors [167]. When magnetic particles are added to a hydrogel network, the magnetic field not only stimulates shape changes but also imparts strong motion to the devices. Magneto-responsive hydrogels can be obtained by filling hydrogels with various magnetically responsive particles, such as Fe_3O_4 nanoparticles [58, 168, 169], Ni nanoparticles [170], and NdFeB particles [171, 172]. Xia et al. [173] developed a millimeter-scale magnetically responsive soft robot named LarvaBot by filling it with NdFeB microparticles (5 μm). LarvaBot provides a platform to understand the agile movements of midge larvae and provide information on the drive, gait selection, and path planning in other untether swimming robots (Fig. 6a). Programmable magnetization enables miniaturized devices with complex responsive deformation degrees of freedom from 2D to 3D. Diller's group proposed a derivative DLP printing technique to program magnetic axes, allowing the orientation of hard magnetic materials to be programmed layer by layer, which resulted in devices with different magnetizations [127]. The printed zigzag spring and centipede can be used for a tunable optical mirror holder and a soft crawling robot, respectively (Fig. 6b). In addition, micro magneto-responsive devices, which are mainly built by TPP technology, have attracted research attention. Dong et al. [129] used TPP to construct 3D microswimmers in a hydrogel, which can be used for targeted delivery and differentiation of neuronal cells. The microswimmers demonstrated high biocompatibility and biodegradation after cell delivery (Fig. 6c). Notably, similar magneto-responsive microrobots have been fabricated to perform cytotoxicity tests [174]. In addition to single magneto-responsive microdevices, microactuator networks with multiple magneto-responsive microdevices can be constructed via the TPP technique [130]. Figure 6d shows the microactuator networks composed of magnetic microparticles and hydrogel linkages. In conclusion, microactuator networks can perform 2D to 3D deformation and can be used for active shape deformation in tissue engineering and wound healing.

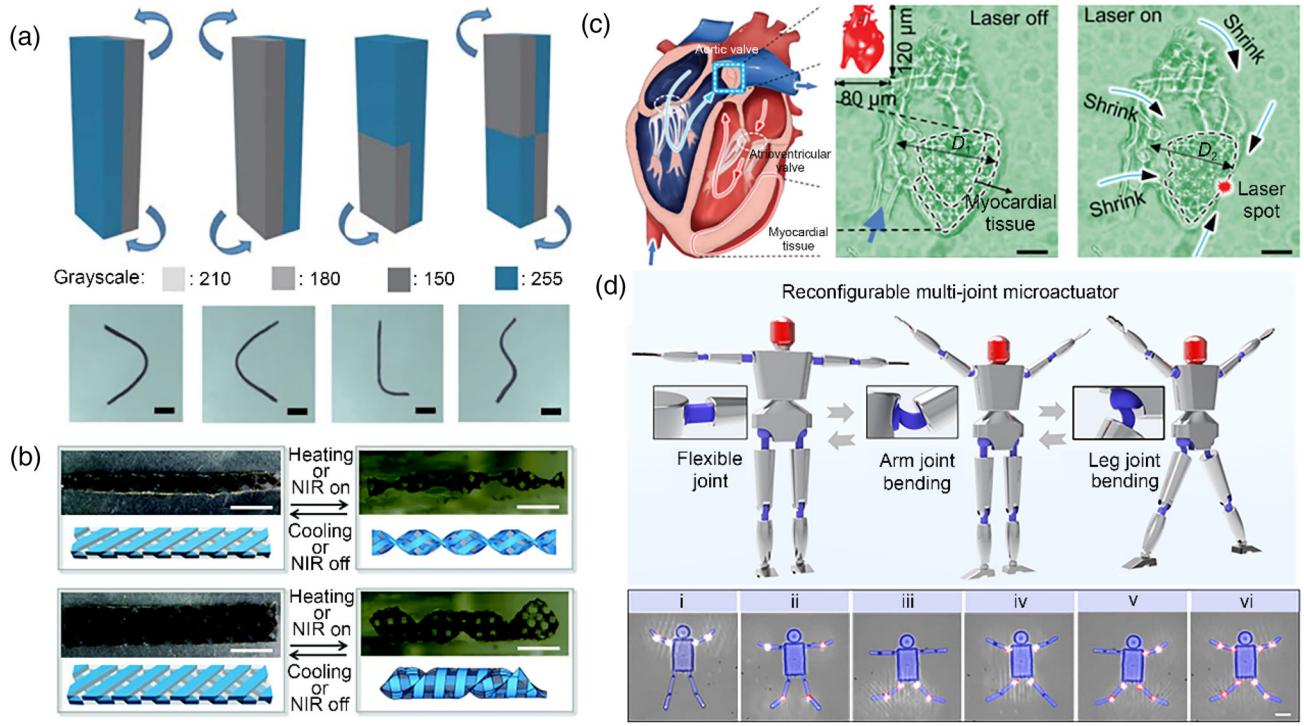


Fig. 5 Light-printed miniature structures based on light-responsive hydrogels. **a** Micro-stereolithography (μSLA) of beam structures with different printing grayscales (scale bar: 10 mm). Reproduced from Ref. [124], Copyright 2021, with permission from the authors, licensed under CC BY 3.0. **b** 3D-printed–light-responsive composite hydrogels that formed distortions when irradiated with near-infrared light (scale bar: 10 mm). Reproduced from Ref. [154], Copyright 2019, with permission from The Royal Society of Chemistry. **c** A light-responsive microheart fabricated by two-photon polymerization (TPP) can deform under a focused laser beam (scale bar: 20 μm). Reproduced from Ref. [125], Copyright 2023, with permission from Wiley–VCH GmbH. **d** TPP of a light-responsive–multijoint microactuators enabling multiple modalities (scale bar: 20 μm). Reproduced from Ref. [126], Copyright 2023, with permission from the authors, licensed under CC BY 4.0

Electrical-responsive hydrogels

Electric fields are a widely used source of stimulation and can be used to trigger hydrogel shape deformation [175–177]. The mechanism is that the polymer chains within these hydrogels carry a large number of ionic groups, and when a voltage is applied to both of their sides, the charged and counter ions in the hydrogel migrate in opposite directions using the electrophoretic force. This condition leads to an ionic concentration gradient within the hydrogel, resulting in different hydrogel osmotic pressures. The differences in osmotic pressure lead to various degrees of swelling of the hydrogel, which ultimately leads to its bending and deformation. Human-like microrobots fabricated by DLP technology can achieve bidirectional locomotion, which also enables walking motion achieved by electric-field-driven actuation (Fig. 7a) [132]. In addition to ion migration, electrically induced biological hydrogel contraction is considered a mode of stimulation. As skeletal muscles can produce contractions to provide power in response to electrical stimulation, the construction of hydrogel biorobots loaded with skeletal muscle cells is a candidate for targeted drug delivery, biological sensors, and drug screen platform. As shown in Fig. 7b, researchers have optimized the geometric design and material properties of electrically responsive hydrogel biorobots using SLA 3D printing. Electric fields triggered cells in the muscle bands of the biorobot to contract and produced a net displacement with a maximum velocity of approximately 156 μm/s [178].

