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**Title: On-board mechanical control systems for untethered microrobots**

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An autonomous robot perceives its environment, makes decisions based on acquired information and programmed routines, and then actuate a movement or perform a manipulation task within that environment. The idea of microrobotics is primarily based on teleoperated mobile micromachines equipped with manipulation capabilities such as actuated grippers and drug-loaded reservoirs. Due to miniaturization challenges, the majority of these micromachines are wirelessly actuated using magnetic fields or acoustic waves. A step towards complete autonomy is the development of on-board control systems that directly transduce environmental stimuli such as heat and pressure into actuation, without going through the perception and computation cycles. Following the analogy of the central nervous system for the architecture of the conventional autonomous robots, the next generation microrobots are expected to possess reflexes that would allow them to autonomously navigate inside structured microenvironments, and perform targeted and triggered operations. This report describes the construction of on-board control systems using stimuli-responsive materials, nonlinear mechanical mechanisms, and fluid-structure interactions. Recent advances in macroscale soft robotics and mechanical metamaterials are highlighted with the hope that they would inspire solutions for microrobotics.

## 1. Introduction

Development of untethered autonomous mobile micro- and nanorobots is one of the holy grails in robotics research because these devices could one day revolutionize medical procedures. It is envisioned that simply administering a group of microrobots into the body would suffice to deliver therapy at the target diseased tissue in a timely manner. An autonomous mobile robot is expected to possess three major faculties: 1) sensors to collect information about the self and the environment (perception), 2) actuators to generate motion and interact with the environment (locomotion and manipulation), 3) hardware and/or software to process the sensory inputs and determine the control output for the actuators (navigation and localization). Almost all macroscale mobile robots are actuated by electric motors, decorated with various electronic sensors, equipped with embedded microprocessors, and powered by electric batteries. One avenue for engineering microscale mobile robots is miniaturizing all the required electronic components using standard microelectromechanical system (MEMS) and semiconductor technologies and providing energy wirelessly using electromagnetic or acoustic waves.<sup>[1]</sup> A successful proof-of-concept example of this strategy has been presented very recently.<sup>[2]</sup> The microrobot had a photovoltaic unit for converting laser light into electric power, which in turn drives electrochemical actuators fabricated using atomic layer deposition. Although sensing and computation units have not been integrated yet, the fabrication process is compatible with accommodating complementary metal-oxide-semiconductor (CMOS) circuits in the future.

In this report, we are going to highlight progress and opportunities in the design of all-mechanical autonomous mobile microrobots. This strategy may appear retrograde as modern embedded systems replaced almost all clockwork and automata. However, not relying on electric power has been proven to be a paradigm shift in the pursuit of miniaturization. The size

of mechanical machines can be reduced to nanoscale as demonstrated by DNA machines<sup>[3]</sup> and molecular motors.<sup>[4]</sup> Meanwhile, soft roboticists have been pursuing a similar direction for different reasons.<sup>[5]</sup> Electronic components are fabricated from rigid materials, thus, the development of entirely soft autonomous robots demands the invention of sensors and controllers based on mechanical logic.<sup>[6]</sup> We highlight relevant advances in macroscale soft robots with the hope that those inventions may inspire the design of microscopic counterparts.

Early research in the field focused primarily on providing power to untethered micromachines for controlled motion. As exemplified by biological systems, extracting chemical energy stored in organic compounds is an efficient and scalable strategy. Seminal work has shown that platinum plates catalyze a reaction that decomposes hydrogen peroxide into water and oxygen gas.<sup>[7]</sup> The gas bubbles are then ejected, generating thrust and propelling the structures. In this propulsion method, the fuel (or food) required for motion is present in the environment and the catalyst can be miniaturized down to the nanoscale. Catalytic motors, in principle, can sustain motion indefinitely as long as the fuel is not depleted. However, dependence on the presence of fuel in the environment is a serious limitation for an engineered vehicle. Following the example of the combustion engine, a special compartment may be engineered for storing and controllably injecting fuel into a reaction chamber. This approach requires sophisticated manufacturing techniques that have not been realized yet, and the fuel stored in a tiny compartment is expected to power a relatively short journey. These challenges pushed roboticists to look into alternative powering techniques. Electromagnetic and acoustic wave fields can be generated easily over long distances through various media. Inspired by the design of microorganisms and considering the capabilities of wireless actuation systems, a variety of microscopic motors have been engineered.<sup>[1,8]</sup> Magnetic fields are quite effective in actuating microswimmers by oscillating and rotating slender filaments,<sup>[9-12]</sup> acoustic waves

generate streaming by vibrating bubbles,<sup>[13–16]</sup> or sharp-edged microstructures at relatively high frequencies,<sup>[17,18]</sup> and light can be harnessed to deform or rotate soft nanocomposite matter through photothermal transduction mechanisms.<sup>[19–22]</sup> Taken together, the field reached the maturity to move to the next level where the devices are not teleoperated but empowered with on-board control systems, essentially transforming them into proper robots.

