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Multi-Responsive Microrobots Enabled by Chemistry and Materials Design

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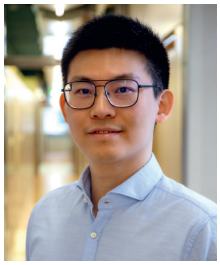
Abstract: At the microscale, robotic intelligence cannot rely on circuits or processors; instead, it must emerge directly from responsive materials. Chemistry provides the means: polymers, catalytic and magnetic materials enable single responsive mechanisms such as propulsion and sensing, forming the foundations of physical intelligence. Yet these functions remain limited in isolation. The next step is multiple responsiveness, where combined mechanisms create richer, autonomous behaviours. Conventional monolithic designs often suffer from interference and poor tunability, but modular assembly strategies now offer a solution by integrating discrete functional units without cross-talk. This review traces the progression from single to modular multi-responsive microrobots and highlights how such systems could achieve life-like adaptability for biomedical and environmental applications.

Keywords: Microrobots · Self-assembly · Stimuli-responsive materials



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1. Introduction

At large scales, robots achieve intelligence by pairing electronic processors with adaptive materials, seamlessly merging computation with physical function. However, at the microscopic scale this pathway closes: circuits, processors, and batteries cannot be embedded. Here, the 'intelligence' of the system must instead emerge directly from the materials themselves, programmed through chemistry and expressed through their interactions with the surrounding environment.[1,2]

Chemistry provides a powerful toolbox for this purpose. Polymers sensitive to temperature or pH conditions, molecular switches triggered by light, liquid-crystal actuators, and catalytic reactions that generate motion all demonstrate how materials can encode function without electronics.[3,4] Each of these mechanisms can serve as the basis for microrobotic behaviour.

The development of chemically programmed microrobots can therefore be viewed as a continuum. The first step is embedding a single responsive mechanism - a design that enables fundamental operations such as propulsion, directional steering, or basic sensing. These elementary responses are the foundation of microrobotic function. The next step is integrating multiple responsive mechanisms within the same system, creating opportunities for richer and more autonomous behaviours. Through such combinations, microrobots can adapt to dynamic environments, navigate complex landscapes, or coordinate with one another in collective tasks (Fig. 1). This review follows this developmental pathway: from single responsiveness, which establishes the basic building blocks of function, to multiple responsiveness, which unlocks higher-order autonomy. By highlighting the chemical and material design strategies that make this progression possible, we aim to illustrate how microscale systems are moving towards increasingly sophisticated and adaptive operation in real-world environments.

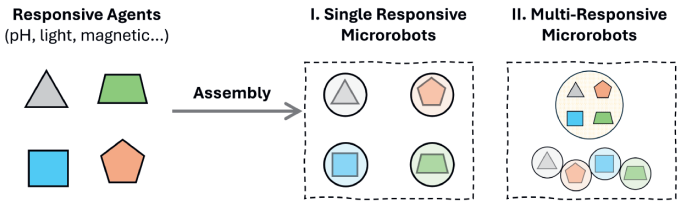

Fig. 1. Overview of developing responsive microrobots.

2. Encoding Single Responsive Mechanisms

The general features of intelligent microrobots can be captured in two essential capabilities: locomotion and sensing, which allow them to move and interact with their surroundings. To physically encode these functions, researchers have used catalytic materials, responsive polymers, and magnetic nanoparticles, processed at the micro- or nanoscale with diverse fabrication methods. Below, I outline how state-of-the-art microrobots achieve these two forms of physical intelligence.

2.1 *Locomotion*

Microrobots achieve propulsion by converting environmental stimuli into motion, and diverse strategies have been developed to control this process with precision. Magnetic actuation

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remains one of the most versatile approaches: Ni films or iron oxide coatings on helices enable motion guided by rotating magnetic fields,[5,6] while Janus particles coated with TiO_2 exhibit light-driven propulsion, swimming away from illumination sources.[7–9] Chemical reactions provide another powerful means, as reactive materials such as Mg or $CaCO_3$ decompose to release gas bubbles in acidic environments, driving bubble propulsion in an asymmetric manner.[10,11]

In addition to inorganic materials, responsive polymers can be used for triggered propulsion. Liquid-crystal elastomers deform upon heating, enabling locomotion or even colour-changing walkers that integrate actuation with visual feedback.[12,13] Ultrasound provides another promising route: acoustic fields induce cavitation and streaming, driving microrobots with rapid propulsion and strong tissue penetration for biomedical use.[14,15]

In parallel, biological systems including bacteria,[16] microalgae,[17] and sperm cells[18] have been incorporated as biohybrid engines, leveraging their natural self-motility for directed tasks.

