



Making robots microscopic

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Wirelessly powered and mass manufactured, the dust-sized robots can crawl, survive harsh environments, and be injected through a hypodermic needle.

The first time I looked into a microscope, I was amazed. Earlier that day, my science teacher had waded into the creek near our elementary school and pulled up a bucket of muddy water. After he distributed samples on microscope slides to the class, I brought the image into focus and found myself staring at a tiny monster—a rotifer, sucking up helpless microbes around it—trapped in a drop of water.

That memory is not unique. Most people are probably stunned the first (or really any) time they peer through a microscope. In spite of their small size, the creatures that populate the tiny worlds that come into view are remarkably complex. They can sense, communicate, process information, and explore. What if it were possible to build a machine the size of a microorganism that engineers could communicate with and directly control? I learned early on that nature builds such organic robots all the time. The question is how to pull it off synthetically for ourselves.

A new technology

Fortunately, scientists already know how to build many of the key components needed for a microscopic robot. Electronics have been shrinking for the past 50 years. And with today's state-of-the-art fabrication technology, nearly a million transistors can fit in the space of a paramecium. The smallest computer—complete with a microprocessor, memory, a thermometer for sensing, and an LED for two-way communication—is just a few times as large as a hair's width. In principle, those technologies could readily be adapted into the core of tiny machines that sense, think, and act.

That's the vision: Steal the powerful design of microelectronics and exploit it for robotics. For five years I worked toward that goal as a postdoc with Paul McEuen and Itai Cohen at Cornell University, and now I head my own group at the University of Pennsylvania. When we started, the biggest roadblock was clear enough: We could build the brain of a micro-robot but not the body. Plenty of semiconductor electronic components were available, but no microscale actuators that could seamlessly integrate with them. The available approaches to building moving parts for microrobots encountered one of two problems: Either the parts couldn't be fabricated to bend without breaking at cellular dimensions or the actuators couldn't be controlled with electronic signals.

To overcome those hurdles, we designed a new technology: surface electrochemical actuators (SEAs). Each SEA is made from a thin layer of platinum—ours is 7 nm thick—capped on one side with a 2 nm layer of titanium. The entire actuator is

just a dozen atoms thick, which makes it flexible enough to deform without breaking.

Put a SEA in water, apply a voltage to it, and you'll find that it bends. That's because aqueous ions attach themselves to the surface of the platinum to an extent that depends on the voltage. And when they attach, they stress the material, but only on the platinum side. The difference in stress between platinum and its capping layer prompts the device to curl. At the microscale, those surface forces are significant thanks to the large surface-to-volume ratio of tiny objects. What's more, the curling is reversible: When the voltage is turned off, the ions detach from the surface and the stress relaxes.

The voltage required to attach or remove ions is a few hundred millivolts. It's constrained by thermodynamics to be essentially the thermal energy per ion, kT/e , where k is the Boltzmann constant, T is temperature, and e is the charge on an electron. The same scale also determines the turn-on voltages for silicon microelectronics. As a result, integration is trivial: One can simply run a wire from the output of a silicon transistor into a SEA. And the same electrical signal used for computation can be used for mechanical work.