**Figure 1** illustrates the envisioned transformation of next-generation microrobots. Conventional untethered micromachines are actuated and steered by the same externally-applied signal. The external control platform has an imaging modality (e.g., cameras, magnetic resonance imaging system, and ultrasound) that continuously localizes the device so that the power sources can generate the right signal to move the device from its current location to the desired location. All the planning and computation is done off-board by a computer program. Several limitations come with this motion control framework. First, real-time localization of microscopic structures is challenging, specifically while they are on the move. Second, very limited information is available on the microenvironment of the device, thus, adjusting the parameters for optimal navigation is deemed to be done with trial and error. Third, for many medical and environmental applications, it would be ideal if the device could autonomously move to a source or respond to a programmed trigger to perform a manipulation task such as the release of therapeutic agents. Here, we survey the literature on mechanisms based on mechanical and materials design principles for the realization of such advanced functionality. We critically review proof-of-concept examples that possess certain aspects of autonomous functionality, to emphasize practical challenges and future opportunities.

## 2. Mechanochemical Control Systems

One promising approach for the implementation of a microscopic on-board control system that regulates the configuration or kinematics of the robot is using smart materials that respond to external stimuli by altering their chemical and/or physical properties.<sup>[23,24]</sup> Seminal work has shown that structures fabricated from stimuli-responsive hydrogels could serve as autonomous flow control systems inside microfluidic channels.<sup>[25]</sup> The control is based on the reversible contraction and expansion of the microgel depending on the pH of the surrounding environment. The smart material was structured around pillars in a way that the actuation would regulate the fluid flow like a valve. The design paradigm was extended to multilayered microfluidic systems by coupling the force associated with these volumetric changes to the deformation of an elastic membrane. Another interesting application of this autonomous valve concept is the development of adaptive liquid microscopic lenses displaying temperature-regulated focusing.<sup>[26]</sup>

A programmable valve could serve as an on-board speed regulator when coupled to a catalytic motor (**Figure 2a**). Recent work has shown the feasibility of this approach using thermoresponsive hydrogels. The prototype consisted of a bowl-shaped polymeric vesicle encapsulating platinum nanoparticles.<sup>[27]</sup> The narrow opening of the motor served as a nozzle for the oxygen generated during the catalytic decomposition of hydrogen peroxide fuel. A temperature-sensitive polymer brush was chemically grown onto the vesicle, whereby the opening of the vesicle was enlarged or narrowed on temperature change, which controlled the access of hydrogen peroxide fuel and, in turn, regulated motion.<sup>[28]</sup> The design space has recently been extended with the introduction of 3D chemical patterning of platinum nanoparticles in arbitrary configurations.<sup>[29]</sup> Advanced on-board speed regulation can be

implemented with the design of more sophisticated transmission systems manufactured from stimuli-responsive polymers.

The shape change induced by the environmental trigger becomes distributed and intricate with the introduction of heterogeneous materials and layered architecture.<sup>[30–33]</sup> Notably, the shape change can be programmed within the nanostructure of 3D microscopic objects by controlling the local orientation of stiff reinforcing elements in the stimuli-responsive matrix.<sup>[34]</sup> The technique is based on the remote control of the orientation and distribution of reinforcing inorganic particles within the hydrogel nanocomposite using a weak external magnetic field.<sup>[35,36]</sup> This formulation generates composites with site-specific, reversible, and programmable shape changes that are autonomously triggered by environmental stimuli. The swimming motion of the magnetically-powered microrobots is highly linked to their 3D shape, specifically for helical microswimmers.<sup>[37]</sup> As illustrated in Figure 2b, coupling the morphology of the machine to the osmolarity or temperature of the microenvironment realizes on-board regulation of swimming speed as well as maneuverability.<sup>[37,38]</sup> This strategy can be extended to create a switch between a motile and non-motile morphology upon encountering a new condition to autonomously localize robots at the target location.<sup>[36,39]</sup> Although the external actuation signal is continuously provided, the shape transformation initiated at the target location would cease the robot motion (Figure 2b). Recent work has shown that these control blocks could be 3D printed using two-photon polymerization, enabling modular design and assembly of compound mechanisms with multiple control units.<sup>[40]</sup> Drastic changes in shape would influence locomotion in fluid media regardless of the propulsion mechanism due to hydrodynamic interactions, thus, these control systems can be incorporated into many other prototypes.