In our work, we advanced a biocompatible magnetic strategy by assembling superparamagnetic nanoparticles into anisotropic supraparticles, creating magnetically actuated microswimmers that retain superparamagnetic behaviour and respond rapidly to external fields (Fig. 2). Their biocompatibility makes them particularly suitable for biomedical applications, where precise navigation and minimal toxicity are essential. Collectively, these approaches highlight how propulsion can be finely tuned through material design, providing the fundamental capability of controlled motion.[19]

2.2 *Sensing*

Alongside locomotion, microrobots can be endowed with sensing functions, enabling them to perceive and respond to their surroundings. Surface functionalization is a common strategy, allowing toxin detection or disease diagnostics through specific molecular recognition.[20] Motion dynamics can also serve as sensitive readouts, for instance, Au-Pt catalytic microrobots exhibit speed changes upon HIV-1 binding, a property that has been translated into a cellphone-based diagnostic tool for rapid viral detection.[21]

Beyond biochemical cues, microrobots can also respond to physicochemical stimuli. pH-sensitive microrobots made of hydrogels can swell, shrink, or disassemble in acidic conditions, enabling targeted release in tumour-like environments.[22,23] DNA-based microrobots undergo conformational switching in acidic media, functioning as nanoscale biosensors for ATP or tumour markers.[24,25] Enzyme-sensitive hydrogels such as GelMA can be engineered to detect elevated levels of cancer-associated enzymes (*e.g.* MMP-2), releasing a therapeutic cargo in response.[26,27] These examples demonstrate how microrobots can be equipped with molecular logic to interpret and react to complex biological environments.

Our work extends sensing into the mechanical domain. We developed damage self-reporting nanocapsules that produce a reversible optical signal in response to stress: turning on with crack formation and off during healing.[28] This design bridges environmental and structural feedback, enabling microrobots not only to detect external cues but also to monitor their own integrity. Such strategies move sensing beyond biochemical responsiveness toward self-diagnostics, a key step toward long-term autonomous operation (Fig. 3).

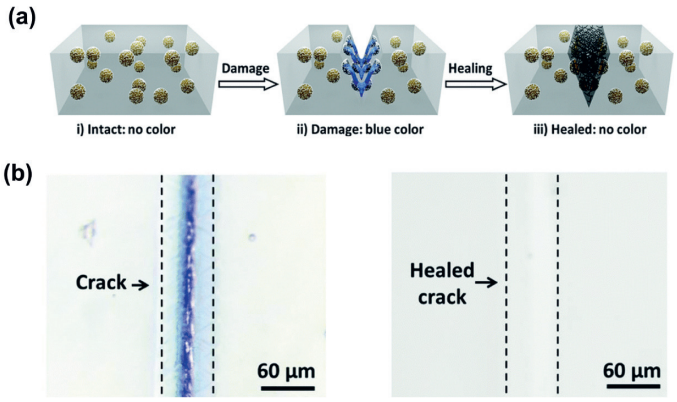

Fig. 3. Stress sensing from self-reporting microcapsules. Images adapted from ref. [28], licensed under CC BY 4.0

Together, propulsion and sensing represent the fundamental building blocks of intelligent microrobots. Other single responsive mechanisms, such as stimuli-triggered shape changes,[29,30] are also possible, but the true leap forward comes when multiple responsivenesses are combined within the same system - a topic addressed in the following section.

3. Combining Multiple Responsive Mechanisms

While single responsive mechanisms such as propulsion and sensing provide the essential building blocks of intelligent microrobots, they remain limited in isolation. A microrobot that can only move, or only detect, cannot autonomously perform sophisticated tasks in dynamic environments. A next step is to combine different responsive functions within the same system, enabling microrobots to react to multiple cues and coordinate their behaviours in richer and more autonomous ways.