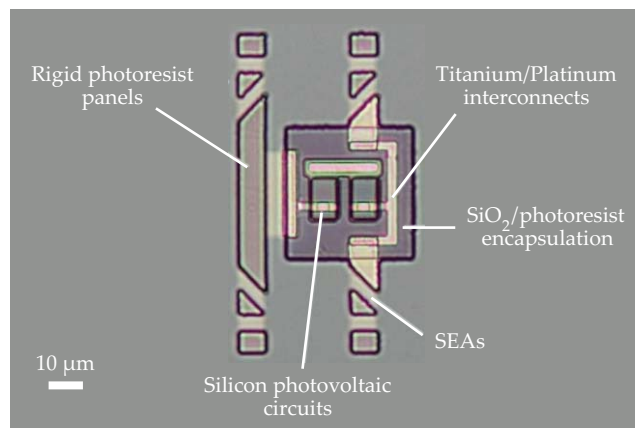


FIGURE 1. THIS MICROSCOPIC ROBOT is composed of a body with internal electronics and four movable legs. The circuits are made from silicon p-n junctions and metal interconnects, encapsulated between a layer of silicon dioxide and a layer of photoresist. The robot is also equipped with two tiny solar cells, the photovoltaic circuits. By shining laser light on each cell, researchers create the voltage that controls the front and back legs, which are made from a new class of surface electrochemical actuators, or SEAs, that allow the robot to move. (Adapted from M. Z. Miskin et al., *Nature* **584**, 557, 2020.)

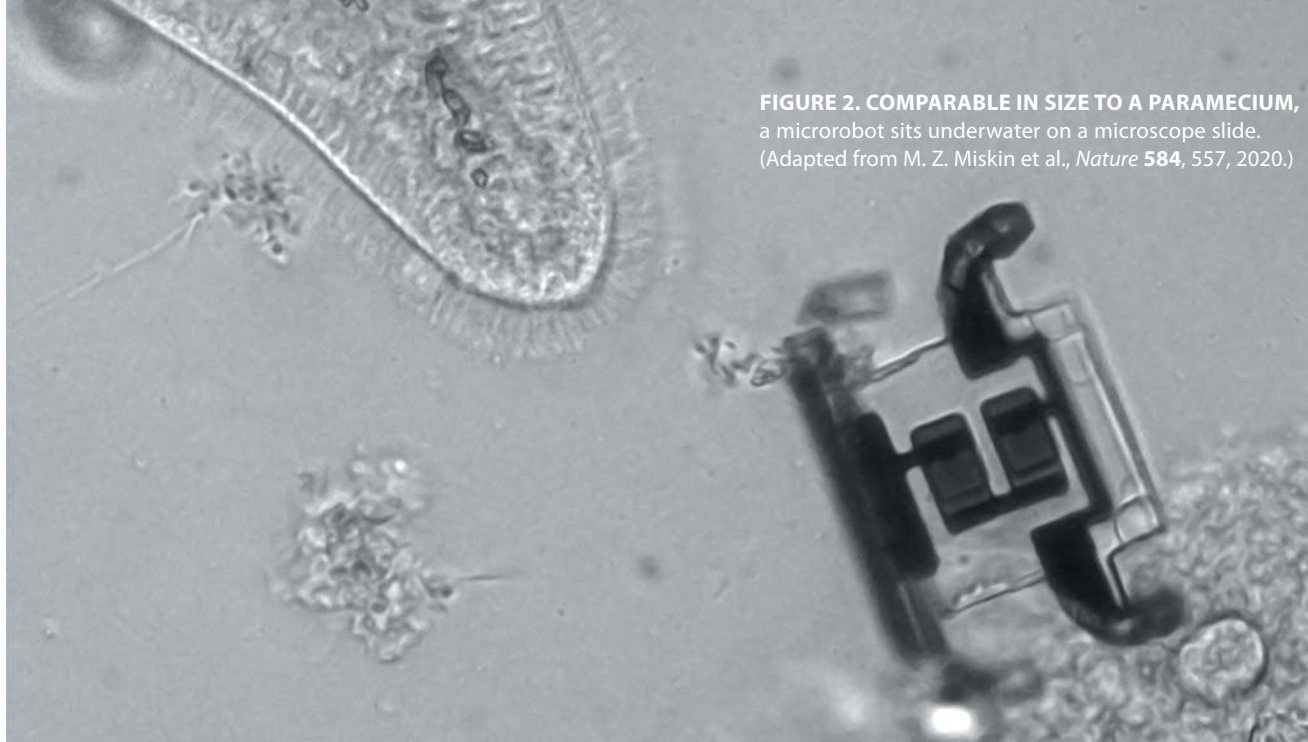


FIGURE 2. COMPARABLE IN SIZE TO A PARAMECIUM, a microrobot sits underwater on a microscope slide. (Adapted from M. Z. Miskin et al., *Nature* **584**, 557, 2020.)