Stimuli-responsive hydrogels are very soft (i.e. Young's modulus on the order of kPa), mechanochemical actuation only works in water, and the response is noisy as the material is very sensitive to the physical and chemical properties of the surrounding media. Although these properties are acceptable and even desirable for biomedical applications, microrobots with robust, versatile, and precise functionality may open new application areas. As for stimuli-responsive hydrogels, liquid crystal elastomers (LCEs) also undergo a temperature-dependent phase transition. Unlike hydrogels, however, these rubber-like materials display an isovolumetric change in shape during the phase transition both in air and water. Using a chemical formulation for the LCE amenable to photothermal actuation, a conception that resembles the automatic closure of a Venus flytrap has been constructed.<sup>[41]</sup> When an object of a suitable size enters into the field of view of the device, the LCE bends toward the object, eventually capturing it. The trigger options for controlling actuation are not limited to laser illumination and heat. Mechanical loading such as interfacial shear stress can also serve as the trigger,<sup>[42]</sup> introducing the capability to process a repertoire of input signals for the control of robot actuation.

Shape transformation can be localized to the end-effector of the microrobot for spatiotemporally controlled manipulation. Self-folding capsules are widely used in the controlled release of pharmaceuticals or cells for biomedical applications.<sup>[43]</sup> Instead of directly modulating the motion of the robot, a pre-programmed change in the configuration of a specific compartment must be initiated by the control system. To this end, microgrippers that are capable of collecting<sup>[42]</sup> or releasing cargo upon environmental triggers have been engineered.<sup>[33,44–46]</sup> As illustrated in Figure 2c, spontaneous bending of the arms in the presence of the stimulus realizes operations such as targeted biopsy or deployment. In principle, these microgrippers can be

attached to any micromotor with compatible design, promoting modular assembly and compartmentalization.

While reversible and graded shape transformation is instrumental for repeated operations or continuous speed-regulation, some applications may require stable switching from one configuration to another. That is to say, exposure to a certain signal would trigger a morphological change in the robot that is not going to be reversed upon removal of that signal, and recovery of the original configuration can only be triggered in the presence of a different signal. A universal soft robotic microgripper has been developed based on the shape-memory property of ionically-crosslinked alginate gels.<sup>[47]</sup> The many degrees of freedom of a microgel are passively actuated upon contact with the surface of target objects. By molding itself around the cargo, the microgripper establishes geometric interlocking, and this new configuration is locked in place with the introduction of calcium ions (Figure 2d). The original state is recovered with the chelation of calcium ions by other chemicals. Another potential direction is the autonomous assembly of self-folding micromachines at target locations. We can envision a microrobot that transforms into a completely different stable configuration to perform a novel task. Such machines are engineered at macroscale using shape-memory composites.<sup>[48]</sup> These devices are also capable of transforming into a variety of predetermined shapes from the same base structure using embedded actuation.<sup>[49]</sup> As a last remark on this topic, it would also be interesting to engineer materials that can store energy and autonomously coordinate shapeshifting without a need for a trigger. A recent report has shown that encoding the rate and trajectory of shape transformations on timescales from seconds to several hours is feasible using dual network hydrogels.<sup>[50]</sup>

### 3. Structural and Microfluidic Logic Elements

The first calculators and computers were built from mechanical components such as levers and gears. Compliant mechanisms are suitable for additive manufacturing both at macro and microscales, and, unlike rotary mechanisms, their operation does not suffer from friction and capillary effects that dominate small scales physics. Several examples of functional materials performing mechanical Boolean logic have been successfully demonstrated by harnessing elastic instabilities and bistable mechanisms.<sup>[51]</sup> Digital mechanical systems usually rely on geometric design and controlled buckling of beam elements. The associated manufacturing paradigm works at microscale; a number of MEMS devices with buckling elements have been fabricated to be used as energy harvesters, sensors, dampers, stabilizers, and isolators. Furthermore, the high-rate motion associated with snap-through buckling has been investigated to develop novel MEMS actuators and optical switching elements.