The most straightforward approach is to mix different responsive agents within a single material, creating multifunctional microrobots.[31] For example, light-magnetic hybrids embed magnetic nanoparticles into photoresponsive polymers, allowing steering by magnetic fields while light induces deformation or actuation.[32–34] pH-magnetic systems incorporate magnetic cores coated with pH-sensitive polymers, enabling external navigation together with site-specific release in acidic microenvironments.[35,36] Thermal and magnetic hydrogels combine magnetically guided motion with thermoresponsive swelling or shrinking, though such designs illustrate a key challenge: heat from magnetic actuation can unintentionally trigger thermal release.[37] These ex-

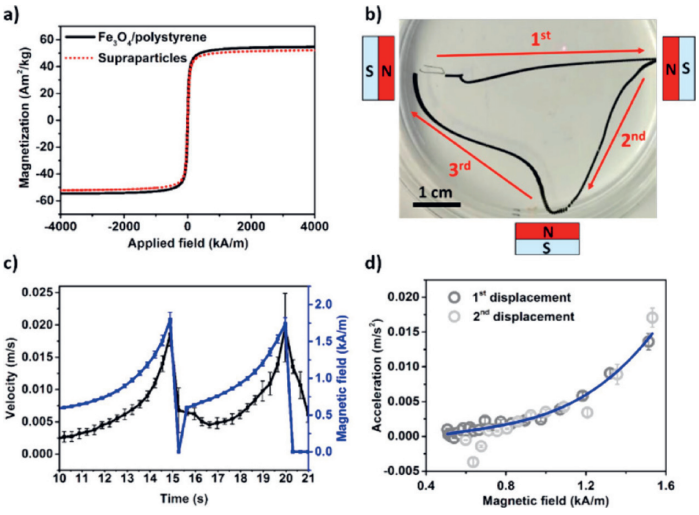

Fig. 2. Magnetic microrobots driven by permanent magnets. a) Magnetic property of the microrobots characterized by vibrating-sample magnetometer. b) Trajectory of a magnetic microrobot in water with varied magnetic fields. c) Velocity and experienced magnetic field of the microrobots shown in Fig. 4b as a function of time. d) Acceleration of microrobots shown in Fig. 4b as a function of the strength of the magnetic field. Images adapted from ref. [19], licensed under CC BY 4.0

amples demonstrate the versatility of blending multiple responsivenesses into a single architecture, but they also highlight the difficulty of avoiding cross-talk when stimuli-sensitive domains overlap.

To overcome these limitations, researchers are turning to modular strategies, in which different responsive units are kept physically separated but functionally combined. Instead of embedding all functions into a single material domain, microrobots can be constructed from discrete modules, each contributing a specific behaviour. For instance, we have developed multi-compartment supracapsules, where nanocapsules with distinct cargos are confined within droplet templates and assembled into uniform multicompartment structures.[38] Each sub-compartment preserves its individual role, while the collective supracapsule exhibits emergent properties such as programmable release profiles and on-demand disassembly. Building on this idea, we demonstrated microswimmers assembled with liquid microcapsules, fabricated through a combination of microfluidic synthesis and sequential capillarity-assisted particle assembly (sCAPA).[39] Monodisperse polymer microcapsules containing different liquid cargos were first generated using microfluidic devices, then precisely arranged into dumbbell-like or multi-compartment geometries *via* sCAPA. The resulting swimmers exhibited controlled motility under AC electric fields due to electrohydrodynamic flows, while also providing a versatile platform for combining propulsion with multiple, separately addressable cargos.[40]

