

Review

Two-Photon Polymerization-Enabled Microrobots: Fabrication, Actuation, and Biomedical Applications

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How To Cite: Chen, J.; Jin, D.; Xin, C.; et al. Two-Photon Polymerization-Enabled Microrobots: Fabrication, Actuation, and Biomedical Applications. *Advanced Mechatronics* **2026**, *1*(1), 5.

Publication History

Received: 23 June 2026

Revised: 24 July 2026

Accepted: 4 September 2026

Published: 15 September 2026

Abstract: Microrobots are being explored for biomedical tasks in complex and confined *in vivo* environments. Clinical translation, however, remains limited by manufacturing bottlenecks, including the submicron integration of heterogeneous functional materials. Two-photon polymerization (TPP) addresses part of this challenge by enabling free-form three-dimensional fabrication and the integration of multiple functional materials, including stimulus-responsive formulations. When printed structures undergo time-dependent changes in response to external stimuli, the process is commonly termed 4D microprinting. This review connects the fabrication principles of TPP-enabled microrobots with their actuation strategies and emerging biomedical applications. We examine innovations in materials science, including programmable hydrogels and liquid-crystal elastomers, together with structural strategies such as biomimetic topologies and 4D multi-material integration. We then evaluate magnetic, optical, acoustic and hybrid actuation strategies that control microrobots in biologically relevant settings. Finally, we discuss cross-scale applications in targeted therapeutic delivery, single-cell micromanipulation, 3D tissue engineering, deep-tissue imaging, *in vivo* fabrication and long-term implantation. Together, these studies define the current capabilities of TPP-enabled microrobots and the remaining constraints in fabrication throughput, material compatibility, biocompatibility and autonomous operation.

Keywords: two-photon polymerization; microrobots; 4D microprinting; multiphysics actuation; biomedical applications

1. Introduction

Microrobots have emerged as a platform in biomedical engineering, with potential in targeted drug delivery, minimally invasive surgery, *in vivo* monitoring and cellular manipulation [1,2]. Their value stems from their ability to navigate complex and confined biological environments that conventional tools cannot access, creating new opportunities for precision medicine. However, the early view of microrobots as static carriers for passive transport no longer meets the demands of realistic biological systems [3]. The field is therefore shifting toward microrobots that combine sensing or localization, state estimation and feedback control

with stimulus-responsive structures [4–6]. In this review, intelligent operation denotes the use of these capabilities to adapt microrobot behavior to task and environmental constraints. Such capabilities may support clinical translation by helping microrobots traverse physiological barriers, perform *in situ* operations and interact with heterogeneous biological microenvironments [7,8].

Despite their promise in biomedical applications, microrobots remain fundamentally constrained by the complexity of the *in vivo* environment. Rapid blood flow, intricate tissue barriers and the risk of immune rejection impose stringent requirements on structural integrity, precise navigation and biocompatibility [9,10]. A further



manufacturing bottleneck arises at the submicron scale, where soft and rigid components must be integrated and stimulus-responsive materials must be positioned with high precision. In this context, two-photon polymerization (TPP) is a suitable fabrication platform because it combines localized three-dimensional writing with compatibility across multiple photocurable and functional material systems [11]. TPP supports complex three-dimensional architectures and can generate 4D systems when printed structures undergo time-dependent responses to stimuli. Examples include pH- and temperature-responsive hydrogels [12] and liquid-crystal elastomers (LCEs) for light-triggered actuation [13]. This capability helps overcome long-standing barriers to multi-material integration at the microscale [14,15]. The same platform also accommodates highly magnetizable materials [10] and biomimetic topological designs [16], enabling microrobots that can be powered and controlled by single or coupled physical fields, such as magnetic, acoustic and optical fields, for controlled navigation and task-specific function in complex biological fluids [17–19].

Although individual aspects of microrobot fabrication and application have advanced substantially, a coherent

synthesis connecting the basic principles of TPP with final biomedical use remains limited. This review addresses that gap by tracing the development of TPP-fabricated microrobots from fabrication principles to biomedical applications. We first summarize recent innovations in materials science and structural design, emphasizing the roles of multi-material and 4D printing strategies and biomimetic topology optimization. We then examine actuation and motion-control strategies based on magnetic, optical, acoustic and hybrid fields, highlighting their functions and synergies. The core of the review critically evaluates the translational relevance of these technologies across three biomedical application domains: targeted precision therapy, including drug and gene delivery; cellular micromanipulation and 3D tissue engineering; and advances in deep-tissue imaging, *in vivo* navigation and direct *in vivo* fabrication. By integrating these connected areas, the review provides a broad view of the field and highlights the potential of TPP-enabled microrobots to address persistent barriers to clinical translation. Figure 1 summarizes the scope of this review across fabrication and structural design, actuation and motion control, and biomedical applications.

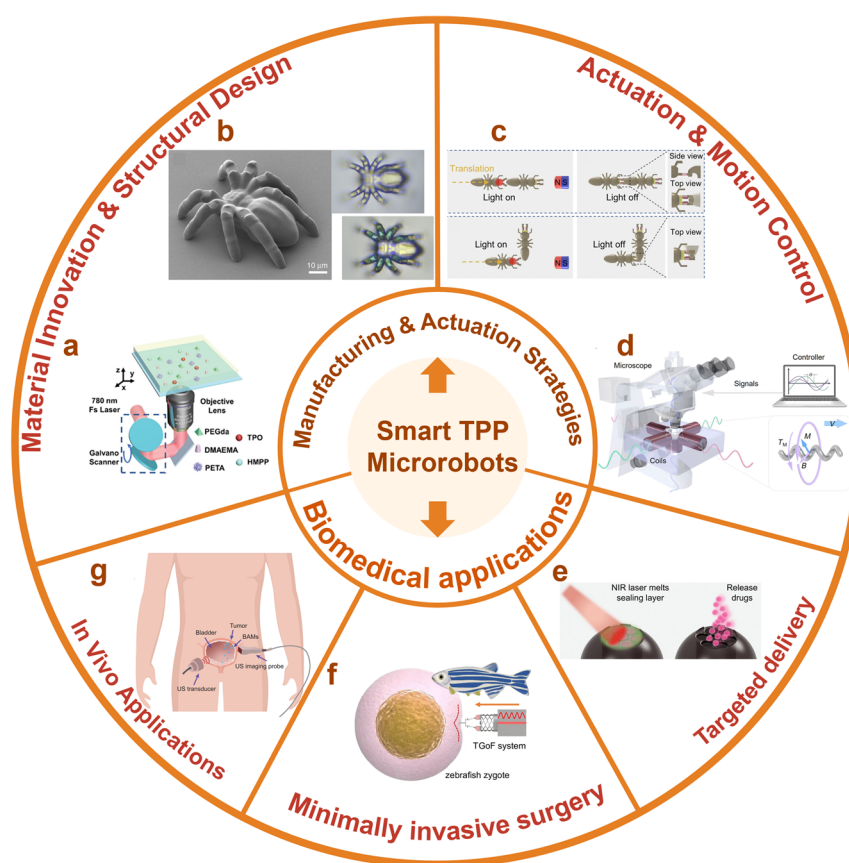


Figure 1. Overview of TPP-enabled microrobots spanning fabrication and structural design, actuation and motion control, and biomedical applications. (a) Fabrication of pH- and temperature-dual-responsive hydrogel micro-actuators. Adapted with permission from Ref. [12]. Copyright 2023, Wiley-VCH GmbH. (b) Spider-inspired microhydraulic structures [16]. (c) Magneto-optically coupled actuation of microrobot collectives [20]. (d) Actuation of hard-magnetic microrobots [10]. (e) Drug-delivery microrobots [21]. (f) Single-cell gripping microrobots [22]. (g) Deep-tissue imaging and tracking [9].

2. Fabrication and Actuation of TPP-Enabled Microrobots

2.1. Fundamentals of TPP-Enabled Microrobot Fabrication

Microrobots impose coupled manufacturing demands because their propulsion, deformation, payload handling and environmental interactions depend on three-dimensional geometry, local mechanics and functional-material placement. Two-photon polymerization (TPP) is most useful when performance requires free-form helices, cavities, overhangs, compliant hinges or submicrometer features that are difficult to produce by planar lithography or layerwise printing. These task-specific advantages do not imply universal superiority. Rather, TPP combines localized voxel writing with photocurable and functional resins, supporting small-batch production of task-specific microrobots [2,4,23].

In TPP, a focused femtosecond laser irradiates a resin containing monomers or oligomers and a photoinitiator. Near-simultaneous absorption of two photons excites the initiator and generates radical or cationic species. Polymerization becomes appreciable where the local dose exceeds the effective threshold [11,24]. This nonlinear response confines polymerization around the laser focus, which is translated through the resin to assemble overlapping voxels. Each voxel is typically elongated along the optical axis because its dimensions reflect both the optical point-spread function and resin kinetics. Consequently, attainable feature size depends on numerical aperture, laser dose, initiator efficiency, resin chemistry, oxygen inhibition and development conditions, rather than wavelength alone. Optimized formulations have yielded lines as narrow as 20–47 nm, although such values do not represent routine three-dimensional resolution across materials and geometries [25].

A typical workflow comprises computer-aided design, slicing and hatching, laser exposure, development, post-

curing or drying, release and, when required, functionalization. Process choices propagate directly into robot performance. Laser power and scan speed jointly determine dose, whereas slice and hatch spacing control voxel overlap, surface quality and build time [11,24]. Conversion and crosslink density also influence stiffness, swelling and dimensional stability. Microrobots add release-specific constraints because hinges and enclosed channels must remain free, while slender elements can deform during development or drying. Particle-loaded resins or post-print modification can introduce magnetic, photothermal or imaging functions. However, increasing nanoparticle loading can raise optical absorption and scattering or exceed the dispersibility limit, narrowing the processing window [26]. Round-robin testing of commercial TPP systems achieved submicrometer features with high-numerical-aperture objectives. Yet fidelity deteriorated markedly below 1 μm and varied with the objective, resin and writing strategy [27].

TPP thus provides a combination of local feature control and free-form three-dimensional fabrication, including suspended, helical, hollow and internally structured architectures. These capabilities are offset by voxel-wise writing, restricted build volumes, costly ultrafast optics and sensitivity to shrinkage, development and release. Holographic and multifocal exposure can increase throughput, but resin kinetics, power distribution and field uniformity remain important constraints [28–30]. Alternative methods occupy complementary design spaces. Projection stereolithography supports layer-parallel batch production, direct ink writing accommodates highly filled or soft inks, and inkjet printing enables programmable droplet placement. Laser-induced forward transfer provides nozzle-free local deposition. Accordingly, Table 1 presents common three-dimensional printing methods for microrobot fabrication and their principal process characteristics.