The basic building block employed in structural logic systems is a bistable mechanism, which has two stable configurations that are characterized by a double-well potential energy landscape (**Figure 3a**). Leveraging mechanical design, the 3D building blocks can be cascaded to create multistable mechanisms with richer potential energy landscapes.<sup>[52,53]</sup> These mechanisms, in turn, can communicate information by guiding acoustic or electromagnetic waves.<sup>[52,54–58]</sup> It has been envisioned that conformable monolithic systems that undergo complex motion directly programmed within the architecture of the material will realize soft robots capable of transforming a simple input, such as a pressure impulse, into a complex sequence of flexion, tension, and torsion outputs.<sup>[59]</sup> The programmed response can be initiated by the environment with the use of stimuli-responsive materials. Bistable structures were cascaded to realize AND, OR, and NAND gates and actuated by the anisotropic swelling of materials that respond to non-polar solvents and water (**Figure 3b**).<sup>[60]</sup> Autonomous release of

strain energy upon encounter with environmental stimuli produced precise actuation events with designated functions such as jumping of structures, opening boxes and propulsion.<sup>[60–62]</sup> The design framework and the nonlinear behavior of the beams is scale-independent, and therefore the systems have the potential to be scaled down. A recent work has shown that microscopic Boolean computation elements based on buckling can be 3D printed and operated using holographic optical tweezers.<sup>[63]</sup> One exciting direction is combining the control features of stimuli-responsive materials with structural elements on the same system using two-photon polymerization.

Additive manufacturing is not the only way of building compliant mechanisms. Guided by origami design principles such as tessellations and Miura fold patterns, complex flexible structures displaying elastic instabilities have been fabricated from 2D layers.<sup>[36,64,65]</sup> A waterbomb base fold pattern with two stable configurations has been introduced as a testbed for demonstrating mechanical logic.<sup>[66]</sup> A humidity responsive polymer was incorporated into the fabric of the mechanism for the transduction of the environmental signals into the mechanical response. If the waterbomb is in a uniform relative humidity environment, both actuators sense and respond to the same signal, producing no net force and no change to the origami structure. However, in a humidity gradient, the stimuli-responsive layer restricts diffusion of water vapor, forcing it to diffuse around rather than through a waterbomb. As a result, the top and bottom sensors detect significantly different local environments, bending the origami structure and, depending on the initial waterbomb state, reconfiguring the structure. Origami patterns are modular,<sup>[36,40,67]</sup> enabling units to be developed independently and combined to create more complicated functional structures. Considering the recent advancements in the design and control methodologies of origami robots at the macroscale,<sup>[68,69]</sup> we can anticipate exciting developments in the microscale.

The structure of a machine can be designed to filter and amplify harmonic signals as demonstrated by MEMS sensors such as gyroscopes and accelerometers. Propulsion strategies based on vibrations such as acoustic streaming rely on the structural design of the robot. Maximum velocities due to harmonic excitation are achieved at eigenfrequencies where the robots are operated for efficient propulsion. Therefore, the architecture of the microrobot may be configured to convert external signals into structural changes that would modulate locomotion through mechanical logic. For example, one can envision a microrobot with several motors that operate at distinct frequencies and each motor drives the robot in a different direction. Indeed, there are untethered microrobots driven by multiple acoustic motors in the form of microbubbles,<sup>[70]</sup> or sharp-edged structures.<sup>[18]</sup> With the incorporation of mechanical logic to these prototypes, the selective activation of motors may be modulated as a response to certain chemicals or mechanical forces. In the presence of spatial gradients of signals, this strategy may lead to autonomous navigation and localization at target locations.

A substrate does not have to be solid to compute as exemplified by the macroscale hydraulic devices.<sup>[71,72]</sup> The elastic instabilities of the structures could be replaced with the nonlinearities associated with non-Newtonian fluids, droplets in two-phase flows, or air bubbles. For example, a bubble traveling in a microfluidic channel represents a bit, providing the capability to perform control operations with AND/OR/NOT gates, flip-flops, and ring oscillators (Figure 3c).<sup>[73]</sup> Likewise, the presence or absence of an oil slug in a continuous aqueous phase represents true or false, respectively.<sup>[74]</sup> A more advanced version of this platform was built using ferrofluid droplets.<sup>[75]</sup> Through magnetic and hydrodynamic interactions among droplets, a variety of logic gates have been constructed, which together led to the development of a finite-state machine. For the realization of on-board microfluidic logic, wirelessly powered pumps must be incorporated into the untethered microrobots. Untethered

micropumps powered by magnetic fields and acoustic waves serve as a first step towards the development of fluid circuits that can compute.<sup>[18,76]</sup>

### 3.2. Harnessing Fluid-Structure Interactions

An elegant method for building digital logic gates inside microfluidic channels is driving the deformation of elastic valves with fluid flow or pressure. Physical gaps and cavities interconnected by holes were fabricated into elastomer structures to form networks of fluidic gates that spontaneously generated cascading and oscillatory flow output using only a constant input flow.<sup>[77]</sup> Following a similar design framework, check-valves (Figure 3d) and switch-valves were replaced with pressure-gain valves, where low and high pressure correspond to the bits of the logic system.<sup>[78]</sup> Digital logic circuits were also constructed from bistable pneumatic valves that rely on snap-through instabilities of hemispherical membranes.<sup>[79]</sup> The concept of programmable regulation of flow by the actuation of integrated flexible membranes has been recently extended to the control of autonomous soft robots.<sup>[6]</sup> A microfluidic oscillator circuit that includes a system of switch and check valves convert pressurized fuel (hydrogen peroxide) inflow into alternating fuel outflow. Downstream decomposition of the fuel inside the reaction chamber by platinum catalyst results in volumetric expansion and programmable actuation of pneumatic arms.

