



Magnetic control devices and their biomedical applications: from untethered robotic intervention to precision nanomedicine

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Externally applied magnetic fields offer a rare combination of properties for biomedical actuation: they penetrate biological tissue with minimal attenuation, interact with embedded materials without physical tethers, and lend themselves to real-time closed-loop control under clinical imaging. Over the past decade, magnetically controlled devices have evolved from proof-of-concept demonstrations to systems now under validation in large-animal and near-clinical settings [1]. This progress spans millimeter-scale soft robots that swim, crawl, and grip inside the body, as well as nanoscale carriers that release therapeutic payloads on demand at a target site. A common thread is the integration of actuation, sensing, and drug-delivery functions directly into the material and structural design of the device, reducing reliance on external wiring or onboard electronics. The studies gathered in this special column reflect this trajectory, spanning device design, actuation strategy, and translational validation (Fig. 1).

1 Untethered magnetic robots for minimally invasive intervention

One prominent direction involves untethered robots whose shape, locomotion mode, and mechanical function are programmed into a spatial magnetization pattern set during fabrication. The design principle was first demonstrated in a landmark study of a small-scale soft-bodied robot that generated rolling, crawling, jumping, and swimming from a single programmed magnetization

profile [2]. It was soon extended to multifunctional platforms: a small-scale soft robot encoded with a multi-segment magnetization profile integrates gripping, sensing, and drug delivery within a single untethered body [3]. Along related lines, a magnetic multi-layer soft robot switches between translational and rolling gaits for targeted adhesion to gastric ulcer sites in living pig stomachs [4], and millimeter-scale fish-like magnetic robots—each about 2 mm long and capable of swimming at roughly 20 body lengths per second—have been assembled into three-dimensional (3D), shape-adaptive swarms for drug delivery [5].

At the colloidal scale, alternating magnetic fields organize hematite particles into microrobotic swarms of liquid, chain, vortex, and ribbon phases; the rapid, reversible transitions between modes enable navigation through confined channels and coordinated handling of heavy loads [6]. Magnetic nanoparticle swarms can likewise be actively generated and navigated in physiological bio-fluids, including blood and vitreous humor, with a strategy proposed for selecting the optimal swarm type according to fluid properties [7]; ribbon-like microswarms of the same family exhibit reversible elongation, splitting, and merging under oscillating magnetic fields [8]. Swarming has since been extended toward imaging-guided intervention: Doppler ultrasound combined with magnetic navigation steers microswarms through blood vessels in real time for active endovascular delivery [9].

Beyond navigation and cargo transport, magnetically actuated microrobots also serve as delivery and sensing

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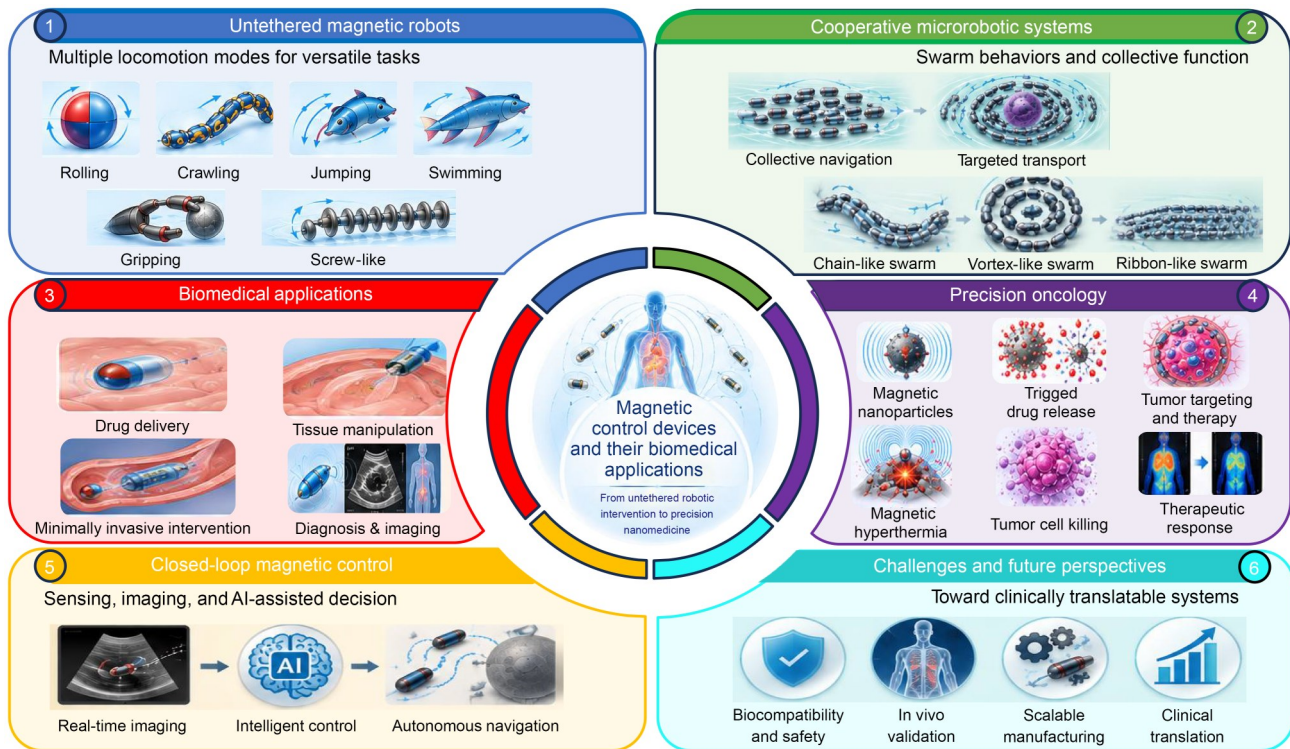