Table 1. Process-level comparison of TPP and other three-dimensional printing routes relevant to microrobot fabrication.

Fabrication Method	Working Principle	Resolution	Representative Materials	Advantages	Limitations	Refs.
Two-photon polymerization/lithography (TPP/TPL)	A focused femtosecond beam induces nonlinear two-photon absorption; the voxel is scanned or multiplexed in 3D.	100 nm	Acrylate/epoxy resists; hybrid polymers; hydrogels; particle-loaded resists	Sub-100-nm capability; free-form 3D; overhangs; parallel multi-focus variants	Low throughput; costly optics; small build volume; shrinkage or development errors	[25,29,30]
Laser-scanned stereolithography (SLA)	A laser scans each layer; liquid-interface variants reduce window adhesion.	10 μm	Photopolymers; hydrogels; particle-filled resins	Mature hardware; smooth surfaces; scalable area; continuous variants	Point scanning; stiction; supports; cure-depth–speed trade-off	[31]
Projection microstereolithography (micro-SLA)/digital light processing (DLP)/continuous liquid interface production (CLIP)	A digital micromirror device (DMD) or liquid-crystal display (LCD) exposes a full layer; CLIP uses an oxygen-inhibited dead zone for continuous growth.	25 μm	Poly(ethylene glycol) diacrylate (PEGDA); acrylate/urethane resins; hydrogels; particle-filled resins	Layer-wide exposure; high throughput; large-area tiling; batch production	Resolution–area trade-off; stitching or overcuring; support removal	[32,33]

Table 1. Cont.

Direct ink writing/ microextrusion (DIW)	A viscoelastic ink is extruded and stabilized by 50 μm rheological recovery, gelation or curing.	Hydrogels; elastomers; particle inks; cell-laden bioinks	Broad materials; high filler loading; cell-compatible; gradients	Clogging; spreading or sagging; anisotropy; nozzle-limited resolution [34,35]
Inkjet/material jetting	Piezoelectric nozzles deposit droplets that are cured or solidified; vision feedback can correct subsequent layers. 50 μm	Acrylates; thiolenes; epoxies; conductive or biological inks	Fast multi-material printing; voxel-level composition; feedback correction	Low-viscosity inks; clogging or cross-talk; spreading; support removal [36]
Laser-induced forward transfer (LIFT)	A pulsed laser transfers a donor voxel or jet to a receiver; repeated transfers form 2D/3D deposits. 10 μm	Metals; nanoparticle inks; polymers or hydrogels; cells or biomolecules	Nozzle-free; contactless; viscous or particle-rich inks; localized multi-material deposition	Donor preparation; fluence and gap sensitivity; satellites and porosity; limited continuous 3D geometry [23,37,38]

2.2. Materials Innovation and Structural Design

TPP is particularly useful for spatially integrating multiple materials within complex three-dimensional architectures, although serial writing, material compatibility and post-processing constrain this capability. This combination supports environmental sensing and programmable shape change in microrobots [39]. Progress from stimulus-responsive monomers to heterogeneous multi-material integration and biomimetic design has tightly coupled materials development with structural innovation, advancing microrobots for biomedical applications.

2.2.1. Stimulus-Responsive Materials

Environmental sensing and programmable deformation in microrobots depend heavily on stimulus-responsive materials. Among conventional physical stimuli, thermoresponsive microactuators based on poly(*N*-isopropylacrylamide) (pNIPAM) hydrogels exploit phase-transition behavior to capture single cells efficiently [40]. Voxelated designs further overcome the limits of isotropic swelling and enable complex twisting motions [41]. To expand the range of responses, asymmetric composite hydrogels containing functional monomers have achieved cooperative pH and temperature actuation [12] (Figure 2a), whereas conjugated-polymer-doped LCEs enable efficient photothermal actuation under near-infrared light without particle aggregation [13]. Chemical responsiveness and mechanical shape-memory materials further enhance microrobot autonomy. Ennis and colleagues developed a phenylboronic-acid-based photoresist whose microstructures undergo rapid osmotic swelling after binding target saccharide analytes, demonstrating a route toward biochemical sensing *in vivo* [42] (Figure 2b). Minnick and colleagues found that TPP-printed microfibers display a shape-memory effect in water and recover their original shape after tensile strain is released [43]. By synthesizing network polymers with tailored functional groups, researchers can integrate tunable pH response, programmable fluorescence

and other multidimensional functions within a single microstructure [44].

2.2.2. Multimaterial Integration and 4D Printing

To overcome the deformation limits of homogeneous actuators, the spatial integration of heterogeneous materials within a single structure, such as rigid skeletons and soft actuators, provides one route to programmable four-dimensional (4D) shape change. Ma and colleagues demonstrated this concept by combining a rigid SU-8 skeleton with pH-responsive protein as an artificial muscle, showing the feasibility of programmable integration of multi-responsive materials [45] (Figure 2c). Rigid hybrid polymers and soft hydrogels have also been used to fabricate magnetically deformable 3D cell-culture substrates [46]. Interpenetrating polymer networks (IPNs) are widely used to control internal stress and material distribution. Acrylate-epoxy IPNs have achieved highly elastic deformation with megapascal-scale moduli [47], whereas poly(ethylene glycol) (PEG) hydrogels containing two independent IPNs enable reversible switching between soft and stiff states by controlling the sequence of enzymatic degradation for mechanobiology studies [48]. Multi-material concepts extend beyond conventional lithography. Abele and colleagues printed hydrogel transmembrane structures inside preformed giant lipid vesicles to serve as DNA transport channels [49]. In parallel, modular design combined with particle printing has enabled polymer chains to connect functional colloids, creating assembly machines that can manipulate DNA particles with precision [14,50]. Together with rapid single-exposure vortex beams [18] (Figure 2d) and dynamic holographic multifocal techniques [51], these approaches have increased the throughput and structural complexity of multi-material 4D manufacturing.

2.2.3. Biomimetic and Structurally Optimized Design

Materials define the functional basis of microrobots, but biomimetic topology and structural design can provide additional physical and locomotor advantages. In external

morphology, patterned devices inspired by plant barbs achieve strong adhesion on rough substrates [52] (Figure 2e). Flexible microstructures inspired by springtail skin enable magnetically controlled switchable wettability across nearly all solvents [53]. Tan and colleagues combined a magnetically responsive SU-8 body, a laser-programmed hydrogel helical tail and a rigid TPP-printed end effector to create flagella-inspired multi-material micro-swimmers whose geometry and propulsion adapt across solvent environments, enabling

confined-gap traversal and targeted object delivery [54] (Figure 2f). Biomimetic design also extends beyond external form to complex internal transmission systems. Using TPP, researchers created a spider-inspired microhydraulic system and reported a 3D-printed hydraulic actuator with a volume of only $4.9 \times 10^{-4} \text{ mm}^3$. This approach bypassed the limitations of conventional two-dimensional MEMS and enabled three-dimensional force transmission at the microscale [16].

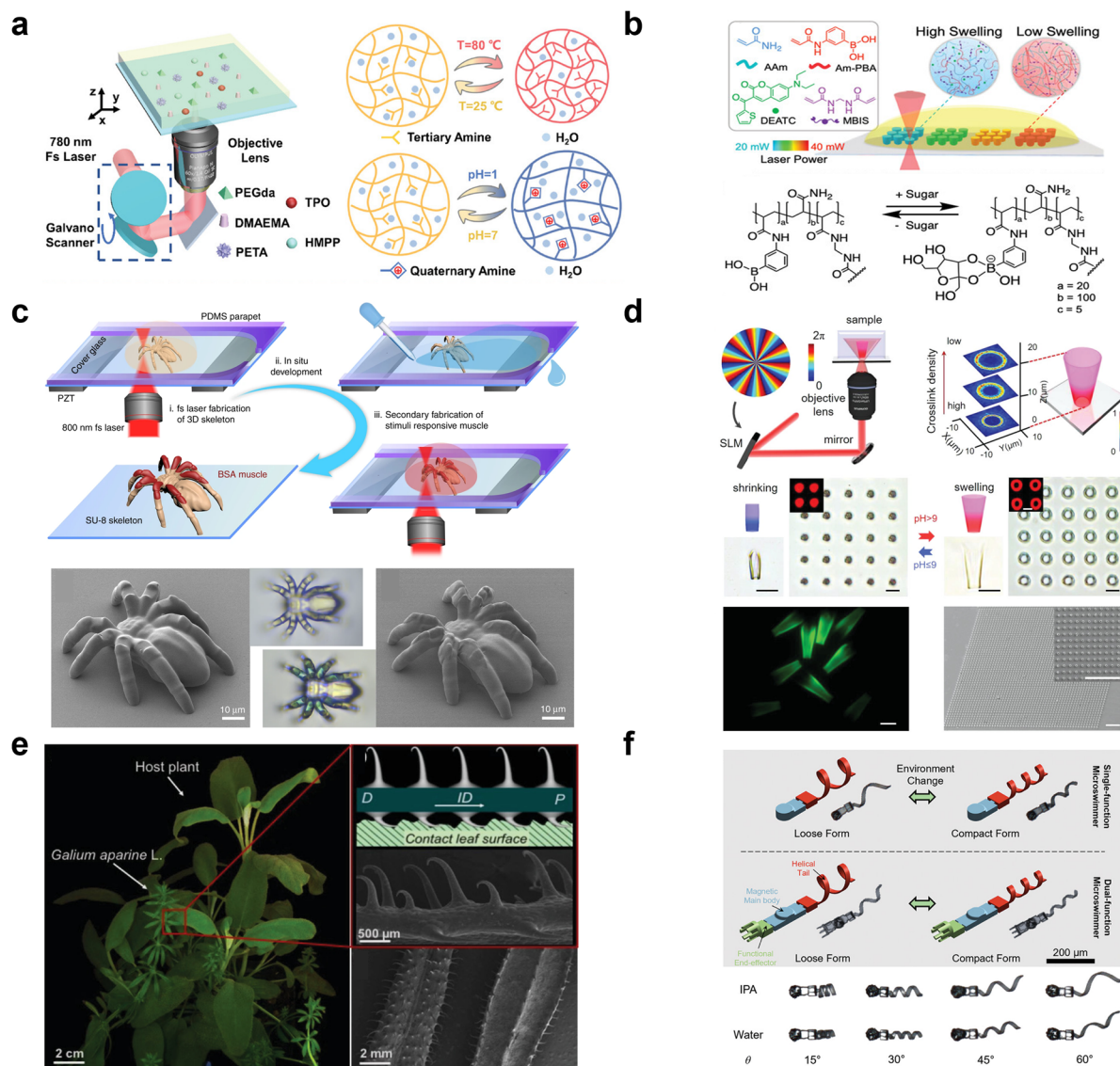


Figure 2. Materials innovation and structural design in microrobots. (a) pH- and temperature-dual-responsive hydrogel micro-actuators. Adapted with permission from Ref. [12]. Copyright 2023, Wiley-VCH GmbH. (b) Saccharide-responsive hydrogel microstructures [42]. (c) Multi-material integrated musculoskeletal systems [45]. (d) Rapid single-exposure vortex-beam 4D printing of topological shape-morphing microstructures. Adapted with permission from Ref. [18]. Copyright 2022, Wiley-VCH GmbH. (e) Biomimetic barbed microdevices [52]. (f) Flagella-inspired shape-programmable multi-material micro-swimmers [54].