Having on-board actuated elements for driving fluid flow or modulating pressure would significantly increase the size and complexity of the microrobots. A more practical way of instantiating computation from FSI is harnessing hydrodynamic forces generated due to the motion of the robot. For this strategy to work, the microrobot must have very flexible structural elements that can be deformed by viscous drag as inertial effects are negligible at the microscale.<sup>[80]</sup> Flexible helices uncoil under viscous flow and slender rods coil once rotated at

a certain angular speed in viscous fluids. Inspired by these fundamental studies, magnetic microswimmers have been engineered to adapt their motility by spontaneously modulating their morphology as a response to changes in the viscosity of the surrounding fluid (**Figure 4a**).<sup>[37]</sup> In essence, the robots are regulating the thrust applied by their propeller on-the-move although the externally applied magnetic field is kept constant. The same mechanism endows the microrobots to adapt to shear flows where the helical body uncoils as the robot passes through a channel with a narrowing profile (**Figure 4b**).<sup>[37]</sup> Using elastohydrodynamic coupling in morphological transitions and gait adaptation enables enticing opportunities for microrobots navigating inside obstructed, heterogeneous, and dynamically changing environments. For example, if the microrobots had multiple flexible propellers, shapeshifting might be localized to select actuators in response to changes in the fluid viscosity, in the presence of boundaries, or passively passing through bifurcations, in order to realize autonomous navigation.

Until now, we considered the mechanical behavior of the materials as continuous mass. Soft microrobots can be manufactured from actuated functional discrete elements. Indeed, one of the first mobile untethered microrobots was a chain of magnetic microparticles attached via DNA linkers.<sup>[11]</sup> More recently, the powering scheme of self-assembled micromachines has been extended to photothermal actuation.<sup>[20,81]</sup> Colloidal physics provides rich resources on the collective motion of actuated particles along with resulting hydrodynamic effects. Flexible structures based on chains of magnetic particles transform both shape and motility under varying magnetic fields.<sup>[82]</sup> Notably, the transformation between different chain morphologies and locomotion modes enables these colloidal chains to navigate through complex 3D environments, such as long and curved channels. If we consider a group of particles, though not physically connected, that stay together due to magnetic and hydrodynamic interactions as a microrobot, the possibilities for on-board control will expand significantly. Dynamic

assemblies of magnetic microparticles demonstrate multimode locomotion and versatile transformation, all thanks to the fluidic nature of the composition.<sup>[83–88]</sup> We can envision that with the incorporation of stimuli-responsive materials and by harnessing FSI, these swarm robotic systems may adapt to the changes in the environment during locomotion and follow gradients of signals to autonomously reach target locations (Figure 4c). Another exciting direction towards instantiating on-board control is the incorporation of feedback control into colloidal systems with space-dependent rotational dynamics.<sup>[89]</sup> As a final remark, colloidal suspensions of chemical motors perform phototactic flocking through electrophoresis.<sup>[90,91]</sup> These physiochemical effects may be harnessed to build more complex and functional mobile autonomous robotic devices.

#### **4. Conclusion**

Microrobotics has been rapidly emerging as a field continuously fed by various established disciplines including polymer chemistry, colloidal physics, condensed matter physics, optics, and mechanics. The richness in the design and actuation principles that have been explored resulted in scientific advancements as well as demonstrations of feasibility for various applications. However, the capabilities of the existing prototypes are limited, particularly due to the lack of technologies for on-board perception and control. In this report, we highlighted three major directions that may lead to the development of untethered autonomous mobile microrobots. A solid understanding of material properties, fluid-structure interactions, and nonlinear mechanics that would enable programmable responses to environmental stimuli will play a critical role in this important quest. We also expect important milestones in computational mechanical design and manufacturing as the mechanical control systems developed for macroscale robots cannot be directly miniaturized using the existing

technology. The modified design principles must be guided by multiphysics simulations that take the dominant forces at microscale into account. Despite the difference due to scale, soft roboticists have been asking the right questions regarding physical intelligence, therefore, both domains of robotics are expected to inspire each other in the following years. The authors are convinced that mechanics is the leading path to autonomy at microscale.