Mechanical-responsive hydrogels

Mechanical forces can change the matrix and chemical bonding state of hydrogels, leading to modifications in their mechanical, optical, and chemical properties. Hydrogels with good biocompatibility can be used to construct cell scaffolds and organ chips and study the behavior of cells and tissues in response to external stimuli, including chemical, electrical, and mechanical responses [179]. The mechanism of cell behavior under different mechanical forces has become an important research topic. Light-printed

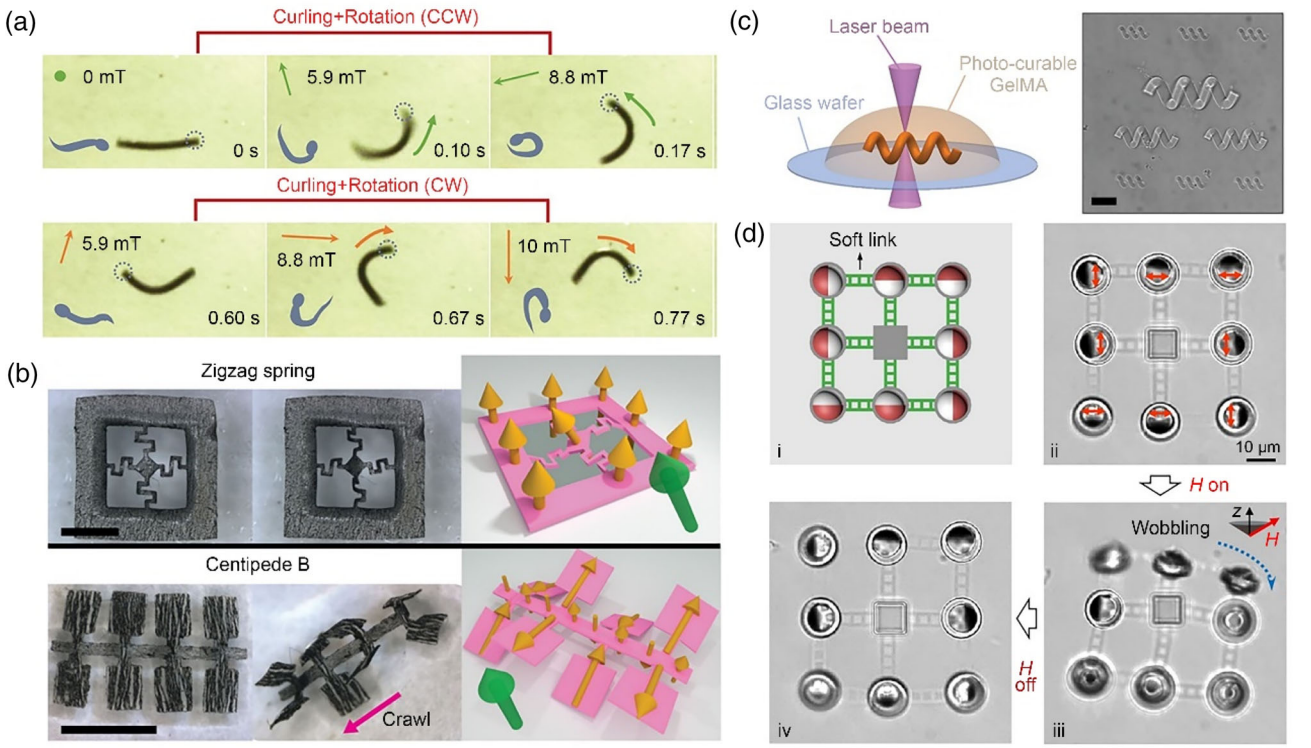


Fig. 6 Light-printed miniature structures based on magneto-responsive hydrogels. **a** Magneto-responsive LarvaBot with multiple locomotion modes printed using ultraviolet (UV) light (reproduced from Ref. [173], Copyright 2022, with permission from Wiley–VCH GmbH). **b** Magneto-responsive structures with programmable 3D magnetization fabricated via the digital light processing (DLP) technique (scale bar: 2 mm). Reproduced from Ref. [127], Copyright 2019, with permission from the authors, under exclusive licence to AAAS. **c** Magneto-responsive microhelix with ferric oxide developed through the two-photon polymerization (TPP) method (scale bar: 50 μm). Reproduced from Ref. [129], Copyright 2020, with permission from WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim. **d** Magneto-responsive networks composed of microparticles and hydrogel constructed using the TPP technique (reproduced from Ref. [130], Copyright 2021, with permission from the authors, under exclusive licence to AAAS)

mechanical-responsive hydrogels can induce cellular stress fiber orientation under cyclic stretching. The interaction with cells is remarkably enhanced under dynamic mechanical force loading (Fig. 7c). In addition to hydrogels that respond to mechanical forces, photonic crystal hydrogels (PCHs) can respond to external mechanical forces by shifting the color of their structure [180, 181]. As shown in Fig. 7d, mechanical-responsive PCHs have been processed by TPP, where the structural color of PCHs is blue-shifted under pressure.

Responsive biomaterials provide very outstanding advantages, such as good biocompatibility and degradability. Based on TPP technology, biomaterials derived from patient blood are used in the 3D printing of personalized magnetic microrobots [118]. These microrobots exhibit pH and dual magnetic–stimulus-responsive properties for controlled cargo delivery and release applications in vivo with reduced biocompatibility and safety risks. BSA is another common pH-responsive biomaterial suitable for use in the manufacture of various tunable optics [117] and microactuators [115]. The mechanical properties of biomaterials are weaker compared with those of synthetic hydrogels. Therefore, combining biomaterials and artificial hydrogel materials is a promising way to build miniaturized devices with high mechanical properties and biofriendliness.

Functions of light-printed miniature devices

Light-based 3D printing enables the construction of high-precision and arbitrary 3D stimulus-responsive devices. Continuous efforts in printing methods and smart material development enable the applications of stimulus-responsive hydrogel-based microdevices science and engineering. In this section, we focus on stimulus-responsive microdevices used for cargo manipulation, targeted drug and cell transport, active scaffolds, environmental sensing, and tunable optics.