2.3. Actuation and Motion Control

Precisely controlled motion is required for microrobots to cross biological barriers and execute tasks [55]. This section examines major actuation modes and control strategies, showing how microrobots achieve efficient navigation.

2.3.1. Magnetic Actuation

Magnetic actuation is widely used for untethered operation because magnetic fields penetrate biological tissues, although permissible field strength and frequency remain application-dependent. Progress in this area has been driven

by the combination of highly magnetizable materials and precise structural design. To overcome torque limitations, the field has expanded from early surface magnetic-film deposition and template-assisted electrodeposition [56–58] to rapid three-dimensional chiral microfabrication [59] and bulk magnetic-material strategies [60,61]. Pure-iron microrobots, for example, exploit high saturation magnetization to move at approximately 20 body lengths per second [60]. Sintered pure-nickel microrobots can push loads up to 200 times their own weight [61], whereas hard-magnetic microrobots infused with NdFeB particles achieve speeds of 3 mm s^{-1} and can swim controllably against blood flow [10] (Figure 3a). High actuation force must be complemented by precise control of motion modes. Magnetic-anisotropy programming, combined with nanoparticle self-assembly and TPP, has produced wobble-free micro-actuators [62]. Tapered ribbon-like microhelices can overcome instability in planar motion under 3D uniform magnetic fields [63]. With more elaborate mechanical architectures, a single magnetic input can be converted into complex biomimetic motion, including undulatory propulsion in multi-rigid-segment designs at low Reynolds numbers [64], rolling and inchworm-like crawling in hinged microgrippers [65], and efficient penetration of artificial mucus by hard-magnetic helical microrobots [66]. These advances have moved magnetic actuation beyond simple wireless pulling toward controllable multimodal manipulation.

2.3.2. Optical, Acoustic and Chemical Actuation

Beyond magnetic fields, light, sound and chemical reactions provide distinct propulsion mechanisms and control dimensions for microrobots. In optical actuation, photothermal effects and photoinduced deformation are central. Conjugated-polymer-doped LCEs, for example, generate rapid actuation strain and aggregation-free photothermal control under near-infrared light [13], whereas photoactive helical bimaterial micro-joints produce precise micronewton-scale deflection forces under laser irradiation [67]. Acoustic actuation provides an additional route to untethered control in fluidic environments. Ultrasound can convert acoustic streaming directly into frequency-selective motion in multibody hydrogel microsystems, enabling bubble-free actuators built entirely from biological soft materials [68]. Acoustically excited oscillating bubbles can provide localized propulsion and flow generation. Resonant bubbles trapped in three-dimensionally aligned microtubes generate frequency-selective three-dimensional propulsion while the device geometry maintains an upright posture [69], and micro-propellers with axisymmetric bubble cavities can rotate at up to 400 rpm under acoustic vibration [17]. Chemical actuation enables complex micromechanics through *in situ* energy conversion. McGovern and colleagues used two-photon lithography and Ni/Pt coating to fabricate chiral micro-propellers powered by catalytic reactions involving H_2O_2 . Their geometry programmed rotation and translation modes that could be switched by a magnetic field for cargo capture and transport [70] (Figure 3b).

2.3.3. Hybrid Actuation

Single-field actuation is often insufficient for multistage medical tasks, motivating systems that combine physical or chemical inputs. Here, multiphysics actuation denotes the coordinated or sequential use of two or more inputs to decouple locomotion, deformation and task execution. At the single-robot level, magneto-acoustic hybrid propellers use magnetic fields for directional navigation and then use acoustic fields to excite bubbles for local high-speed micro-mixing [17]. Scorpion-inspired actuators combine contact-free magnetic locomotion with pH-responsive gripper opening and closing, enabling programmable targeted capture that cannot be achieved by magnetic control alone [19]. At the collective level, multiphysics coupling enables complex micro-robotic swarm behaviors. Ant-inspired microrobots use magnetic fields for collective movement and light stimulation to trigger reversible directional assembly between individuals, allowing the collective to bridge physical gaps [20] (Figure 3c). Multi-material 4D-printed micromachines can also switch on demand between magnetic and chemically driven bubble propulsion to traverse narrow micro-networks efficiently [18]. Coupled fields can even coordinate cascade tasks. Using stepwise multi-material TPP, Wang and colleagues integrated Fe_3O_4 -enabled magnetic navigation, pH-responsive morphing and diffractive structural-color sensing within a fish-shaped microrobot [71] (Figure 3d). This coupling unifies locomotion, environmental feedback and adaptive task execution in one 4D-printed platform.

2.4. Integrated Design and Control Framework for TPP-Enabled Microrobots

The functional performance of a TPP-enabled microrobot is not determined by fabrication, material selection or actuation alone. It emerges from coordinated choices in geometry, mechanical properties, functional-material distribution, imaging visibility and control strategy [2,4,72]. Geometry sets hydrodynamic resistance and feasible motion modes, whereas stiffness governs structural stability and deformability. The spatial distribution of magnetic or optical components determines available force, torque or deformation and image contrast. Manufacturing deviations can further shift the robot dynamics away from the model used for control. Design and control should therefore be treated as a coupled problem rather than sequential engineering stages. The resulting framework is summarized in Figure 4.

A task-oriented workflow should begin with the biological objective and working environment, not with a preferred robot morphology. Targeted delivery, cell manipulation, upstream navigation and tissue anchoring impose different requirements [7,8,72]. Channel dimensions, flow and shear, viscosity and non-Newtonian behavior, tissue barriers, biochemical conditions, imaging depth and permissible field exposure define the feasible design space. These constraints can be translated into robot variables including size, aspect ratio, topology, stiffness distribution, surface texture, cavities, payload volume, functional-material

placement, degradability and image contrast. TPP is useful here because it can spatially encode several of these variables within free-form three-dimensional architectures [2,4]. Nevertheless, a design remains viable only if the selected

resin chemistry, feature size and filler content, together with the post-development release process, preserve the intended geometry and material response.

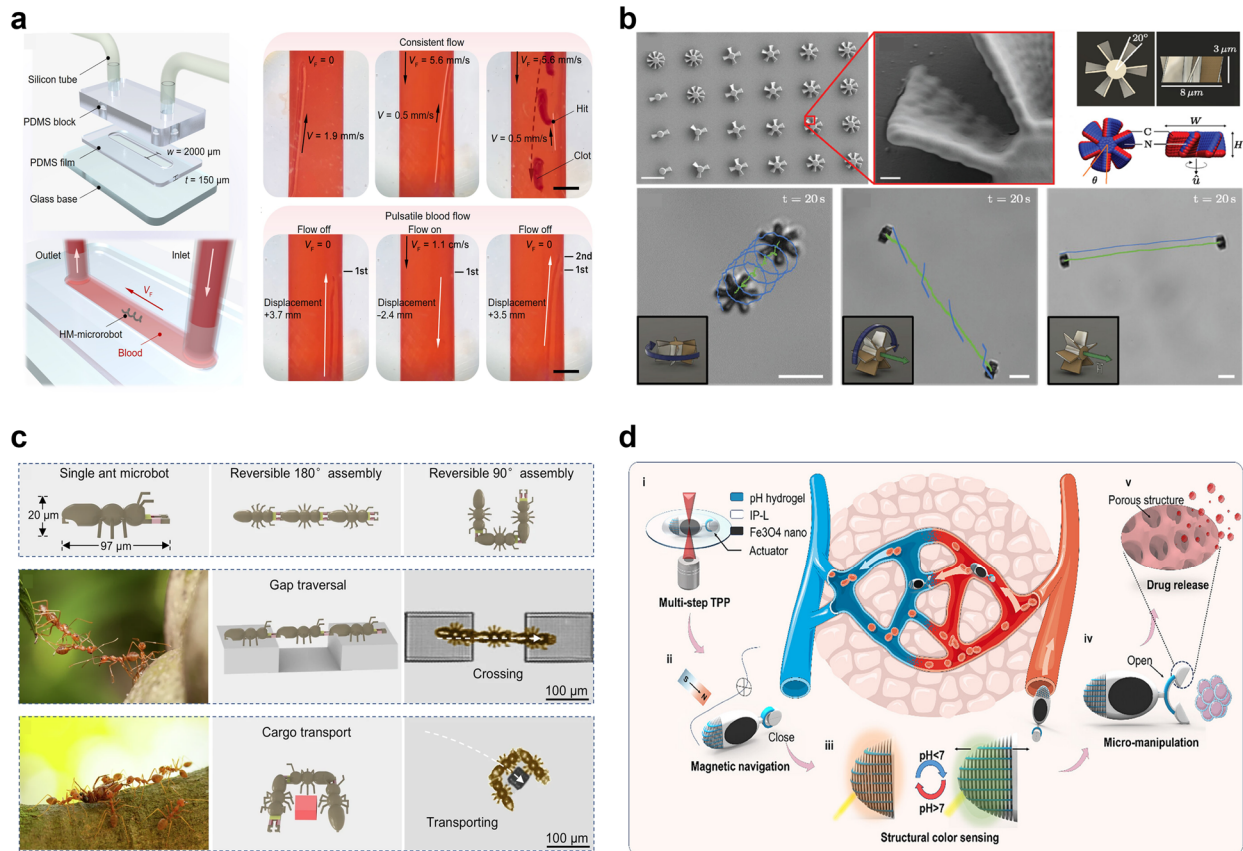


Figure 3. Multiphysics actuation and control strategies for microrobots. **(a)** Magnetic actuation: upstream navigation of hard-magnetic microrobots in blood flow [10]. **(b)** Chemical actuation: H_2O_2 -powered chiral micro-propellers with switchable motion modes [70]. **(c)** Magneto-optical actuation: ant-inspired collective cooperation [20]. **(d)** Magnetic, chemical and optical integration in a pH-adaptive 4D-printed microrobot. Reprinted with permission from Ref. [71]. Copyright 2025, Wiley-VCH GmbH.