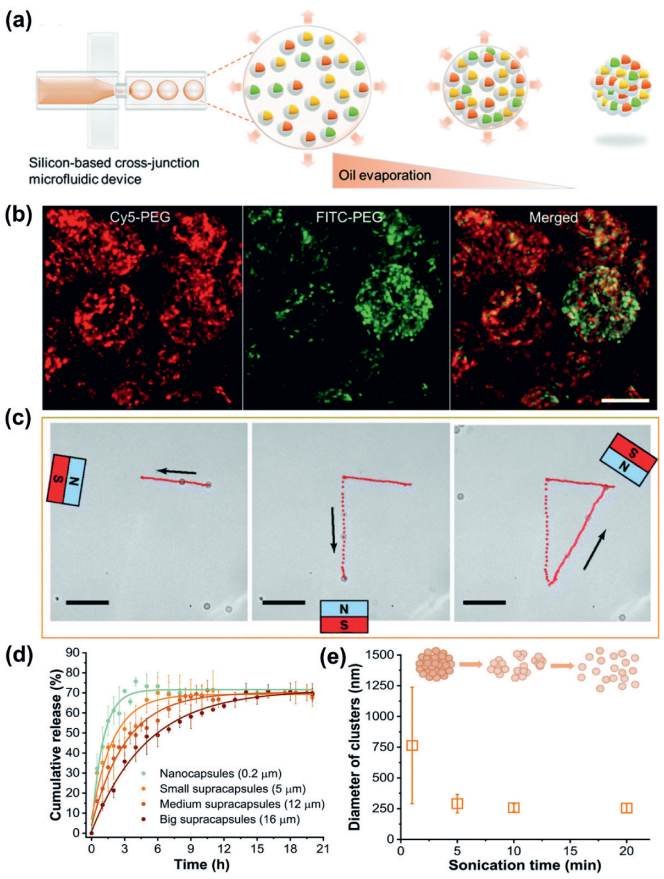

Fig. 4. Multi-responsive microrobots made from multi-compartmental structures. a) Scheme of fabricating multi-compartment microrobots from microfluidic assembly. b) Confocal microscopy images of microrobots with multi-compartmental structures. Scale bar is 5 μm. c) Magnetic response of multi-compartment microrobots. Scale bars are 50 μm. d) Programmable release profiles of multi-compartment microrobots with various sizes. e) Disassembly of microrobots triggered by sonication process. Images adapted from ref. [38], licensed under CC BY 4.0

Complementary approaches from other groups demonstrate the breadth of modular design: Tan and Cappelleri created hydrogel-based modular microrobots, in which responsive hydrogel joints act as mating components that couple a magnetic base to interchangeable end-effectors, enabling dynamic assembly and reconfiguration for micromanipulation tasks.[41] More recently, Lee and coworkers introduced chiplet-based 'smartlets', where self-folding membranes integrate microelectronics, light emitters, energy harvesters, and bubble generators into modular robotic units capable of propulsion, communication, and collective behaviours in aqueous environments. Taken together, these examples illustrate how modular architectures - whether based on chemical compartments, responsive hydrogels, or chiplet integration - provide powerful routes to multi-responsive microrobots that minimize cross-talk, preserve tunability, and open the door to programmable and cooperative operation. Current multi-responsive materials often integrate several stimuli-sensitive domains within a single matrix, leading to cross-functional interference.[42]

Together, these approaches illustrate a clear trajectory: from blending multiple responsive agents within a single matrix to assembling distinct modules into programmable architectures. By separating functions into discrete yet cooperative units, modular microrobots overcome the limitations of monolithic designs, enabling multi-responsiveness without cross-talk and paving the way for systems that are not only multifunctional but also reconfigurable and adaptive.

4. Conclusions

The development of intelligent microrobots at the microscale relies on embedding physical responsiveness directly into materials. We have seen how single responsive mechanisms, such as locomotion and sensing, provide the essential building blocks of microrobotic intelligence. These elementary functions demonstrate how chemistry and material design can encode motion, perception, and interaction without electronics. Building on this foundation, the field is now moving toward multiple responsiveness, where integrated mechanisms enable more complex and autonomous behaviours. However, conventional monolithic strategies often suffer from cross-talk and lack of tunability, underscoring the importance of modular assembly approaches that preserve independent control while enabling programmable combinations of function.

Looking ahead, modular and multi-responsive microrobots hold enormous promise for real-world applications. In biomedicine, biocompatible magnetically actuated swimmers and stress-responsive materials point toward microrobots capable of targeted delivery, *in situ* diagnostics, and self-reporting health states. In environmental science, modular cargo carriers with programmable release may offer new tools for sensing.

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