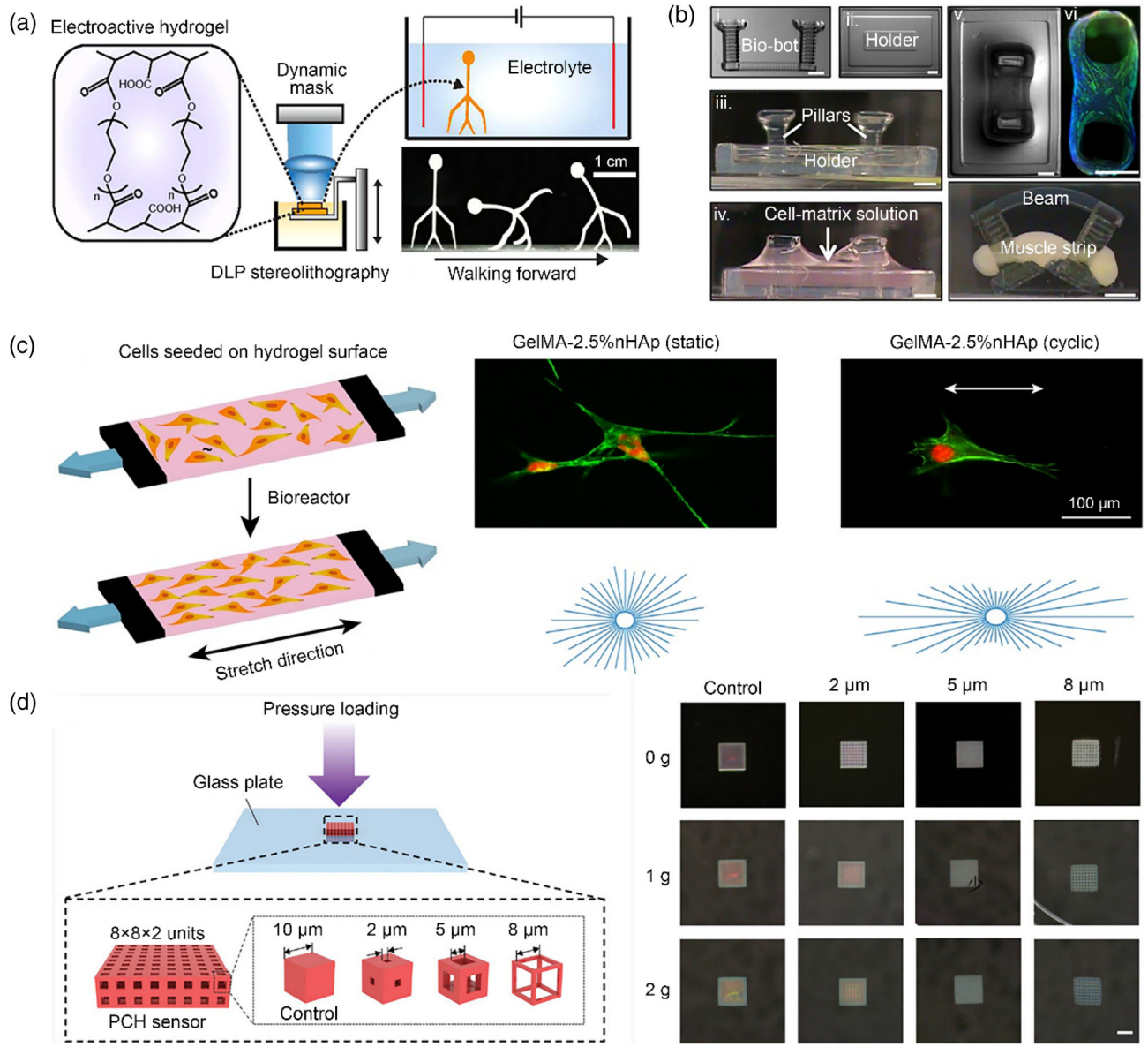


Fig. 7 Light-printed hydrogel based on electric- and mechanical-responsive hydrogels. **a** Digital light processing (DLP)-printed electroactive hydrogels enabled soft robotic manipulation and locomotion (reproduced from Ref. [132], Copyright 2018, with permission from the American Chemical Society). **b** Stereolithography 3D printing of electrically stimulated triggered biorobotic muscles (scale bar: 1 mm). Reproduced from Ref. [178], Copyright 2014, with permission from National Academy of Sciences. **c** Photo-crosslinked–mechanical-responsive nanocomposite hydrogels with enhanced interactions with cells (reproduced from Ref. [133], Copyright 2016, with permission from Wiley Periodicals, Inc.). **d** Two-photon polymerization processed–mechanical-responsive hydrogel used to construct photonic crystal with adjustable colors (scale bar: 50 μm). Reproduced from Ref. [135], Copyright 2023, with permission from Wiley–VCH GmbH

Cargo manipulation

Miniaturized actuators printed from stimulus-responsive hydrogels can operate on multiple cargo scales (from microns to centimeters). They can not only manipulate hard materials but also grip and transfer soft biological materials, such as cells and sperm [34, 179, 182–184]. A 3D-printed temperature-responsive gripper enables hollow cage grasping and transport under intelligent control of liquid temperature. When the liquid temperature was lower than the LCST, the gripper closes and grabs a cargo (approximately 10 mm) within 7 s (Fig. 8a) [120]. In addition to tethered grippers which can grip and transport cargo under an external magnetic field, wireless grippers can be fabricated based on magneto-responsive hydrogels (Fig. 8b). Given the flexible magnetic field control, the magnetic gripper enables the grasping of cargos and crossing of