Actuation generates force, torque or deformation, whereas control adjusts these inputs using the task objective and measured robot state. A complete loop comprises task definition, path planning, actuation, robot-environment dynamics, imaging or localization, state estimation and feedback control [55,73,74]. Many demonstrations still rely on microscopy and manual field adjustment. Such open-loop operation cannot reliably compensate for flow disturbances, tissue motion, robot-to-robot variability or fabrication error [55]. Closed-loop operation requires position and orientation estimates to update the field in real time. Optical imaging is effective for transparent *in vitro* settings, while deeper operation may require ultrasound, magnetic resonance, magnetic particle imaging or other contrast strategies [55,73]. The usable control bandwidth is then constrained by localization accuracy, imaging rate, computation latency and actuator response. Recent reinforcement-learning and magnetic-localization studies illustrate routes toward adaptive three-dimensional navigation. However, they also show that performance depends on the training domain, sensing geometry and hardware limits [74–76].

Treating design and control jointly reveals trade-offs hidden by separate component optimization. Faster propulsion may reduce turning authority or attitude stability, whereas compliant bodies improve tissue adaptation but complicate modeling and state estimation. Increasing magnetic or imaging-agent loading can strengthen actuation or visibility while degrading print fidelity, material homogeneity or biocompatibility [2,72,73]. Likewise, shape reconfiguration and additional degrees of freedom expand task capability but increase observability and controller complexity. A TPP-enabled microrobot should therefore be assessed against five linked criteria: manufacturability, actuatability, observability, controllability and task effectiveness. This framework shifts evaluation beyond fabrication resolution or maximum speed. It provides a basis for assessing whether these capabilities satisfy a specific biomedical task. Figure 4 illustrates the task-oriented framework linking biological objectives and working environments to TPP-enabled microrobot design, closed-loop control and performance evaluation.

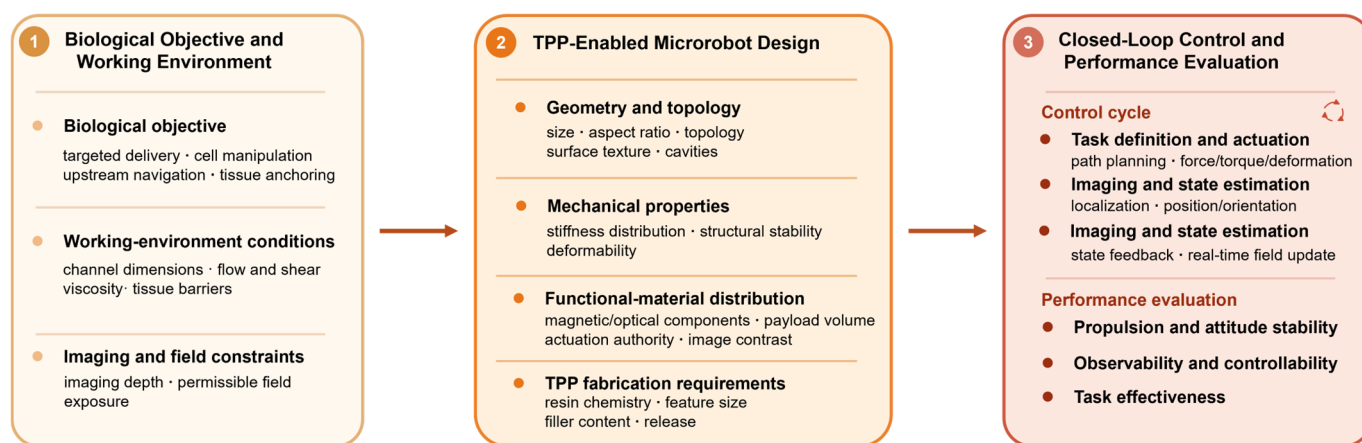


Figure 4. Integrated design and closed-loop control framework for TPP-enabled microrobots.

3. Biomedical and *In Vivo* Applications of Microrobots

3.1. Targeted Delivery and Precision Therapy

Drug delivery and targeted therapy are among the most prominent biomedical applications of microrobots [77]. To address the intrinsic limitations of conventional drug-delivery systems, including insufficient loading and premature leakage, microrobots can be designed for high spatiotemporal precision, on-demand release and multimodal synergistic therapy. To increase payload capacity, Song and colleagues developed puffball-inspired micro-robotic systems (PIMs). These systems use internal chambers to spatially isolate high drug doses. Their near-infrared-responsive sealing layer minimizes leakage and enables efficient on-demand release under laser irradiation [21], providing a broadly applicable basis for precision therapy (Figure 5a).

3.1.1. Antitumor Applications and Multimodal Targeted Release

In antitumor therapy, the key challenge is to balance potent cell killing with systemic toxicity through on-demand responses to physical stimuli or tumor microenvironmental cues. For external physical stimulation, Bozuyuk and colleagues developed magnetically driven chitosan microrobots incorporating photocleavable linkers. Under 365 nm illumination, these microrobots released the chemotherapeutic drug doxorubicin within 5 min, enabling temporal control over dosing [78]. Park and colleagues developed degradable hyperthermia microrobots (DHMs) that, under an alternating magnetic field, not only produce burst release of 5-fluorouracil but also promote cancer-cell death through synergistic hyperthermia [79]. For internal biochemical responsiveness, Ceylan and colleagues used pathologically relevant concentrations of matrix metalloproteinase-2 (MMP-2) to trigger matrix swelling and cargo release from gelatin methacryloyl (GelMA) microrobots. The material ultimately degraded into nontoxic products, supporting autonomous delivery with high safety [80]. To further overcome physiological barriers and support sustained release, needle-like

microrobots with magnetically controlled speeds of $714 \mu\text{m s}^{-1}$ have been used to physically anchor to target microtissues, eliminating the need for continuous external force [81]. Levy and colleagues designed ingestible microinjectors that deploy directly in the intestine and penetrate the mucosal barrier, achieving tunable drug release from 4 s to 118 d [82].

3.1.2. Macromolecular Biologics and Gene or Vaccine Delivery

Beyond conventional chemotherapeutics, microrobots show substantial potential for delivering macromolecular biologics. Chen and colleagues constructed polyethyleneimine-functionalized GelMA microrobots that successfully delivered DNA vaccines to dendritic cells and primary cells in a mouse model, inducing rapid and durable antigen expression [83] (Figure 5b). For proteins and antibodies, Peeler and colleagues introduced the spatiotemporal controlled release inks of biocompatible polyesters (SCRIBE) platform based on 3D-printed biodegradable polyesters. By precisely tuning microsphere chemistry and geometry, this platform enables spatiotemporal control of protein release and modulation of antibody class switching. A single injection can generate prolonged immune-induction kinetics, although translation will require stringent control over manufacturing and degradation [84].

3.2. Cellular Micromanipulation and Tissue Engineering

TPP has become a foundational micro- and nanofabrication platform connecting precise microscale manipulation with tissue engineering. By providing submicron resolution and material multifunctionality, it expands the intervention space from single-cell biophysical probing to the construction of complex *in vitro* models.

3.2.1. Single-Cell Manipulation

As microscale tools, microrobots can translate physical interactions into highly precise biological manipulation and measurement. For active capture and handling, Yang and colleagues fabricated magnetic tubular micromotors that

simultaneously captured individual HeLa cells and drug particles for *in situ* observation [85]. Wang and colleagues integrated pH-responsive hydrogels into 4D-printable micro-tentacles, embedding dynamic capture behavior within a microscale tool [86]. For mechanical measurement and analysis, a biomimetic tactile gripper integrated onto a single-mode optical fiber sorted small objects and measured the Young’s modulus of zebrafish eggs *in situ* [22] (Figure 5c). A micrometer-scale optical lever also enabled single-molecule stretching of double-stranded DNA [87]. In addition, physical confinement by microscale structures has revealed new mechanobiological mechanisms. Perera and colleagues used micro-cages to confine mesenchymal stromal cells, showing how 3D confinement regulates the cytoskeleton and Yes-associated protein (YAP) localization [88]. Taale and colleagues fabricated dome-like constraints *in situ* around tumor spheroids and showed that physical confinement substantially alters collective 3D cancer-cell migration and actin dynamics [89].

3.2.2. Cell Delivery and 3D Culture

Beyond precise manipulation, microrobots are being developed as smart cell carriers that transport cells to defined locations and provide 3D growth microenvironments. Early work by Kim and colleagues established a paradigm for targeted transport of HEK 293 cells using porous microrobots [57]. To address degradation barriers to clinical translation, Noh and colleagues developed spherical GelMA microrobots loaded with superparamagnetic iron oxide nanoparticles (SPIONs). Under magnetic guidance, these microrobots delivered stem cells and promoted their differentiation into neurons after enzymatic degradation, improving system scalability [90]. Further integration of microdevices with tissue assembly has also been achieved. Balasubramanian and colleagues developed scaffolded spheroids by integrating mesenchymal stromal cell spheroids into high-resolution 3D-printed micro-scaffolds. This strategy maintained cell viability, improved compressive performance and provided a new route for bottom-up tissue regeneration [91] (Figure 5d).