Fig. 1 Overview of magnetic control devices and their biomedical applications (generated with ChatGPT-5.6s' assistance and manually edited and calibrated)

platforms. Scaffold microrobots support 3D culture of hippocampal neural stem cells and their precise delivery and transplantation *in vitro*, *ex vivo*, and *in vivo* [10], while fluorescent magnetic spore-based microrobots can be tracked in real time and used to remotely detect *Clostridium difficile* toxins in the gastrointestinal tract [11]. In the circulatory system, tardigrade-inspired swimming microrobots with claw-engaged surfaces and red-blood-cell-membrane coatings anchor to vascular walls, achieving active retention for more than 36 h in rabbit jugular veins under physiological flow [12]. Within luminal structures of the body, an endoscopy-assisted magnetic actuation platform with dual imaging has delivered biohybrid stem-cell spheroid microrobots through natural orifices to the bile duct, covering a total distance of roughly 100 cm within 8 min [13]; a vine-like magnetic continuum robot, whose phase-change cores alternate under programmable magnetic fields, achieves environment-independent shaping and safe transluminal intervention, validated in gastric and cardiac procedures in living pigs [14]. Targeted therapy has also been achieved through biohybrid design: magnetically driven fibers, made from the patient's own blood combined with magnetic particles, can travel through the cerebrospinal fluid to reach intracranial tumor sites under external magnetic fields, release their encapsulated drug on demand, and then break down naturally after the procedure [15].

On the fabrication side, programmable spatial-magnetization stereolithographic printing produces thin-walled, biomimetic soft machines with an embedded magnetization pattern, addressing a key manufacturing bottleneck [16]; an alternative route exploits extruded ferromagnetic fibers based on thermoplastic polyurethane/NdFeB composites, which can be printed into complex 3D magnetic soft robots using a desktop fused-deposition-modeling printer and recycled after use, offering a path to sustainable, mass-producible devices [17]. At the system level, analyses of robotic wireless capsule endoscopy show how magnetic actuation, wireless power, and artificial intelligence (AI)-based lesion detection can be integrated to move capsule robots from passive imaging toward autonomous diagnostic tools [18]; building on this view, a dual-functional capsule robot driven by a magnetic torsion spring performs both drug delivery and tissue biopsy within a single wireless capsule, demonstrating the integration of diagnostic and therapeutic functions in *ex vivo* porcine stomach models [19]. Beyond free-swimming robots and swarms, magnetic actuation is also being applied to engineered surfaces: magnetically programmable cilia carpets, whose coordinated metachronal waves transport fluids and particles at low Reynolds numbers, provide a surface-based route to pumping, mixing, and cargo handling in confined biomedical settings [20].

Two studies reported in this special column carry this direction into concrete clinical settings. A millimeter-scale magnetic soft microrobot switches between fish-like oscillatory locomotion and helical rotation by changing the frequency of an oscillating magnetic field, without altering the field geometry or control hardware [21]. The two gaits operate in non-overlapping frequency bands, allowing the robot to reach 57 mm/s in open flow while navigating channels as narrow as 3 mm in an *ex vivo* porcine bronchial tree and liver vein, where it released a near-infrared-triggered drug payload from a photothermal-responsive hydrogel coating. Addressing a different clinical problem, a magnetic “slime” robot—a non-Newtonian polyvinyl alcohol–borax matrix embedded with NdFeB particles—retrieves residual kidney stone fragments after percutaneous nephrolithotomy, a common cause of stone recurrence [22]. Driven by a hybrid system of electromagnetic coils and a robotic-arm-mounted magnet, the slime robot encapsulated stone fragments up to 8 mm in diameter, tracked target positions with ≤ 1.3 mm error, and cleared fragments from a porcine kidney model within 3 min.