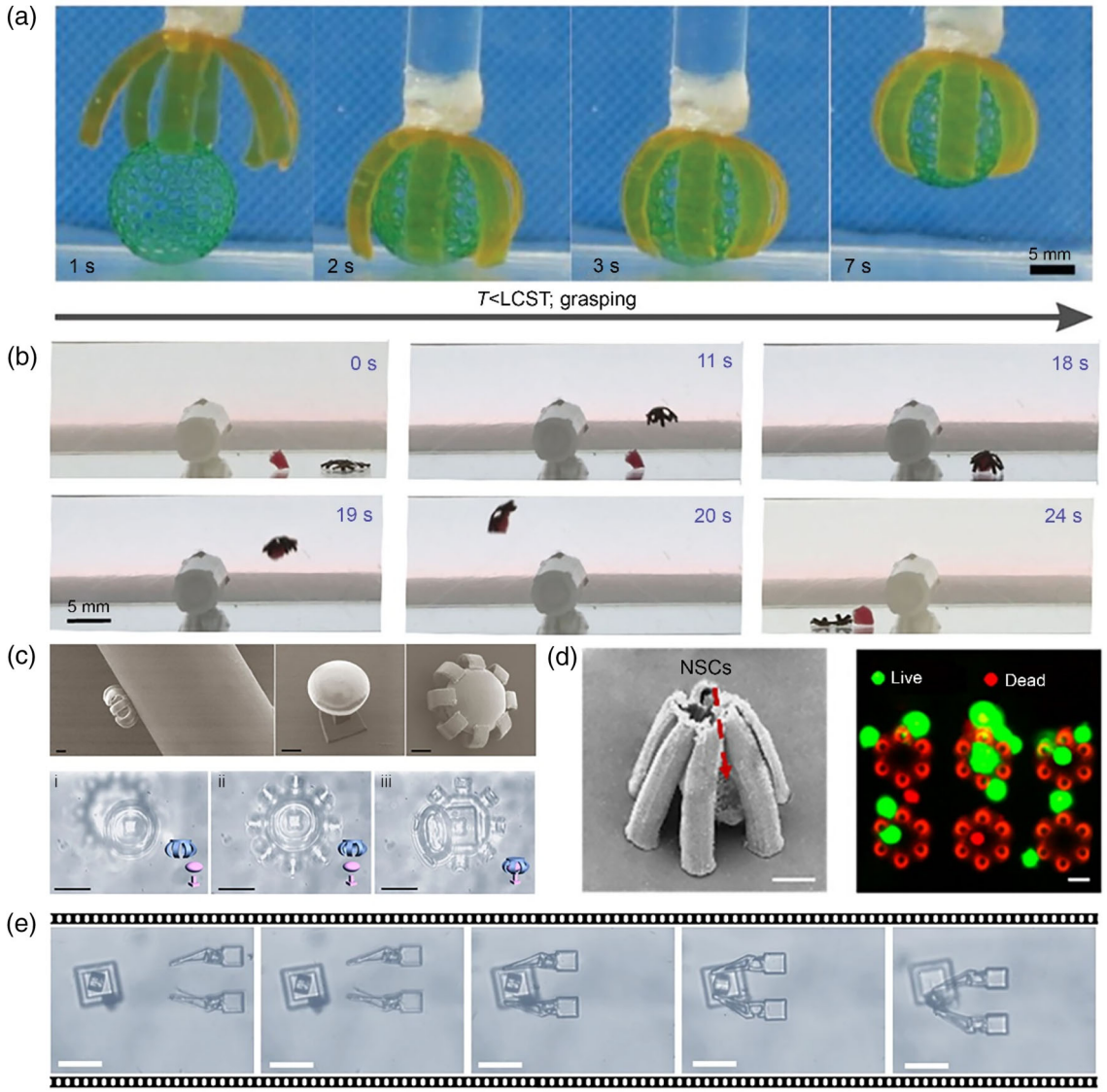


Fig. 8 Cargo manipulation based on stimulus-responsive devices. **a** Temperature-responsive gripper for cage capture and release (reproduced from Ref. [120], Copyright 2019, with permission from WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim). **b** Magneto-responsive robot for cargo transportation across barriers (reproduced from Ref. [185], Copyright 2020, with permission from the authors, licensed under CC BY). **c** Organic solvent-responsive microgripper for microparticle capture (scale bars: 10 μm for the top row and 20 μm for the bottom row). Reproduced from Ref. [186], Copyright 2019, with permission from the American Chemical Society. **d** pH-responsive 3D microgripper for neural stem cell (NSC) capture (scale bar: 10 μm). Reproduced from Ref. [184], Copyright 2020, with permission from the American Chemical Society. **e** pH-responsive artificial musculoskeletal system for microcube manipulation (scale bar: 20 μm). Reproduced from Ref. [115], Copyright 2020, with permission from the authors, licensed under CC BY 4.0

obstacles [185]. In particular, the operation of microcargos is challenging for microdevices. The stimulus-responsive microactuators developed by TPP technology allow for the controlled pickup and transfer of miniature cargos, including microparticles and cells. Zhang's group [186] developed a microactuator based on pH-responsive hydrogels, which can be used to grasp microparticles up to 10 μm in diameter. The microscopy and scanning electron microscopy images demonstrated the grasping process achieved by the microactuator (Fig. 8c). In addition, Wu's group [184] proposed a dynamic Bessel-beam TPP processing method for the fabrication of pH-responsive hydrogel microgrippers. The grippers can be used to capture neural stem cells (NSCs) in situ (Fig. 8d). Moreover, Ma et al. [115] proposed an on-chip TPP technique for the continuous fabrication of two photosensitive materials on a chip, which was accomplished

with the use of a microfluidic chip. The artificial musculoskeletal system was fabricated at the microscale, which enabled flexible clamping and transfer of microparticles on the platform (Fig. 8e). Aside from cargo grasping and transportation, light-printed hydrogel microrobots can be used to modulate the immune capacity of macrophages for potential-targeted immunotherapy applications [187].

Targeted drug and cell delivery

Benefiting from high biocompatibility and micro–nanocargo loading capability, medical robots based on hydrogels are suitable for loading drugs and cells for on-demand treatment and cell transplantation [188]. As hydrogels contain nanopore networks, drug molecules can be stored in these porous networks along with water molecules. When it reached the target area, the medical robot was stimulated to contract and extrude the drug molecules to complete precise drug delivery. Sitti's group proposed a double-helix microrobot measuring 6 μm in diameter and 20 μm in length that can actively release the chemotherapeutic drug doxorubicin (DOX) on demand using external light stimulation [104]. Exposure to UV light for 30 min with a notable decrease in fluorescence intensity indicated that DOX was cleaved and released from the microrobotic hydrogel network (Fig. 9a). In addition, precise drug release can be characterized by shape switching of stimulus-responsive microrobots. Xin et al. [111] used a dual magnetic–pH stimulus-responsive hydrogel to fabricate fish-shaped microrobots, in which the magnetic field controls motion and pH controls fish-mouth shape switching. The microrobot can release drug molecules by opening the mouth for on-demand tumor cell treatment within an artificial microcapillary (Fig. 9b). In addition, TPP-manufactured microrobots can be used for targeted cell delivery. Yasa et al. [105] printed magneto-responsive double-helix microrobots (20 μm length and 3 μm inner cavity diameter) that can load and deliver stem cells within a recapitulated cell niche. Figure 9c displays the fluorescent images demonstrating the 3D migration of cells in Matrigel. Li et al. [131] presented a burr-like porous spherical microrobot designed to carry and deliver target cells under a magnetic gradient field-driven mechanism. In vitro experiments demonstrated the capability of microrobots to release cells directly to the desired site or reach the delivery area via vascular-like microchannels (Fig. 9d). Eventually, successful cell-release experiments were conducted on nude mice. The biocompatibility and degradability of the material are critical to achieve in vivo biomedical applications. Several degradable microdevices have been successively developed for targeted drug and cell delivery [189–191]. Biodegradable microrobots were modified using DNA vaccines for targeted delivery in vivo [192]. In mice, functionalized microsphere-delivered DNA vaccines elicited rapid, enhanced, and persistent antigenic expression, which possibly led to prolonged protection. To improve the biosafety of microrobots for in vivo applications, researchers have proposed the modification of functional materials, such as polyethylene glycol (PEG), dextran, and silica (SiO_2) [193], on the surface of these magnetic particles to enhance their biocompatibility. In addition, the degradation rate of hydrogel microrobots in vivo can be precisely tuned by controlling the percentage of hydrogel precursors and the degree of photopolymerization, preventing degradation that is extremely slow to lead to thrombosis or extremely fast to lose their function [193, 194].