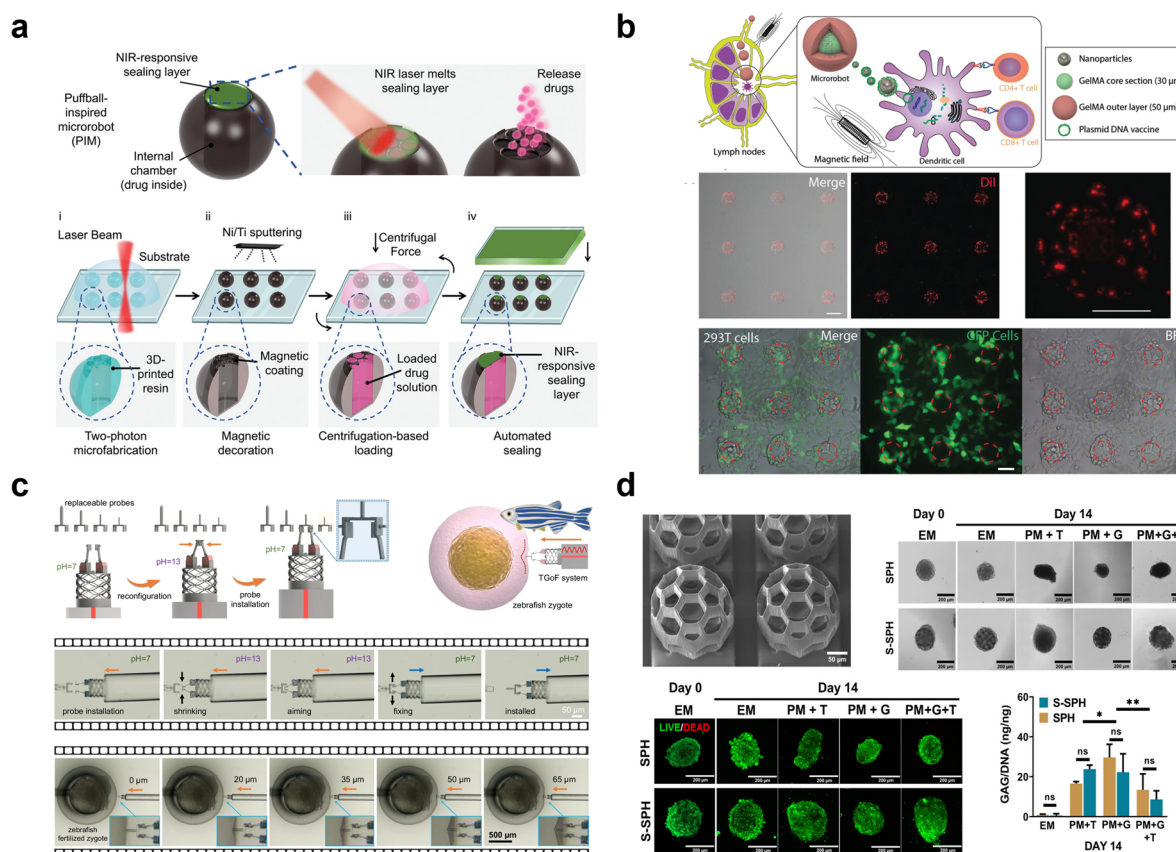


Figure 5. Applications of microrobots in targeted delivery and cellular micromanipulation. **(a)** Puffball-inspired drug-delivery microrobots [21]. **(b)** Targeted delivery of DNA vaccines. Adapted with permission from Ref. [83]. Copyright 2023, Wiley-VCH GmbH. **(c)** Biomimetic tactile grippers for cellular mechanical measurement [22]. **(d)** Scaffolded spheroids for tissue regeneration [91]. In **(d)**, * and ** indicate $p < 0.05$ and $p < 0.01$, respectively; ns, not significant.

3.2.3. *In Vitro* Models of Pathology and Physiology

The convergence of precise physical control and smart materials is most apparent in the *in vitro* construction of functional 3D disease and physiological models. By fabricating microenvironments with defined geometries,

researchers can probe cell behavior and disease mechanisms in greater depth. In an advanced physiological model, Striebel and colleagues printed human neural circuits with single-cell precision. By combining direct laser writing (DLW) templates with soft lithography, they positioned neurons

precisely on microelectrode arrays. This high-fidelity system validated action-potential conduction velocity and ephaptic coupling, and enabled mechanistic analyses that random neural networks cannot provide [92]. It therefore offers a robust platform for *in vitro* neuropathology studies.

3.3. Tissue Imaging, Navigation and In Vivo Applications

Deployment of microrobots in living systems requires advances in three areas: deep-tissue imaging, dynamic operation and long-term implant stability. Recent work combining materials design with multimodal systems has begun to address these challenges.

3.3.1. Deep-Tissue Imaging and Tracking

Real-time, high-resolution visualization of microdevices within deep living tissue is a prerequisite for effective navigation and therapeutic function. To overcome optical scattering in tissue and the trade-offs between imaging modalities, microrobots are increasingly being integrated with micro-optical and multimodal imaging strategies. For example, TPP-printed lens-in-lens microprobes simultaneously satisfy the low numerical aperture required for optical coherence tomography (OCT) and the high numerical aperture required for fluorescence imaging, enabling simultaneous *in vivo* imaging by both modalities in mouse arteries [93]. To mitigate deep-tissue optical scattering, implantable micro-optical elements such as plano-convex microlenses provide passive aberration correction, substantially reducing spherical aberration and improving the signal-to-noise ratio in nonlinear excitation microscopy [94]. For deeper-tissue applications, TriMag microrobots incorporate Fe_3O_4 and CoFe_2O_4 nanoparticles into TPP-printed hydrogels. The resulting platform combines magnetic actuation, magnetic particle imaging (MPI)-compatible nondestructive tracking and tumor ablation [95] (Figure 6a). Bioresorbable acoustic microrobots (BAMs) use dual-opening cavities to stably trap microbubbles. Under focused ultrasound, the oscillating bubbles generate propulsion and substantially enhance ultrasound contrast, supporting real-time tracking and demonstrating integrated imaging, actuation and therapy [9] (Figure 6b).

3.3.2. In Situ In Vivo Fabrication and Precision Operation

Unlike the conventional therapeutic workflow in which microrobots are manufactured first and implanted later, TPP and related technologies have recently been applied to *in situ* bioprinting. This approach can directly construct functional structures across scales within living systems, with the

potential to reduce surgical complications and implantation risks associated with prefabricated devices. Zhang and colleagues used up-conversion nanoparticles (UCNPs) to convert near-infrared light into the spectrum required for monomer polymerization, providing a proof of concept for non-invasive 3D printing of subcutaneous fracture-fixation scaffolds [96]. To extend this strategy to more complex multicellular biological environments, Afting and colleagues established an integrated platform combining single-photon and multiphoton 3D laser printing with biocompatible elastomer inks. The platform directly fabricated micro-implants in living medaka and *Drosophila* embryos [97]. Mur and colleagues demonstrated direct fabrication of microstructures inside living nonphagocytic cells. By injecting biocompatible photoresist into the cytoplasm and using femtosecond-laser TPP with submicron resolution, they printed complex intracellular objects, including micro-lasers and trackable barcodes, providing a route toward intracellular sensing and targeted delivery [98] (Figure 6c).

Whether devices are fabricated *in situ* or introduced from outside the body, precise navigation and minimally invasive manipulation in dynamic living environments remain major challenges. In the vasculature, hard-magnetic microrobots containing NdFeB particles show strong propulsion, reaching maximum swimming speeds of 22.6 body lengths per second, or 3 mm s^{-1} , in subcentimeter-per-second blood flow and enabling controllable upstream motion [10]. Cat-tongue-papilla-inspired Swiss-roll magnetic fiber robots use multiscale distal structures to physically capture intravascular thrombi and deliver fluids precisely under magnetic guidance [99].

3.3.3. Long-Term Implant Stability

For microrobots to function over extended periods *in vivo*, they must overcome immune rejection and long-term stability challenges associated with implants. In the central nervous system, where synchronized optical and electrical operation is critical, researchers have fabricated tapered fiber electrodes with integrated electrodes [100,101] and TPP-printed 3D high-aspect-ratio microelectrode arrays (MEAs) [102] (Figure 6d). These devices allow precise optical activation while providing high-fidelity, low-noise electrical readout from individual neurons. For long-term implantation, direct laser writing of electrode arrays onto curved fiber surfaces followed by encapsulation in biocompatible polymers provides greater mechanical bending durability and markedly lower inflammatory responses than conventional probes. This strategy reduces immune rejection *in vivo* and supports sustained neural stimulation and long-term monitoring [103].

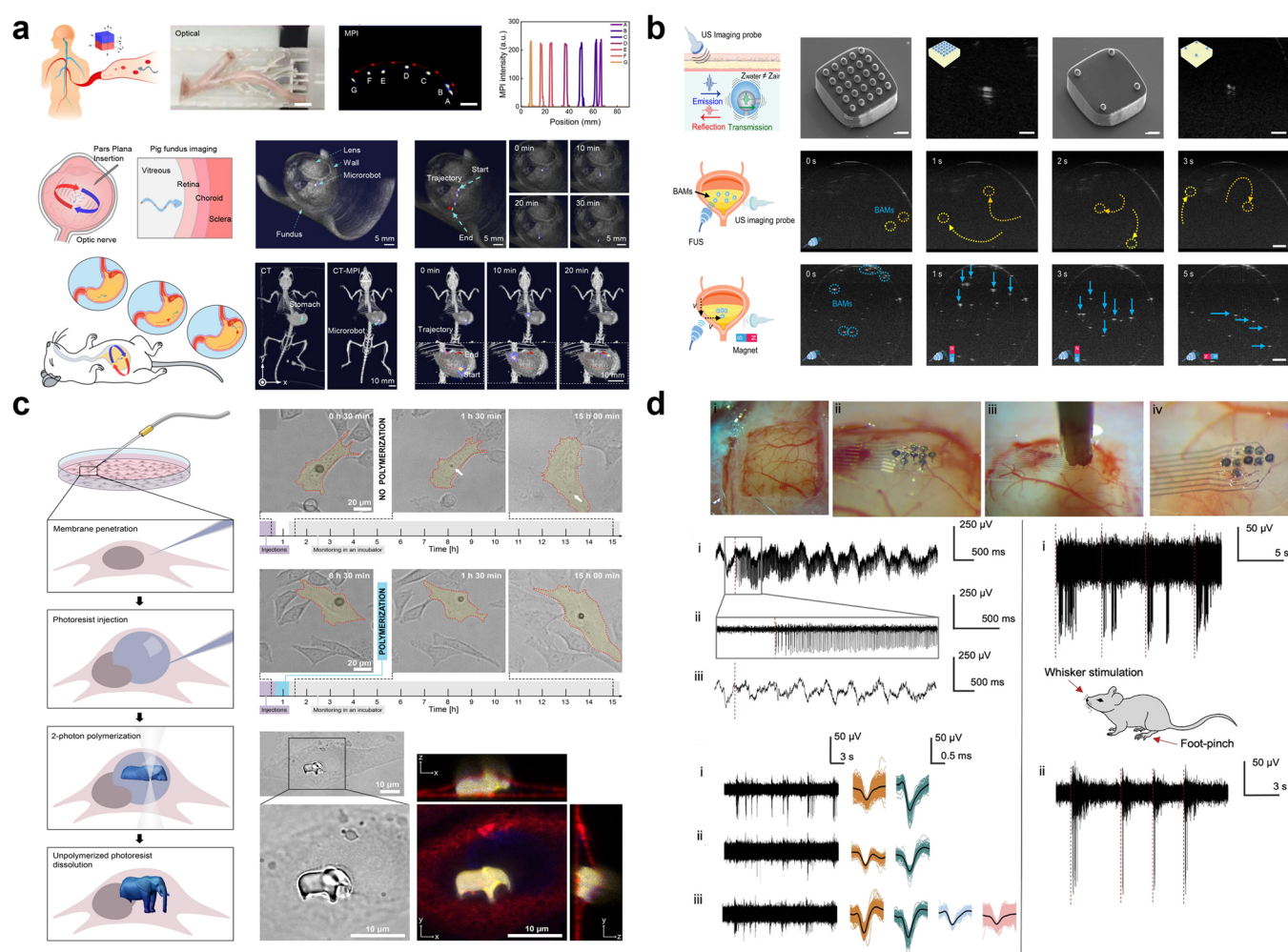


Figure 6. *In Vivo* imaging, navigation and *in situ* implantation of microrobots. (a) Magnetically actuated microrobots compatible with multimodal imaging [95]. (b) Ultrasound-imaging-guided acoustic microrobots [9]. (c) *In Situ* printing of microstructures inside living cells [98]. (d) Long-term-stable 3D microelectrode arrays [102].