2 Magnetically triggered nanoplatforms for precision oncology

A second direction uses magnetic fields not to propel a device but to trigger a chemical or biological process locally within the tumor microenvironment. This approach builds on magnetic hyperthermia and on the chemistry of ferroptosis-inducing magnetic nanomaterials, where iron-based nanoparticles link magnetic responsiveness to redox activity that can be modulated by an external field.

This concept has been extended toward more selective and multimodal control by two studies reported here. Rotating-magnetic-field-driven nanorobots—doxorubicin-loaded, hollow mesoporous iron-oxide cores cloaked in 4T1 cancer-cell membranes—self-assemble into dynamic chains under a 5 Hz, 100 mT rotating field, avoiding the aggregation that limits static-field approaches and achieving three-fold higher intratumoral drug concentration than uncoated carriers [23]. The rotating field also depleted intracellular glutathione by 70% and elevated reactive oxygen species, driving ferroptosis; in 4T1 tumor-bearing mice, the combination of nanorobots and rotating-field guidance shrank tumors by 90%, compared with 45% for free doxorubicin, without detectable systemic toxicity. In a mechanistically distinct approach, a chiral magnetic nanoreactor couples histidine-modified manganese ferrite nanoparticles to cysteine-modified black phosphorus nanosheets through a reactive-oxygen-species-sensitive linker [24]. Under an alternating magnetic field, the linker breaks to release chiral black-phosphorus fragments that amplify photodynamic

therapy, while the nanoreactor’s catalase-like activity relieves tumor hypoxia; the resulting reactive-oxygen-species burst activates a mitogen-activated protein kinase (MAPK)/caspase-3 signaling cascade that drives anoikis, a metastasis-suppressing form of cell death, in both cultured cells and animal models. These studies show how magnetic fields can serve not only as actuation cues but also as selective triggers for tumor-specific therapeutic mechanisms.

3 Toward intelligent, closed-loop magnetic control

Beyond the studies described above, magnetic actuation is increasingly intersecting with embodied intelligence. Recent work has begun encoding physical computation—oscillators, reservoir computing, mechanical logic—directly into soft robotic bodies, enabling coordinated movement, obstacle avoidance, and simple decision-making through material design alone, without an onboard controller [25]. Learning-based control is being integrated into clinical platforms in parallel, exemplified by an AI co-pilot bronchoscope robot in which shared human–AI control, trained on expert demonstrations, lets novice doctors perform airway examinations as safely as experienced practitioners [26]. For magnetically actuated robots and nanoplatforms operating under real-time imaging in physiological environments, this convergence of field-responsive material intelligence and machine-learning-based field control represents a promising direction for future device development. On the sensing side, scanning superlens microscopy has extended label-free, real-time optical imaging to the nanoscale, providing the visual feedback needed for robotic manipulation and observation down to cellular dimensions [27].

4 Challenges and opportunities

Several obstacles remain before the laboratory demonstrations described above can translate into routine clinical use. Systematic assessment of magnetic actuation systems points to key challenges: workspace-size and field-strength trade-offs in electromagnetic coil design, sub-millimeter closed-loop accuracy under real-time imaging constraints, and the absence of harmonized regulatory pathways for actively steered, field-responsive devices [28]. Long-term biocompatibility and clearance of magnetic nanomaterials after repeated dosing are not yet fully characterized, particularly for iron-oxide-based and black-phosphorus-based platforms intended for chronic or repeated administration. Scaling up millimeter-robot fabrication—especially multi-step programmable-magnetization processes—from single research prototypes to reproducible, quality-controlled

batches will require closer integration with established manufacturing pipelines. Multi-physics modeling that couples magnetic field distribution, fluid–structure interaction, and patient-specific anatomy is still maturing, but will be essential for planning safe navigation through narrow, branching, or variable anatomical spaces such as the vasculature, biliary tree, or urinary tract.

We hope that the range of work gathered here—from dual-mode microrobots and bio-inspired slime robots to dual-functional capsule robots and field-triggered nanoreactors—will contribute to establishing magnetic control devices as a coherent and clinically viable platform technology, and we look forward to further advances from the biofabrication and robotics communities.

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