Active scaffold

Hydrogels have great potential as scaffolds in tissue engineering due to their porous structure, which supports cell proliferation, migration, and differentiation and allows nutrient transport [136, 195–199]. Stimulus-responsive hydrogels have been developed as active scaffolds to resolve blood vessel and airway blockages. Shape-memory hydrogels fabricated using DLP printing technology can open stents at the target position in response to room temperature in a time-programmed manner (Fig. 10a). The hydrogel programs the recovery onset delay using the degree of phase separation, which provides a unique mechanism for the preparation of shape-memory devices with controllable trigger times [134]. A temperature-responsive hydrogel consisting of gelatin methacryloyl (GelMA) and PEG dimethacrylate was developed for DLP 3D printing. The technique achieves structural anisotropy using light absorber-induced differential crosslinking, leading to rapid deformation of hydrogel scaffolds upon hydration (Fig. 10b). Tubular hydrogel structures hold considerable potential for a variety of tissue engineering applications, including regeneration and disease modeling [195]. Light-triggered cardiac structures with highly aligned microstructures and tunable curvature have also been fabricated using the same DLP-based printing technique (Fig. 10c). Remote light-triggered–shape-adjustable heart cell scaffolds can further inspire researchers to explore mechanical forces that improve heart function [198]. As the precision of light-based printing processing increases to the micro to nanometer scale, microscaffolds for studying the mechanisms of cellular behavior will be the center of scientific queries. Currently, most cellular microscaffolds are fabricated by femtosecond laser TPP technology. Cellular microscaffolds composed of stimulus-responsive hydrogels have adjustable shapes (Fig. 10d). Changes in the shape of microscaffolds generate mechanical forces on the cells, and the resulting mechanisms of cell behavior can be studied in situ [136]. Moreover, stimulus-responsive cellular microscaffolds can be applied as drug-molecule-loading and releasing structures and microplatforms for the assessment

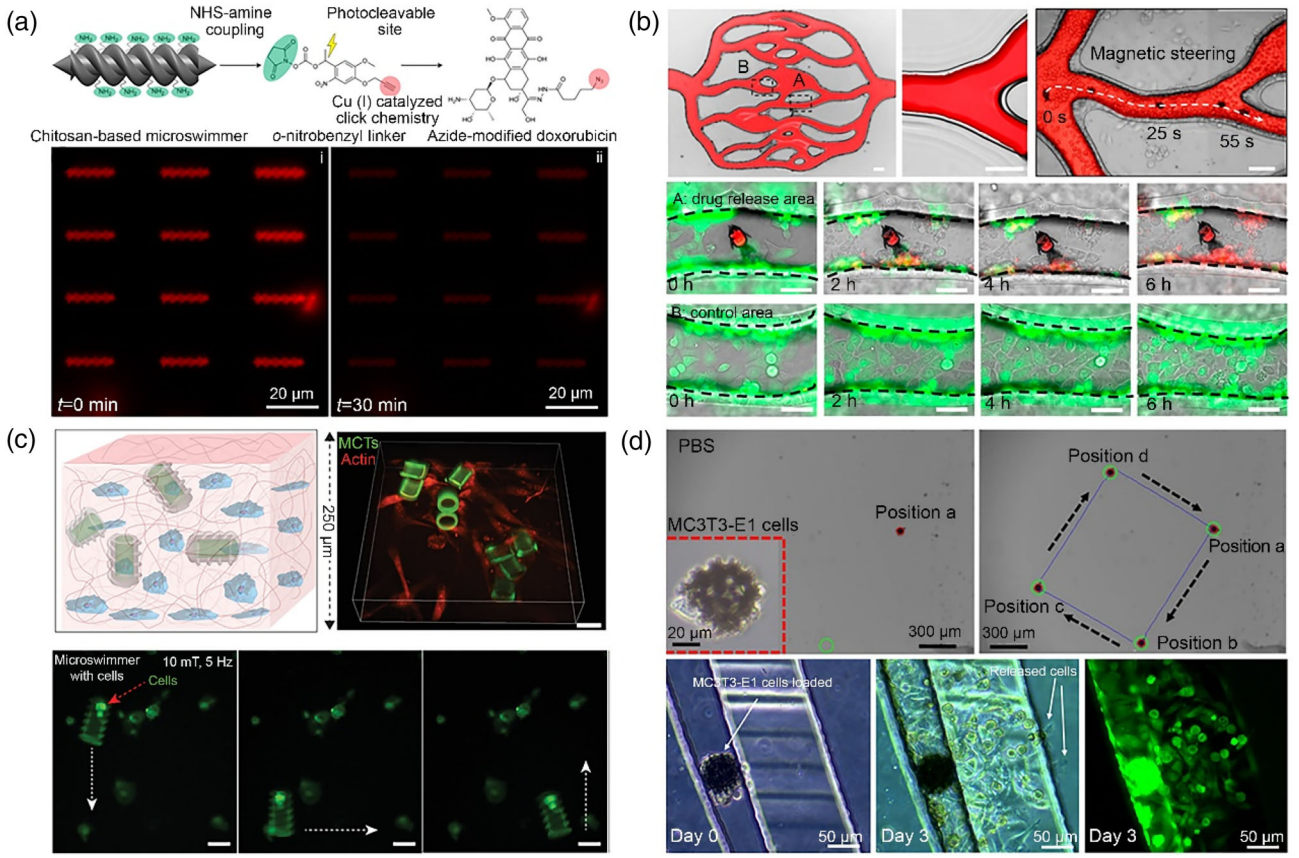


Fig. 9 Targeted drug and cell delivery based on stimulus-responsive devices. **a** Light-responsive microhelix enabled precise drug release under ultraviolet (UV) light (reproduced from Ref. [104], Copyright 2018, with permission from the American Chemical Society). **b** pH-responsive microfish enabled on-demand drug delivery via its open mouth (scale bars: 100 μm for the first row and 50 μm for the second/third row). Reproduced from Ref. [111], Copyright 2021, with permission from the American Chemical Society. **c** Magneto-responsive microrobots enabled stem cell delivery within a recapitulated cell niche (scale bars: 60 μm for the top row and 50 μm for the bottom row). Reproduced from Ref. [105], Copyright 2019, with permission from WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim. **d** Magneto-responsive microrobots enabled loading of various cells (MC3T3-E1 and mesenchymal stem cells (MSCs)), their delivery, and release (reproduced from Ref. [131], Copyright 2018, with permission from the authors, under exclusive licence to AAAS)

and monitoring of the therapeutic efficacy of cancer cells (Fig. 10e) [113].

Environmental sensors

The advancements in light-based 3D printing technology and stimulus-responsive materials paved the way for the development of several types of miniaturized devices for environmental sensing. These sensors can detect changes in chemical and physical signals, such as liquid pH and heat [114, 123]. An optical maskless SLA technique with large-area, high-precision patterning of pH-stimulated responsive hydrogels has been proposed [114]. The technique can be used for high-precision patterning printing on fiber surfaces and in high-precision pH sensors (Fig. 11a), which can exhibit a distinguishable pH change of 0.0027. Maldonado et al. reported a 3D-printed composite object made of non-porous coordination hydrogels. This composite device was used as a water sensor in organic solvents. Figure 11b shows that the 3D device appears blue in air and purple when in organic solvents, such as ethanol, methanol, and tetrahydrofuran [108]. In addition to chemical changes, miniature sensors can detect physical quantities. Temperature is a common sensing indicator among the many physical quantities. A developed soft hydrogel-based actuator can sense temperature changes and sweat autonomously to keep the body temperature stable [123]. In a strong convective environment, the sensor can sense changes in the surface temperature and demonstrate strong thermoregulation through its sweating (Fig. 11c). Furthermore, microrobots can be used to detect and absorb toxins. Figure 11d demonstrates that the hydrogel microfish processed using microscale continuous optical printing technology can be used to modify polydiacetylene (PDA) nanoparticles for toxin sensing and detoxification. The decreased fluorescence intensity indicated the uptake of environmental toxins by microfish [128]. In particular,