4. Conclusions and Outlook

The integration of TPP with stimulus-responsive materials has expanded microrobots from static structures toward dynamic 4D systems with programmable shape change and sensing functions. TPP provides submicrometer feature control and free-form geometry for integrating functional materials within biomimetic structures. Functional materials such as LCEs and hydrogels can further support stimulus-responsive operation in targeted delivery, single-cell manipulation and *in vitro* disease modeling. Taken together, these studies connect TPP-based fabrication, actuation and biomedical function, while exposing manufacturing, material, biocompatibility and control barriers that currently limit clinical translation.

Despite the advantages of TPP in high-precision fabrication and multi-material integration, clinical translation still faces three central challenges that should be priorities for future work.

Manufacturing throughput and process stability. The current point-by-point serial writing mode creates a throughput bottleneck and cannot readily meet the demands

of large-scale production. Future work should focus on parallel processing strategies, including multifocal scanning and vortex-beam exposure, to substantially increase manufacturing efficiency while retaining submicron resolution. At the same time, the mechanical compatibility and long-term reliability of interfaces between heterogeneous materials should be systematically optimized through interface engineering and material-matching strategies.

Biocompatibility and molecular programmability of material systems. The degradation pathways and immunogenicity of existing photoresists after long-term implantation remain insufficiently understood. Future studies should develop next-generation bioactive materials with molecular backbones that provide predictable degradation kinetics and ensure safe clearance of metabolites through physiological routes. Deep integration of biomacromolecules, cell-membrane components and even living cells with synthetic structures may create biohybrid systems that provide molecular-scale recognition and immune-evasive capabilities.

Reliable operation and autonomous decision-making in complex physiological environments. Idealized laboratory conditions do not reproduce the heterogeneous *in vivo*

conditions characterized by non-Newtonian fluids, tissue barriers and dynamic blood-flow shear. Future work should systematically examine microrobot propulsion in complex biological fluids and the physical and biochemical interactions at tissue interfaces. Key questions include how to achieve long-term immune evasion, how collective cooperation can overcome the spatial and temporal limits of individual robots, and how environmental sensing and autonomous decision-making can be integrated at micro- and nanoscales. Progress will require integrated analysis of fluid mechanics, immunology and microsystem control, together with task-specific validation in living systems.

Author Contributions

Conceptualization, J.C. and X.S.; literature curation, J.C., D.J. and C.X.; writing—original draft preparation, J.C. and D.J.; writing—review and editing, C.X., X.M. and X.S.; supervision, X.M. and X.S.; funding acquisition, X.S. All authors have read and agreed to the published version of the manuscript.

Funding

The authors acknowledge financial support from the City University of Hong Kong with grant numbers 9610728 and 6000929, and the Hong Kong Research Grants Council (RGC) with project no. 21210026.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation and proofreading of this work, the authors used OpenAI Codex (GPT-5.6; OpenAI) for language polishing only. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

1. Spiegel, C.A.; Hippler, M.; Münchinger, A.; et al. 4D printing at the microscale. *Adv. Funct. Mater.* **2020**, *30*, 1907615. <https://doi.org/10.1002/adfm.201907615>.
2. Mainik, P.; Spiegel, C.A.; Blasco, E. Recent advances in multi-photon 3D laser printing: Active materials and applications. *Adv. Mater.* **2024**, *36*, 2310100. <https://doi.org/10.1002/adma.202310100>.
3. Wang, B.; Kostarelos, K.; Nelson, B.J.; et al. Trends in micro-nanorobotics: Materials development, actuation, localization, and system integration for biomedical applications. *Adv. Mater.* **2021**, *33*, 2002047. <https://doi.org/10.1002/adma.202002047>.
4. Wang, L.; Sai, H.; Tang, Y.Y.; et al. 4D direct laser writing for intelligent micromachines. *Adv. Funct. Mater.* **2025**, *35*, 2414571. <https://doi.org/10.1002/adfm.202414571>.
5. del Pozo, M.; Sol, J.A.H.P.; Schenning, A.P.H.J.; et al. 4D printing of liquid crystals: What's right for me? *Adv. Mater.* **2022**, *34*, e2104390. <https://doi.org/10.1002/adma.202104390>.
6. Sun, R.; Song, X.; Zhou, K.; et al. Assembly of fillable microrobotic systems by microfluidic loading with dip sealing. *Adv. Mater.* **2023**, *35*, e2207791. <https://doi.org/10.1002/adma.202207791>.
7. Bozuyuk, U.; Wrede, P.; Yildiz, E.; et al. Roadmap for clinical translation of mobile microrobotics. *Adv. Mater.* **2024**, *36*, 2311462. <https://doi.org/10.1002/adma.202311462>.
8. Quan, X.; Sun, B.; Song, X.; et al. Biophysics-informed design of biohybrid microrobots. *Nat. Rev. Bioeng.* **2026**, *4*, 559–579. <https://doi.org/10.1038/s44222-026-00416-8>.
9. Han, H.; Ma, X.; Deng, W.; et al. Imaging-guided bioresorbable acoustic hydrogel microrobots. *Sci. Robot.* **2024**, *9*, eadp3593. <https://doi.org/10.1126/scirobotics.adp3593>.
10. Wu, D.; Wang, X.; Li, R.; et al. Femtosecond laser-assisted printing of hard magnetic microrobots for swimming upstream in subcentimeter-per-second blood flow. *Sci. Adv.* **2025**, *11*, eadw1272. <https://doi.org/10.1126/sciadv.adw1272>.
11. Wang, H.; Zhang, W.; Ladika, D.; et al. Two-photon polymerization lithography for optics and photonics: Fundamentals, materials, technologies, and applications. *Adv. Funct. Mater.* **2023**, *33*, 2214211. <https://doi.org/10.1002/adfm.202214211>.
12. Wang, J.Y.; Jin, F.; Dong, X.Z.; et al. Dual-stimuli cooperative responsive hydrogel microactuators via two-photon lithography. *Small* **2023**, *19*, 2303166. <https://doi.org/10.1002/smll.202303166>.
13. Huang, Z.; Tsui, G.C.P.; Yeung, K.W.; et al. 4D direct laser writing of photo-triggered liquid crystal elastomer microactuators with large actuation strain. *Mater. Des.* **2023**, *232*, 112101. <https://doi.org/10.1016/j.matdes.2023.112101>.
14. van Kesteren, S.; Shen, X.; Aldeghi, M.; et al. Printing on particles: Combining two-photon nanolithography and capillary assembly to fabricate multimaterial microstructures. *Adv. Mater.* **2023**, *35*, 2207101. <https://doi.org/10.1002/adma.202207101>.
15. Lyu, X.; Zheng, Z.; Shiva, A.; et al. Capillary trapping of various nanomaterials on additively manufactured scaffolds for 3D micro-/nanofabrication. *Nat. Commun.* **2024**, *15*, 6693. <https://doi.org/10.1038/s41467-024-51086-2>.
16. Smith, G.L.; Tyler, J.B.; Lazarus, N.; et al. Spider-inspired, fully 3D-printed micro-hydraulics for tiny, soft robotics. *Adv. Funct. Mater.* **2023**, *33*, 2207435. <https://doi.org/10.1002/adfm.202207435>.
17. Mohanty, S.; Zhang, J.; McNeill, J.M.; et al. Acoustically-actuated bubble-powered rotational micro-propellers. *Sens. Actuators B Chem.* **2021**, *347*, 130589. <https://doi.org/10.1016/j.snb.2021.130589>.