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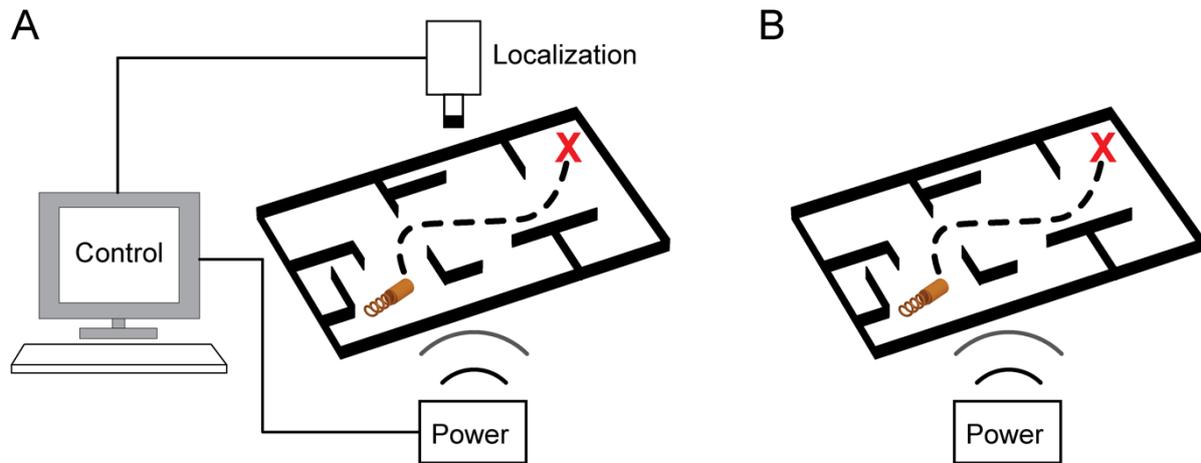
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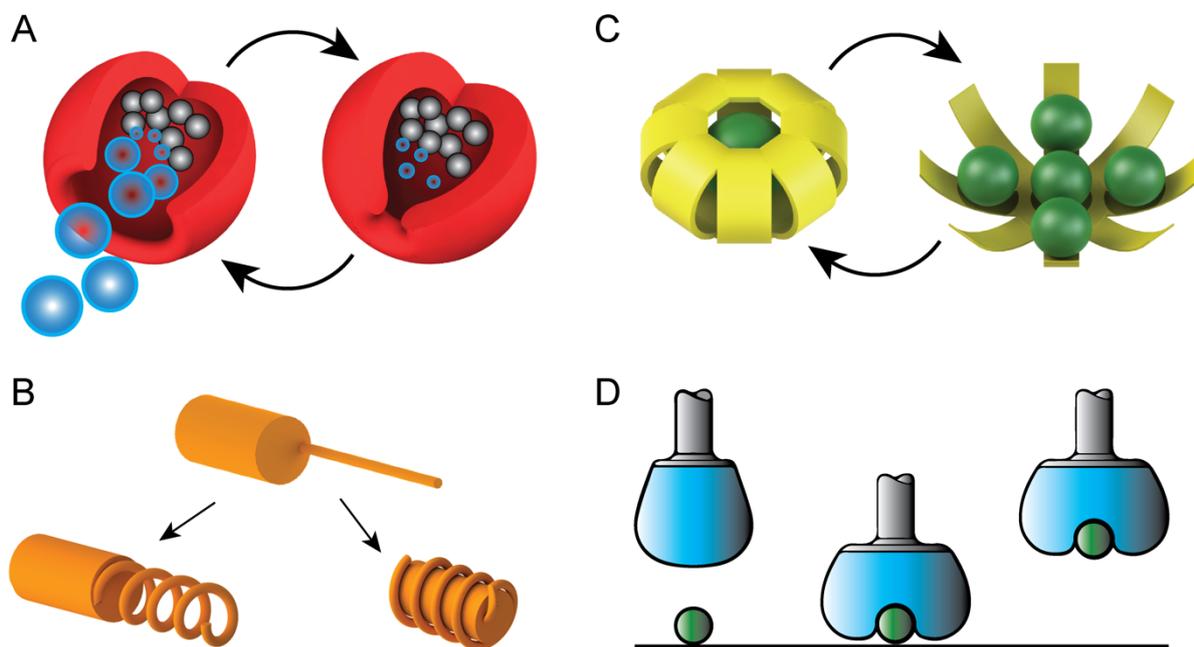
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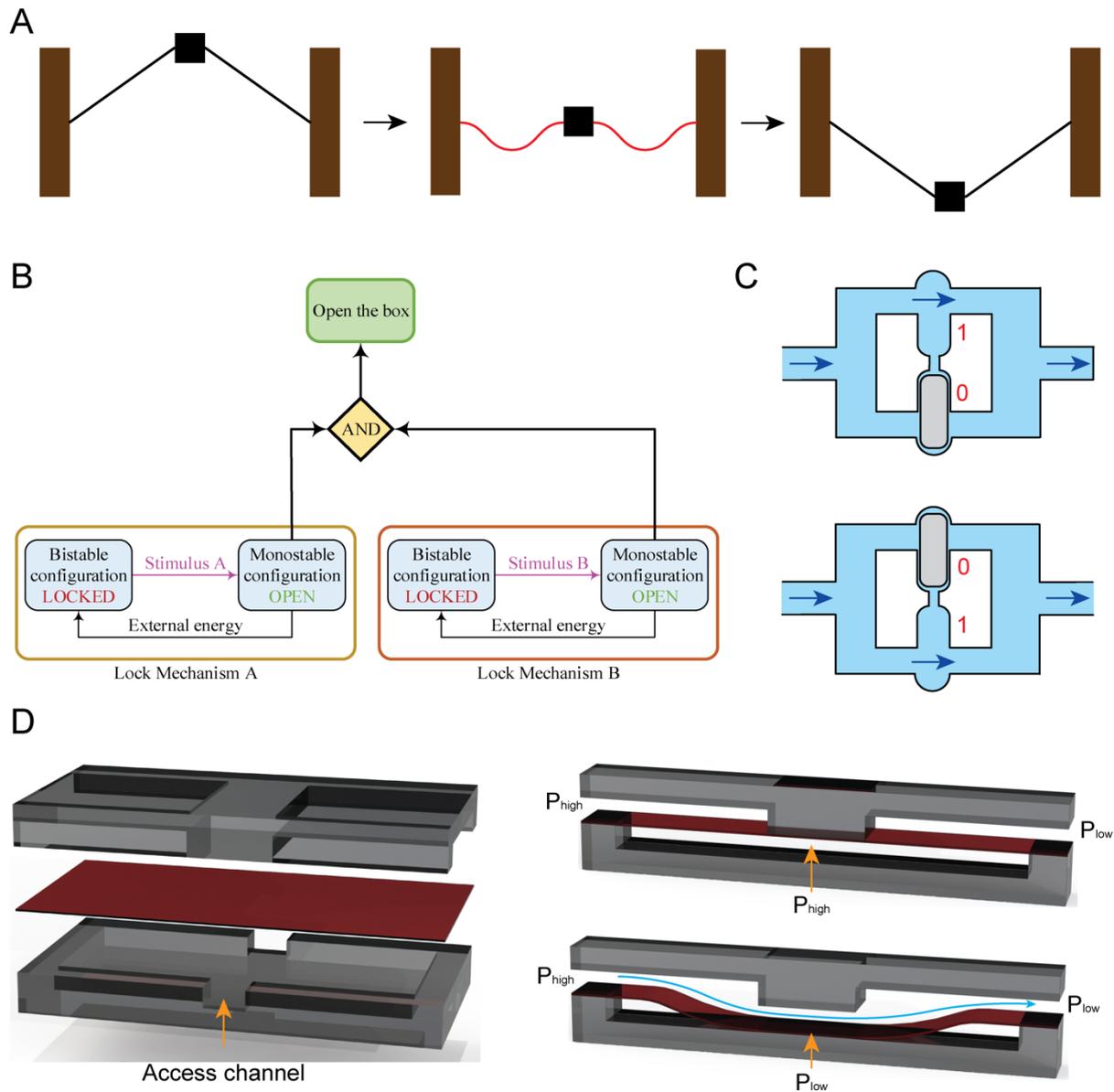
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**Figure 1. Progress and outlook for untethered mobile microrobots.** **A** The majority of existing microrobotic manipulation platforms are based on computer vision and teleoperation. The localization can also be performed using magnetic resonance imaging systems or ultrasound probes. The computation and control are completely delegated to external hardware and software. **B** Next generation microrobots will still be actuated by an external power source. However, it is envisioned that they will be designed to possess autonomous functionality such as agglomerating at target locations or performing triggered manipulation tasks with the incorporation of on-board control systems.