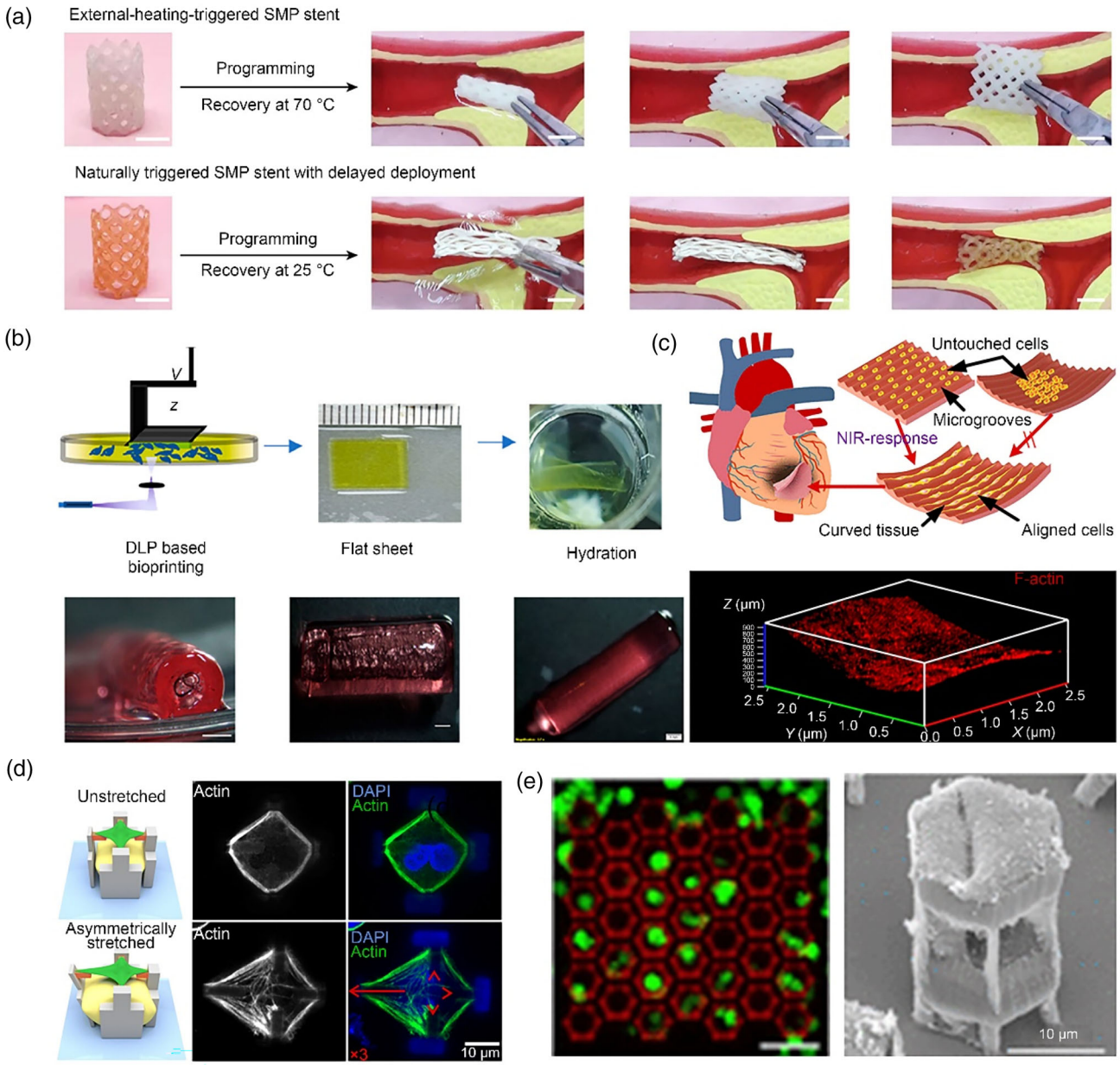


Fig. 10 Active scaffolds based on stimulus-responsive hydrogels. **a** Hydrogel polymer scaffolds with time-programmed shape memory for on-demand medical deployment (scale bar: 10 mm). Reproduced from Ref. [134], Copyright 2023, with permission from the authors, under exclusive licence to Springer Nature Limited. **b** Visible-light digital light processing (DLP) printing of responsive hydrogel cell scaffolds for tissue regeneration engineering (scale bar: 1 mm). Reproduced from Ref. [195], Copyright 2023, with permission from the American Chemical Society. **c** Generation of curvature-tunable myocardial tissue scaffolds using DLP printing technology (reproduced from Ref. [198], Copyright 2021, with permission from the American Chemical Society). **d** Stimulus-responsive cellular scaffolds based on two-photon polymerization for the study of force-responsive behavior of cells (reproduced from Ref. [136], Copyright 2020, with permission from the authors, under exclusive licence to AAAS). **e** pH-responsive 3D microscaffolds for cell proliferation (reproduced from Ref. [113], Copyright 2022, with permission from the American Chemical Society)