18. Xin, C.; Jin, D.; Li, R.; et al. Rapid and multimaterial 4D printing of shape-morphing micromachines for narrow micronetworks traversing. *Small* **2022**, *18*, e2202272. <https://doi.org/10.1002/sml.202202272>.
19. Tian, Y.; Lu, X.; Wang, T.; et al. Two-photon polymerized heterogeneous materials microactuators for local responsiveness and remote locomotion. *Adv. Funct. Mater.* **2026**, *36*, e19908. <https://doi.org/10.1002/adfm.202519908>.
20. Ren, Z.; Xin, C.; Liang, K.; et al. Femtosecond laser writing of ant-inspired reconfigurable microbot collectives. *Nat. Commun.* **2024**, *15*, 7253. <https://doi.org/10.1038/s41467-024-51567-4>.
21. Song, X.; Sun, R.; Wang, R.; et al. Puffball-inspired microrobotic systems with robust payload, strong protection, and targeted locomotion for on-demand drug delivery. *Adv. Mater.* **2022**, *34*, 2204791. <https://doi.org/10.1002/adma.202204791>.
22. Li, C.X.; Liu, Y.Q.; Han, D.D.; et al. A tactile gripper on an optical fiber for perception and actuation. *Nat. Commun.* **2025**, *16*, 11513. <https://doi.org/10.1038/s41467-025-66575-1>.
23. Dabbagh, S.R.; Sarabi, M.R.; Birtek, M.T.; et al. 3D-printed microrobots from design to translation. *Nat. Commun.* **2022**, *13*, 5875. <https://doi.org/10.1038/s41467-022-33409-3>.
24. O'Halloran, S.; Pandit, A.; Heise, A.; et al. Two-photon polymerization: Fundamentals, materials, and chemical modification strategies. *Adv. Sci.* **2023**, *10*, 2204072. <https://doi.org/10.1002/advs.202204072>.
25. Cao, C.; Shen, X.; Chen, S.; et al. High-precision and rapid direct laser writing using a liquid two-photon polymerization initiator. *ACS Appl. Mater. Interfaces* **2023**, *15*, 30870–30879. <https://doi.org/10.1021/acsami.3c06601>.
26. Kilic, N.I.; Saladino, G.M.; Johansson, S.; et al. Two-photon polymerization printing with high metal nanoparticle loading. *ACS Appl. Mater. Interfaces* **2023**, *15*, 49794–49804. <https://doi.org/10.1021/acsami.3c10581>.
27. Cantoni, F.; Maher, D.; Bosler, E.; et al. Round-robin testing of commercial two-photon polymerization 3D printers. *Addit. Manuf.* **2023**, *76*, 103761. <https://doi.org/10.1016/j.addma.2023.103761>.
28. Balena, A.; Bianco, M.; Pisanello, F.; et al. Recent advances on high-speed and holographic two-photon direct laser writing. *Adv. Funct. Mater.* **2023**, *33*, 2211773. <https://doi.org/10.1002/adfm.202211773>.
29. Ouyang, W.; Xu, X.; Lu, W.; et al. Ultrafast 3D nanofabrication via digital holography. *Nat. Commun.* **2023**, *14*, 1716. <https://doi.org/10.1038/s41467-023-37163-y>.
30. Zhang, L.; Wang, C.; Zhang, C.; et al. High-throughput two-photon 3D printing enabled by holographic multi-foci high-speed scanning. *Nano Lett.* **2024**, *24*, 2671–2679. <https://doi.org/10.1021/acs.nanolett.4c00505>.
31. Bhanvadia, A.A.; Farley, R.T.; Noh, Y.; et al. High-resolution stereolithography using a static liquid constrained interface. *Commun. Mater.* **2021**, *2*, 41. <https://doi.org/10.1038/s43246-021-00145-y>.
32. Vidler, C.; Crozier, K.; Collins, D. Ultra-resolution scalable microprinting. *Microsyst. Nanoeng.* **2023**, *9*, 67. <https://doi.org/10.1038/s41378-023-00537-9>.
33. Kronenfeld, J.M.; Rother, L.; Saccone, M.A.; et al. Roll-to-roll, high-resolution 3D printing of shape-specific particles. *Nature* **2024**, *627*, 306–312. <https://doi.org/10.1038/s41586-024-07061-4>.
34. Rezaei, F.; Carlsson, D.O.; Hedin Dahlstrom, J.; et al. Direct ink writing of high-resolution cellulose structures. *Sci. Rep.* **2023**, *13*, 22044. <https://doi.org/10.1038/s41598-023-49128-8>.
35. Eom, W.; Hossain, M.T.; Parasramka, V.; et al. Fast 3D printing of fine, continuous, and soft fibers via embedded solvent exchange. *Nat. Commun.* **2025**, *16*, 842. <https://doi.org/10.1038/s41467-025-55972-1>.
36. Buchner, T.J.K.; Rogler, S.; Weirich, S.; et al. Vision-controlled jetting for composite systems and robots. *Nature* **2023**, *623*, 522–530. <https://doi.org/10.1038/s41586-023-06684-3>.
37. Makrygianni, M.; Zacharatos, F.; Andritsos, K.; et al. Eco-friendly lead-free solder paste printing via laser-induced forward transfer for the assembly of ultra-fine pitch electronic components. *Materials* **2021**, *14*, 3353. <https://doi.org/10.3390/ma14123353>.
38. Long, J.; Zhou, Y.; Lin, J.; et al. Printing dense and low-resistance copper microstructures via highly directional laser-induced forward transfer. *Addit. Manuf.* **2025**, *103*, 104755. <https://doi.org/10.1016/j.addma.2025.104755>.
39. Zhu, C.; Gameda, H.B.; Duoss, E.B.; et al. Toward multiscale, multimaterial 3D printing. *Adv. Mater.* **2024**, *36*, 2314204. <https://doi.org/10.1002/adma.202314204>.
40. Barwig, C.; Sonn, A.; Spratte, T.; et al. Two-photon direct laser writing of pNIPAM actuators in microchannels for dynamic microfluidics. *Adv. Intell. Syst.* **2024**, *6*, 2300829. <https://doi.org/10.1002/aisy.202300829>.
41. Decroly, G.; Chafaï, A.; de Timary, G.; et al. A voxel-based approach for the generation of advanced kinematics at the microscale. *Adv. Intell. Syst.* **2023**, *5*, 2200394. <https://doi.org/10.1002/aisy.202200394>.
42. Ennis, A.; Nicdao, D.; Kolagatla, S.; et al. Two-photon polymerization of sugar responsive 4D microstructures. *Adv. Funct. Mater.* **2023**, *33*, 2213947. <https://doi.org/10.1002/adfm.202213947>.
43. Minnick, G.; Safa, B.T.; Rosenbohm, J.; et al. Two-photon polymerized shape memory microfibers: A new mechanical characterization method in liquid. *Adv. Funct. Mater.* **2023**, *33*, 2206739.
44. Zhang, Y.; Yu, H.; Zhang, X.; et al. A novel multifunctional material for constructing 3D multi-response structures using programmable two-photon laser fabrication. *Adv. Funct. Mater.* **2024**, *34*, 2313922. <https://doi.org/10.1002/adfm.202313922>.
45. Ma, Z.C.; Zhang, Y.L.; Han, B.; et al. Femtosecond laser programmed artificial musculoskeletal systems. *Nat. Commun.* **2020**, *11*, 4536. <https://doi.org/10.1038/s41467-020-18117-0>.
46. Pétrot, R.; Devillers, T.; Stéphan, O.; et al. Multi-material 3D microprinting of magnetically deformable biocompatible structures. *Adv. Funct. Mater.* **2023**, *33*, 2304445. <https://doi.org/10.1002/adfm.202304445>.
47. Silbernagl, D.; Szymoniak, P.; Tavasolyzadeh, Z.; et al. Multiphoton lithography of interpenetrating polymer networks for tailored microstructure thermal and micromechanical

- properties. *Small* **2024**, *20*, 2310580. <https://doi.org/10.1002/sml.202310580>.
48. Kopyeva, I.; Goldner, E.C.; Hoyer, J.W.; et al. Stepwise stiffening/softening of and cell recovery from reversibly formulated hydrogel interpenetrating networks. *Adv. Mater.* **2024**, *36*, 2404880. <https://doi.org/10.1002/adma.202404880>.
 49. Abele, T.; Messer, T.; Jahnke, K.; et al. Two-photon 3D laser printing inside synthetic cells. *Adv. Mater.* **2022**, *34*, 2106709. <https://doi.org/10.1002/adma.202106709>.
 50. Tan, L.; Cappelleri, D.J. Responsive hydrogel-based modular microrobots for multi-functional micromanipulation. *Small* **2024**, *20*, 2404311. <https://doi.org/10.1002/sml.202404311>.
 51. Zhang, L.; Liu, B.; Wang, C.; et al. Functional shape-morphing microarchitectures fabricated by dynamic holographically shifted femtosecond multifoci. *Nano Lett.* **2022**, *22*, 5277–5286. <https://doi.org/10.1021/acs.nanolett.2c01178>.
 52. Fiorello, I.; Tricinci, O.; Naselli, G.A.; et al. Climbing plant-inspired micropatterned devices for reversible attachment. *Adv. Funct. Mater.* **2020**, *30*, 2003380. <https://doi.org/10.1002/adfm.202003380>.
 53. Zhang, Z.; Han, B.; He, R.; et al. Springtail-inspired doubly reentrant soft microstructures with magnetically switchable wettability fabricated by two-photon lithography-assisted molding. *Adv. Funct. Mater.* **2026**, *36*, e10215. <https://doi.org/10.1002/adfm.202510215>.
 54. Tan, L.; Yang, Y.; Fang, L.; et al. Shape-programmable adaptive multi-material microswimmers for biomedical applications. *Adv. Funct. Mater.* **2024**, *34*, 2401876. <https://doi.org/10.1002/adfm.202401876>.
 55. Jiang, J.; Yang, Z.; Ferreira, A.; et al. Control and autonomy of microrobots: Recent progress and perspective. *Adv. Intell. Syst.* **2022**, *4*, 2100279. <https://doi.org/10.1002/aisy.202100279>.
 56. Tottori, S.; Zhang, L.; Qiu, F.; et al. Magnetic helical micromachines: Fabrication, controlled swimming, and cargo transport. *Adv. Mater.* **2012**, *24*, 811–816. <https://doi.org/10.1002/adma.201103818>.
 57. Kim, S.; Qiu, F.; Kim, S.; et al. Fabrication and characterization of magnetic microrobots for three-dimensional cell culture and targeted transportation. *Adv. Mater.* **2013**, *25*, 5863–5868. <https://doi.org/10.1002/adma.201301484>.
 58. Zeeshan, M.A.; Grisch, R.; Pellicer, E.; et al. Hybrid helical magnetic microrobots obtained by 3D template-assisted electrodeposition. *Small* **2014**, *10*, 1284–1288. <https://doi.org/10.1002/sml.201302856>.
 59. Pan, D.; Liu, S.; Li, J.; et al. Rapid fabrication of 3D chiral microstructures by single exposure of interfered femtosecond vortex beams and capillary-force-assisted self-assembly. *Adv. Funct. Mater.* **2022**, *32*, 2106917. <https://doi.org/10.1002/adfm.202106917>.
 60. Alcântara, C.C.J.; Kim, S.; Lee, S.; et al. 3D fabrication of fully iron magnetic microrobots. *Small* **2019**, *15*, e1805006. <https://doi.org/10.1002/sml.201805006>.
 61. Li, R.; Jiang, M.; Liu, B.; et al. High-performance magnetic metal microrobot prepared by a two-photon polymerization and sintering method. *Lab Chip* **2024**, *24*, 832–842. <https://doi.org/10.1039/d3lc01084h>.
 62. Peters, C.; Erganeman, O.; García, P.D.W.; et al. Superparamagnetic twist-type actuators with shape-independent magnetic properties and surface functionalization for advanced biomedical applications. *Adv. Funct. Mater.* **2014**, *24*, 5269–5276. <https://doi.org/10.1002/adfm.201400596>.
 63. Jia, Y.; Zhu, Z.; Jing, X.; et al. Fabrication and performance evaluation of magnetically driven double curved conical ribbon micro-helical robot. *Mater. Des.* **2023**, *226*, 111651. <https://doi.org/10.1016/j.matdes.2023.111651>.
 64. Liao, P.; Xing, L.; Zhang, S.; et al. Magnetically driven undulatory microswimmers integrating multiple rigid segments. *Small* **2019**, *15*, 1901197. <https://doi.org/10.1002/sml.201901197>.
 65. Zhao, H.; Li, J.; Chen, Z.; et al. Design of a versatile microrobot for cargo delivery. *IEEE/ASME Trans. Mechatron.* **2024**, *29*, 2463–2474. <https://doi.org/10.1109/tmech.2023.3336687>.
 66. Raj, R.R.; Day, N.B.; Loomis, N.E.; et al. Transport of adoptive cell transfers with magnetic helical microrobots. *Small* **2025**, *21*, e05946. <https://doi.org/10.1002/sml.202505946>.
 67. Ahmad, B.; Barbot, A.; Ulliac, G.; et al. Remotely actuated optothermal robotic microjoints based on spiral bimaterial design. *IEEE/ASME Trans. Mechatron.* **2022**, *27*, 4090–4100. <https://doi.org/10.1109/tmech.2022.3145646>.
 68. Kaynak, M.; Dirix, P.; Sakar, M.S. Addressable acoustic actuation of 3D printed soft robotic microsystems. *Adv. Sci.* **2020**, *7*, 2001120. <https://doi.org/10.1002/advs.202001120>.
 69. Liu, F.W.; Cho, S.K. 3-D swimming microdrone powered by acoustic bubbles. *Lab Chip* **2021**, *21*, 355–364. <https://doi.org/10.1039/d0lc00976h>.
 70. McGovern, A.D.; Huang, M.J.; Wang, J.; et al. Multifunctional chiral chemically-powered micropropellers for cargo transport and manipulation. *Small* **2024**, *20*, 2304773. <https://doi.org/10.1002/sml.202304773>.
 71. Wang, J.; Zheng, J.; Zhang, C.; et al. 4D-printed microrobots with synergistic integration of magnetic actuation, diffractive optical sensing, and pH-adaptive morphing. *Adv. Funct. Mater.* **2026**, *36*, e18838. <https://doi.org/10.1002/adfm.202518838>.
 72. Chen, C.; Ding, S.; Wang, J. Materials consideration for the design, fabrication and operation of microscale robots. *Nat. Rev. Mater.* **2024**, *9*, 159–172. <https://doi.org/10.1038/s41578-023-00641-2>.
 73. Wrede, P.; Remlova, E.; Chen, Y.; et al. Synergistic integration of materials in medical microrobots for advanced imaging and actuation. *Nat. Rev. Mater.* **2025**, *10*, 888–906. <https://doi.org/10.1038/s41578-025-00811-4>.
 74. Yang, L.; Jiang, J.; Ji, F.; et al. Machine learning for micro- and nanorobots. *Nat. Mach. Intell.* **2024**, *6*, 605–618. <https://doi.org/10.1038/s42256-024-00859-x>.
 75. Abbasi, S.A.; Ahmed, A.; Noh, S.; et al. Autonomous 3D positional control of a magnetic microrobot using reinforcement learning. *Nat. Mach. Intell.* **2024**, *6*, 92–105. <https://doi.org/10.1038/s42256-023-00779-2>.