From principle to proof

We built a first prototype about two years ago by linking electronics with actuators. The robot, shown in figure 1, is simple. Atop its body, it supports two silicon photovoltaic circuits that convert laser light into electrical energy. The photovoltaics power two sets of legs, one in the front of the body and the other in the back. Laser pulses shining on the photovoltaics force each set of legs to move on command. By repeatedly switching between moving the front and rear legs, we can make the robot walk around its environment. As far as we're aware, the device is the smallest-legged walking robot in existence. At just under $100\text{ }\mu\text{m}$ in length, it is too small to be seen by the naked eye (see figure 2).

Actually, we didn't build *a* prototype; we built 1 million. The technology used for microfabrication is massively parallel. We can literally make the million robots atop a 4-inch silicon wafer. We also figured out how to release them in parallel: We can reliably set the robots free into an aqueous environment to produce tiny robot swarms that float freely and are ready to walk. The largest swarm we've built so far had about 10,000 members in it.

Built millions at a time, microrobots wind up being extremely inexpensive, with each costing fractions of a penny. They're essentially disposable, a far cry from their expensive macroscopic cousins. Indeed, being tiny endows the robots with a host of unique properties. Walking at the microscale consumes just nanowatts. With solar cells and SEAs as actuators, the robots can be powered by laser light or even ordinary sunlight and walk around indefinitely. They can respond to the light signal in 10 ms—a limit imposed by the viscous drag of the fluid—and exert forces on the order of nanonewtons. That's on par with the forces biological cells generate during locomotion and more than enough to lift and move the 50 pN weight of the robot's body. Currently robots walk at about $1\text{ }\mu\text{m/s}$, a speed set by how fast we switch the laser. Yet the peak speeds can be as fast as $30\text{ }\mu\text{m/s}$ —almost one body length per second.

The tiny machines are also remarkably robust. Their exterior is made of platinum, glass, and a durable polymer epoxy. The result is extreme chemical and thermal stability. We've exposed our robots to strong acids, strong bases, and temperature

variations of several hundred degrees, and we've shot them through syringes. In each case, they survived.

An active field

Beyond our group, research teams around the world are working on other ways to build microscale machines. Some groups use magnetic fields, ultrasound, or chemical reactions to power and control robots. Some are working to adapt those advances to the medical field, so the robots can operate deep in the human body at single-cell resolution. The microworld is emerging as an environment that humans can now control, manipulate, and engineer.

A bright future awaits. Scientists can now adapt the new actuators into systems designed for locomotion, for grasping, and for manipulating the local environment. My own group is in the early stages of designing and building walking robots whose on-board circuitry responds to stimuli, times maneuvers, and is even capable of basic programmability.

We're starting to envision applications such as rewiring damaged nerves, cleaning battery electrodes, and using microrobots themselves as model systems for investigating the physics of biological swarms. If you're wondering what else is possible from building small machines, think back to your own experiences looking into a microscope. The microworld is the fundamental scale of biology. Even the simplest living things on Earth hint at the awesome opportunities for microscale machines.

Additional resources

- M. Miskin, P. McEuen, "Tiny robots with giant potential," TED talk (November 2019).
- M. Z. Miskin et al., "Electronically integrated, mass-manufactured, microscopic robots," *Nature* **584**, 557 (2020).
- M. Z. Miskin et al., "Graphene-based bimorphs for micron-sized autonomous origami machines," *Proc. Natl. Acad. Sci. USA* **115**, 466 (2018).
- K. J. Dorsey et al., "Atomic layer deposition for membranes, metamaterials, and mechanisms," *Adv. Mater.* **31**, 1901944 (2019).
- M. F. Reynolds et al., "Capillary origami with atomically thin membranes," *Nano Lett.* **19**, 6221 (2019).

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