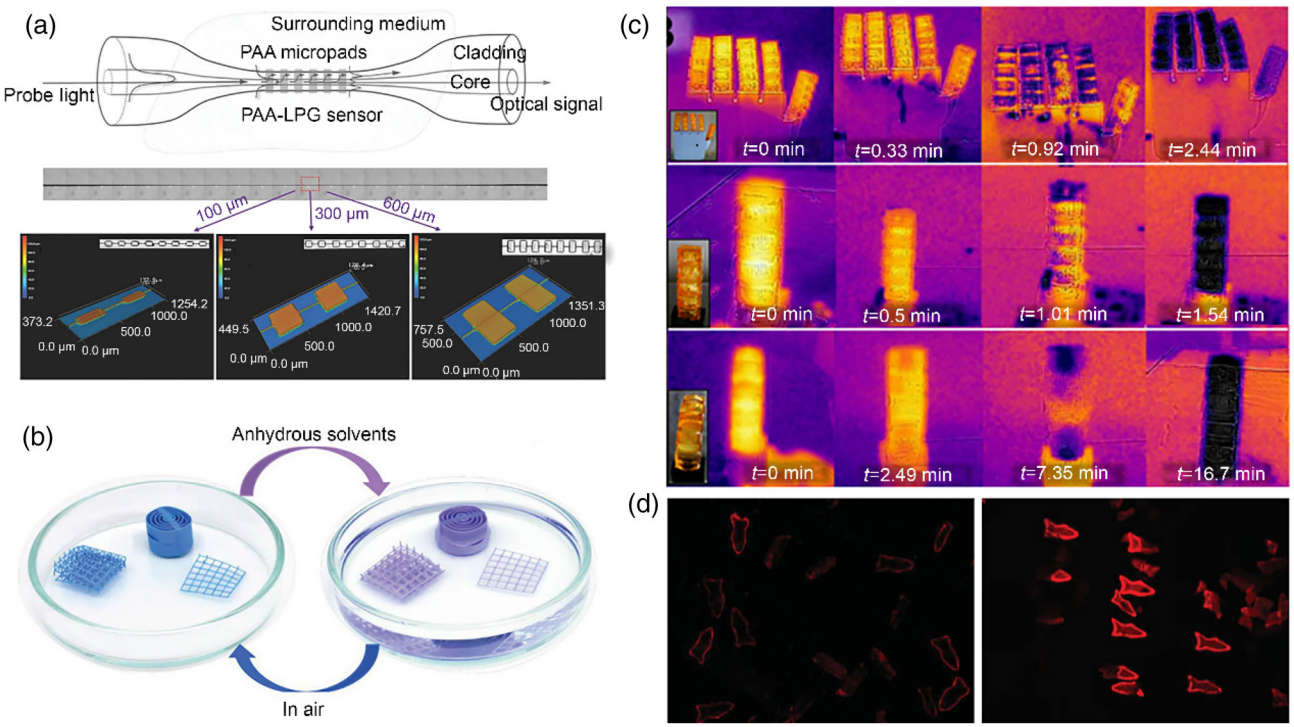


Fig. 11 Precise sensing based on stimulus-responsive devices. **a** Ultrasensitive fiber-optic pH sensor fabricated using the digital light processing (DLP) technique (reproduced from Ref. [114], Copyright 2015, with permission from WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim). **b** 3D-printed organic solvent sensor used to detect dry solvents, such as ethanol, methanol, and tetrahydrofuran (reproduced from Ref. [108], Copyright 2019, with permission from WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim). **c** Hydrogel actuator with temperature sensing and thermoregulation capability by autonomous sweating through microscopic pores (reproduced from Ref. [123], Copyright 2020, with permission from the authors, under exclusive licence to AAAS). **d** DLP-printed microfish with toxin sensing and removal capacity (reproduced from Ref. [128], Copyright 2015, with permission from WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim)

the types of sensing and detection substances can be flexibly adjusted using functional materials, and these miniature devices are expected to become application platforms with powerful environmental sensing capabilities in the future.

Tunable optical devices

Various tunable microoptical devices that can dynamically adjust parameters, such as the focal length, FOV, and phase of a light beam, have been developed to adapt to dynamic imaging and display requirements [200, 201]. Compared with traditional rigid optical devices, tunable optical devices show stronger adjustability and environmental adaptability. Chen et al. [202] proposed a novel light-based 3D-printed hydrogel with excellent toughness and stretchability (up to 1500%), which can exhibit different light transmissions above and below the LCST. When the temperature was below the LCST, the light transmission can reach as high as 85.847%. By contrast, when the temperature was above LCST, the light transmission decreased by 79.332%. Thus, the optical device fabricated using the SLA technique holds wide application prospects for the next generation of smart windows (Fig. 12a). In addition, Sun's group [116] constructed focal tunable microlens based on femtosecond laser direct writing technology. The microlens consisted of pH-responsive hydrogels that can reversibly change their focal length with the alterations in pH (Fig. 12b). In addition, inspired by the eye of flies, the same group prepared a smart compound eye based on pH-responsive hydrogels [117]. Benefiting from the size variation of hydrogels under different pH conditions, the compound eye enables the adjustment of FOV (35°–80°) and variable focal length (Fig. 12c). Miniature devices with tunable structural colors have also shown tremendous development, with structural color devices based on shape-memory polymers and liquid–crystal elastomers exhibiting high tuning and recovery capabilities in the air. By contrast, stimulus-responsive hydrogels are suitable for building microdevices with tunable structural colors underwater. Wu's group developed color-tunable 3D photonic crystals in liquid based on pH-responsive hydrogels [112]. Each color block was a 3D woodpile structure, and by regulating the spacing of the woodpile structure, different colors can

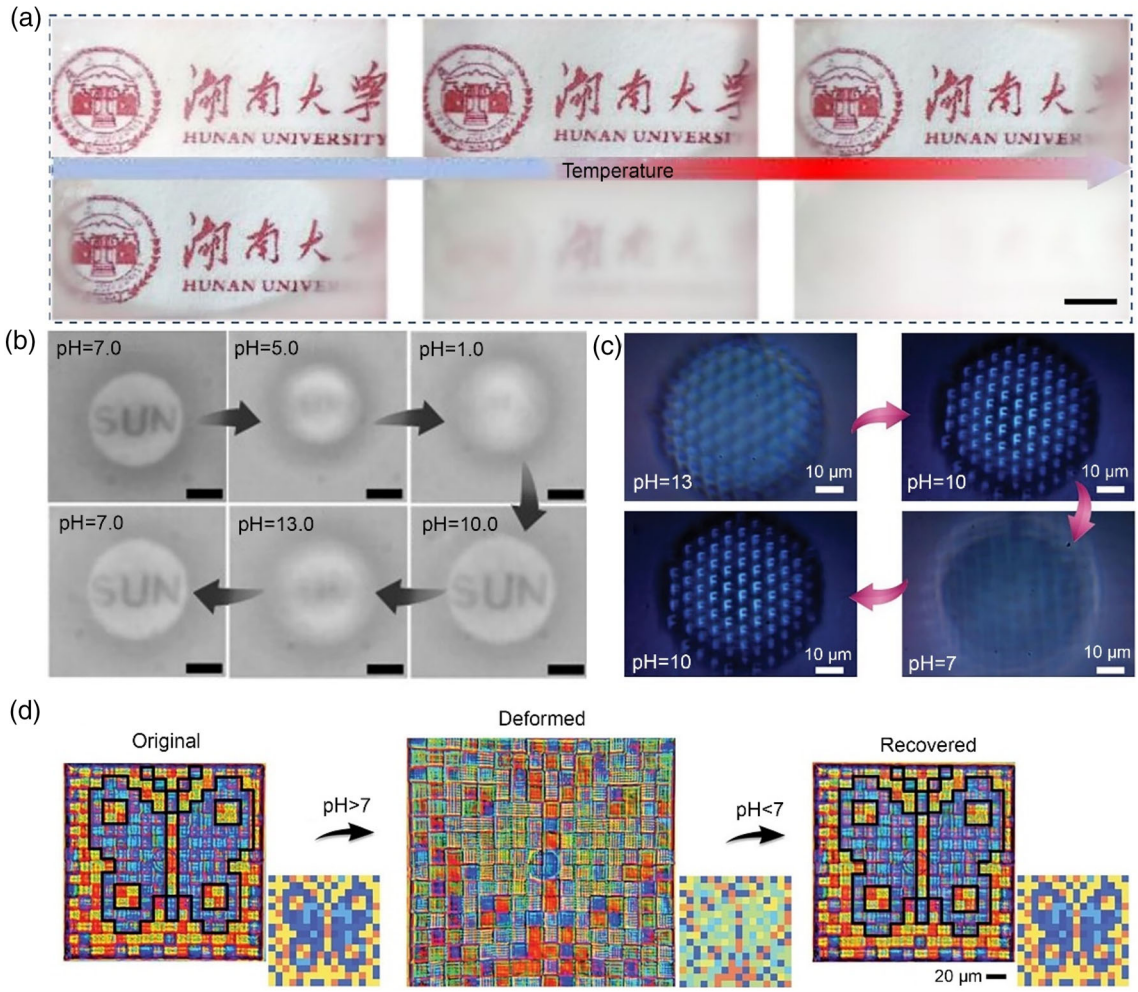


Fig. 12 Tunable optical devices based on stimulus-responsive hydrogel. **a** 3D-printed–temperature-responsive smart windows with adjustable transmittance (scale bar: 5 mm). Reproduced from Ref. [202], Copyright 2022, with permission from the authors, licensed under CC BY 3.0. **b** pH-responsive microlens with a tunable focal length based on two-photon polymerization (TPP). Scale bar: 10 μm. Reproduced from Ref. [116], Copyright 2012, with permission from Wiley–VCH Verlag GmbH & Co. KGaA, Weinheim. **c** pH-responsive compound eyes with a tunable field of view (FOV, 35°–80°) and variable focal length (reproduced from Ref. [117], Copyright 2019, with permission from WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim). **d** pH-responsive microlattice with tunable structural colors (blue to red) based on TPP (reproduced from Ref. [112], Copyright 2022, with permission from Wiley–VCH GmbH)