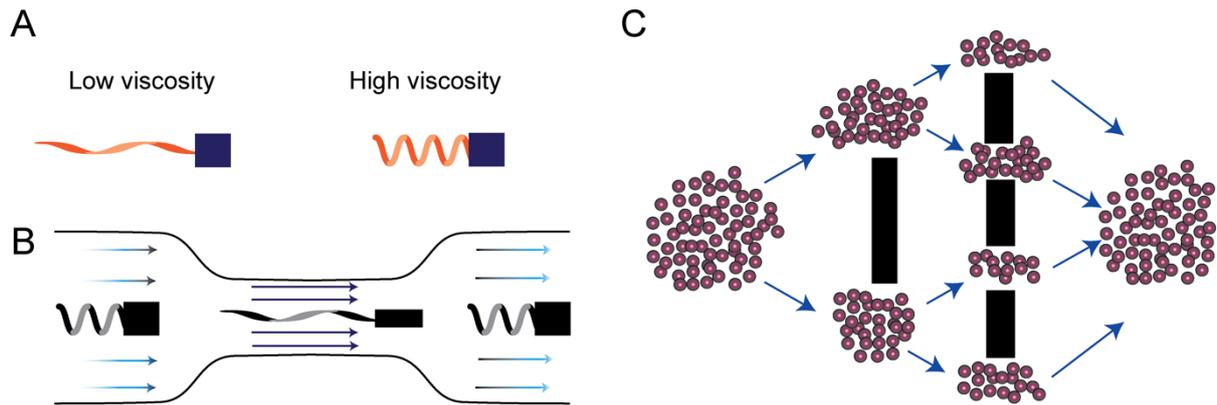


**Figure 2. Mechanochemical control systems based on stimuli-responsive and shape memory materials.** **A** On-board speed regulation for chemical motors using a thermoresponsive valve. The contraction of the gel blocks the access of the fuel to the catalyst (shown as gray particles) encapsulated inside a vesicle (red). **B** The coiling of the tail of a magnetic microswimmer as a response to changes in the environment regulates both the mobility and maneuverability of the machine. The machine can transform into a completely different shape to perform a different task. **C** Shape transformation initiated by external stimuli can drive targeted manipulation tasks such as release of cargo. As the response is reversible, the self-controlled actuation can be repeated to perform multiple tasks or go through load-release cycles. **D** Shape-memory property of hydrogels can be harnessed to perform universal gripping and transport of cargo. Ionic crosslinking of the gel after contacting the cargo locks the shape of the gel. This effect can be harnessed to transform machines at target locations.



**Figure 3. Structural and microfluidic logic for building control systems.** **A** Bistable mechanism based on buckling beam elements. The mechanism has two stable states and, thus, it can be used as a bit or register. **B** Combining mechanochemical control with structural logic leads to the development of AND gates. Stimuli A and B generate swelling of two different responsive materials, and, therefore, treated as two different inputs. The design of the bistable mechanism controls the energy landscape. **C** Mechanical flip-flop based on air bubble (gray)

traveling inside the channel along with the fluid flow. Upon the introduction of a new bubble into the input channel, the entrapped bubble is ejected and the system switches states. **D** A switch-valve that is based on snap-through instability of an elastomer membrane. The flow or pressure inside the channel can self-regulate the opening and closing of embedded valves.



**Figure 4. Harnessing fluid-structure interactions for instantiating on-board control.** **A** Elastohydrodynamic interactions between the flexible microswimmer and the surrounding fluid can modulate the shape of the swimmer, and whereby the mobility and maneuverability of the machine. Viscosity is one of the major parameters that has direct effect of viscous stresses. Microscopic helices driven at a fixed angular speed can start coiling with increasing viscosity. **B** The shear stress generated by external flow can deform flexible microswimmers. This deformation is a form of adaptation as it allows navigation inside narrow channels. **C** Dynamic assemblies of actuated colloidal particles display adaptive locomotion by splitting and merging during forward motion inside structured environments.

## Author Biographies



Amit Dolev received his B.Sc. (Suma cum laude) in Mechanical Engineering at Technion – Israel Institute of Technology and Ph.D. in the Dynamics laboratory headed by Prof. Izhak Bucher at the Technion-IIT. He is currently a postdoctoral associate at the MicroBioRobotic Systems (MICROBS) Laboratory at EPFL, where he works on utilization of acoustics for powering microscale technologies. He pursues a broad range of research interests including nonlinear dynamics, fluid-structure interactions, vibrations, signal processing, acoustics, and control.



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Mahmut Selman Sakar is the head of the MicroBioRobotic Systems (MICROBS) Laboratory and tenure-track assistant professor in the Institute of Mechanical Engineering at EPFL. He received his Ph.D. degree in Electrical and Systems Engineering from the University of Pennsylvania in 2010, and performed post-graduate research at Massachusetts Institute of Technology and ETH Zurich before moving to Lausanne in 2016. His current work focuses on the applications of small-scale robotics in life sciences including mechanobiology, developmental biology, neuroscience, and minimally invasive medical technologies.