76. Fischer, F.; Gletter, C.; Jeong, M.; et al. Magneto-oscillatory localization for small-scale robots. *npj Robot.* **2024**, *2*, 1. <https://doi.org/10.1038/s44182-024-00008-x>.
77. Liu, D.; Wang, T.; Lu, Y. Untethered microrobots for active drug delivery: From rational design to clinical settings. *Adv. Healthc. Mater.* **2022**, *11*, 2102253. <https://doi.org/10.1002/adhm.202102253>.
78. Bozuyuk, U.; Yasa, O.; Yasa, I.C.; et al. Light-triggered drug release from 3D-printed magnetic chitosan microswimmers. *ACS Nano* **2018**, *12*, 9617–9625. <https://doi.org/10.1021/acsnano.8b05997>.
79. Park, J.; Jin, C.; Lee, S.; et al. Magnetically actuated degradable microrobots for actively controlled drug release and hyperthermia therapy. *Adv. Healthc. Mater.* **2019**, *8*, 1900213. <https://doi.org/10.1002/adhm.201900213>.
80. Ceylan, H.; Yasa, I.C.; Yasa, O.; et al. 3D-printed biodegradable microswimmer for theranostic cargo delivery and release. *ACS Nano* **2019**, *13*, 3353–3362. <https://doi.org/10.1021/acsnano.8b09233>.
81. Lee, S.; Kim, J.Y.; Kim, J.; et al. A needle-type microrobot for targeted drug delivery by affixing to a microtissue. *Adv. Healthc. Mater.* **2020**, *9*, e1901697. <https://doi.org/10.1002/adhm.201901697>.
82. Levy, J.A.; Straker, M.A.; Stine, J.M.; et al. Microinjectors for controlled cross-barrier drug delivery in the gastrointestinal tract. *ACS Appl. Mater. Interfaces* **2025**, *17*, 36420–36432. <https://doi.org/10.1021/acsmi.5c05183>.
83. Chen, S.; Tan, Z.; Liao, P.; et al. Biodegradable microrobots for DNA vaccine delivery. *Adv. Healthc. Mater.* **2023**, *12*, e2202921. <https://doi.org/10.1002/adhm.202202921>.
84. Peeler, D.J.; Sun, R.; Küthya, C.; et al. Nanoscale biodegradable printing for designed tuneability of vaccine delivery kinetics. *Adv. Mater.* **2025**, *37*, 2417290. <https://doi.org/10.1002/adma.202417290>.
85. Yang, L.; Chen, X.; Wang, L.; et al. Targeted single-cell therapeutics with magnetic tubular micromotor by one-step exposure of structured femtosecond optical vortices. *Adv. Funct. Mater.* **2019**, *29*, 1905745. <https://doi.org/10.1002/adfm.201905745>.
86. Wang, J.; Zhang, Y.; Zheng, J.; et al. 4D-printed micro-tentacles exhibiting wide-spectrum deformability. *Addit. Manuf.* **2024**, *84*, 104122. <https://doi.org/10.1016/j.addma.2024.104122>.
87. Andrew, P.K.; Raudsepp, A.; Fan, D.; et al. Optical microlever assisted DNA stretching. *Opt. Express* **2021**, *29*, 25836–25847. <https://doi.org/10.1364/oe.430465>.
88. Perera, W.R.; Ansari, A.; Nowell, C.; et al. Two-photon polymerized 3D geometries to study single-cell mechanotransduction and force generation in mesenchymal stromal cells. *Small* **2026**, *22*, e08899. <https://doi.org/10.1002/sml.202508899>.
89. Taale, M.; Schamberger, B.; Taheri, F.; et al. In situ fabrication of constraints for multicellular micro-spheroids using two-photon lithography. *Adv. Funct. Mater.* **2024**, *34*, 2302356. <https://doi.org/10.1002/adfm.202302356>.
90. Noh, S.; Jeon, S.; Kim, E.; et al. A biodegradable magnetic microrobot based on gelatin methacrylate for precise delivery of stem cells with mass production capability. *Small* **2022**, *18*, 2107888. <https://doi.org/10.1002/sml.202107888>.
91. Balasubramanian, R.V.; Muerner, M.; Kopinski-Grünwald, O.; et al. Exploring injectable scaffolded spheroids for nucleus pulposus therapy in degenerated intervertebral discs. *ACS Appl. Mater. Interfaces* **2026**, *18*, 10994–11007. <https://doi.org/10.1021/acsmi.5c24306>.
92. Striebel, J.; Habibey, R.; Wendland, D.; et al. Reproducible human neural circuits printed with single-cell precision reveal the functional roles of ephaptic coupling. *ACS Nano* **2025**, *19*, 38457–38471. <https://doi.org/10.1021/acsnano.5c11482>.
93. Li, J.; Thiele, S.; Kirk, R.W.; et al. 3D-printed micro lens-in-lens for in vivo multimodal microendoscopy. *Small* **2022**, *18*, e2107032. <https://doi.org/10.1002/sml.202107032>.
94. Marini, M.; Nardini, A.; Martínez Vázquez, R.; et al. Microlenses fabricated by two-photon laser polymerization for cell imaging with non-linear excitation microscopy. *Adv. Funct. Mater.* **2023**, *33*, 2213926. <https://doi.org/10.1002/adfm.202213926>.
95. Xing, L.; Cai, Y.; Zhang, Y.; et al. TriMag microrobots: 3D-printed microrobots for magnetic actuation, imaging, and hyperthermia. *Adv. Mater.* **2025**, *37*, e19708. <https://doi.org/10.1002/adma.202419708>.
96. Zhang, P.; Teng, Z.; Zhou, M.; et al. Upconversion 3D bioprinting for noninvasive in vivo molding. *Adv. Mater.* **2024**, *36*, e2310617. <https://doi.org/10.1002/adma.202310617>.
97. Afting, C.; Mainik, P.; Vazquez-Martel, C.; et al. Minimal-invasive 3D laser printing of microimplants in organismo. *Adv. Sci.* **2024**, *11*, 2401110. <https://doi.org/10.1002/advs.202401110>.
98. Mur, M.; Kavčič, A.; Jagodič, U.; et al. Two-photon 3D printing of functional microstructures inside living cells. *Adv. Mater.* **2026**, *38*, e19286. <https://doi.org/10.1002/adma.202519286>.
99. Fan, J.; Ren, S.; Han, B.; et al. Magnetic fiber robots with multiscale functional structures at the distal end. *Adv. Funct. Mater.* **2024**, *34*, 2309424. <https://doi.org/10.1002/adfm.202309424>.
100. Balena, A.; Bianco, M.; Andriani, M.S.; et al. Fabrication of nonplanar tapered fibers to integrate optical and electrical signals for neural interfaces in vivo. *Nat. Protoc.* **2025**, *20*, 1768–1809. <https://doi.org/10.1038/s41596-024-01105-9>.
101. Spagnolo, B.; Balena, A.; Peixoto, R.T.; et al. Tapered fibertrodes for optoelectrical neural interfacing in small brain volumes with reduced artefacts. *Nat. Mater.* **2022**, *21*, 826–835. <https://doi.org/10.1038/s41563-022-01272-8>.
102. Abu Shihada, J.; Jung, M.; Decke, S.; et al. Highly customizable 3D microelectrode arrays for in vitro and in vivo neuronal tissue recordings. *Adv. Sci.* **2024**, *11*, e2305944. <https://doi.org/10.1002/advs.202305944>.
103. Zhang, L.; Wang, S.; Xia, J.; et al. Monolithic multimodal neural probes for sustained stimulation and long-term neural recording. *Sci. Adv.* **2025**, *11*, eadu1753. <https://doi.org/10.1126/sciadv.adu1753>.