be displayed at different pH. Thus, by arranging and combining multiple woodpile structures, colored structural surfaces with encryption functions were constructed (Fig. 12d).

Conclusions and perspective

Tunable 3D-printed miniaturized devices have achieved tremendous advances and developments in the past decade. This paper summarizes the state-of-the-art light-based 3D printing technologies and stimulus-responsive hydrogel materials and describes the applications of miniaturized functional devices developed based on the above technologies and materials for cargo manipulation, targeted drug and cell delivery, active scaffolds, environmental sensing, and tunable optical devices. Although miniaturized devices with stimulus responsiveness demonstrate many unique advantages, a number of challenges must be overcome for their extensive adoption as practical tools for real-world applications. The following points should be considered before these devices are industrially applied (Fig. 13).

First, strong mechanical properties, including high strength, toughness, and self-healing properties [203], should be further enhanced. Whether for microrobots for medical applications or miniature devices for optical modulation, high mechanical properties are crucial to environmental adaptability and robustness to cope with complex and

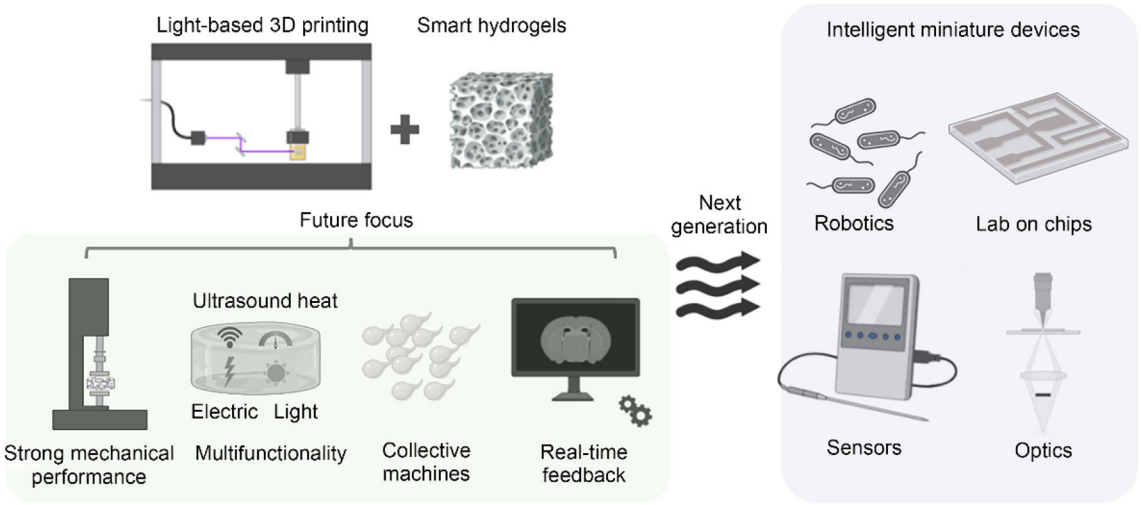


Fig. 13 Future developments and research directions for the next generation of intelligent miniature devices

severe application scenarios. The weak mechanical properties of existing stimulus-responsive hydrogels are insufficient for long-term and cyclic applications. Thus, continuous enhancement of the mechanical properties of hydrogels is essential [204]. Second, multifunctional integration is also a key to expanding the application range of miniature devices. Current devices are well suited for single or dual functions. Magnetic fields enable the flexible and controlled motion of miniature machines in 3D space, and pH-responsive hydrogels exhibit stable environmental pH-sensing capabilities. However, the integration of multiple functions into a single device remains challenging. Multifunctionality often implies the precise integration of multiple materials that requires further development of multi-material light-based 3D printing technology [205–207], especially for devices at the microscale. More importantly, additional effort should be put into the research on collective machines composed of multiple microdevices. In general, compared with individual devices with limited manipulation capabilities and functionalities, collective machines can accomplish more complex tasks through synergies between multiple devices [208, 209]. In the field of robotics, various robot collectives ranging from macro to microscales have been developed [210–212]. Typically, magnetically driven microcollectives exhibit powerful manipulation capabilities, such as caging of large objects, interface manipulation, and 3D cooperative assembly. In addition, in the field of optics, micromirror arrays comprising a plurality of microlens can be used to modulate the beams [213, 214]. Advanced light-printed stimulus-responsive hydrogels have considerably increased the complexity and intelligence of individual microdevices, and their smart collectives supposedly exhibit high environmental adaptability and functionality. Finally, real-time status feedback and adjustment endow miniature devices with high controllability and intelligence. Most of the current devices verify the feasibility of positive actuation function. However, real-time state monitoring, feedback, and device adjustment during operation are still lacking. For medical devices aimed at targeted drug delivery, providing real-time feedback on their drug release rates in practical applications remains difficult, and it can only be roughly estimated through normalization experiments, which is inapplicable to scenarios that require precise drug delivery. In addition, small changes in the operating environment of optical devices can have a huge influence on their imaging. Therefore, real-time feedback components must be added to existing tunable optical device systems. The incorporation of artificial intelligence computation within miniature devices may be considered for the improvement of signal processing and feedback in miniature devices [215–217]. The next phase of microdevice development will focus on a complete system of execution, feedback, and adjustment.

In summary, the development of the next generation of microdevices will prioritize intelligent microdevices, which will also have promising applications in areas, such as robotics, lab on chips, sensors, and optics. Intelligent microdevices are an emerging field at the intersection of engineering, materials science, mechanics, robotics, optics, and biomedicine. Close collaboration between researchers in the academia with diverse expertise in different fields and industry is needed to realize stimulus-responsive microrobots that can perform therapeutic functions in vivo and optical devices that can be tuned under complex operating conditions.

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Author contributions Conceptualization was contributed by CX and LZ; writing–original draft was done by CX and NX; writing–review and editing was done by CX and LZ; funding acquisition was involved by LZ; and supervision was performed by LZ.

Data availability All data are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest LZ is an editorial board member for *Bio-Design and Manufacturing* and was not involved in the editorial review or the decision to publish this article. On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical approval This article does not contain any studies with human or animal subjects performed by any of the authors.

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