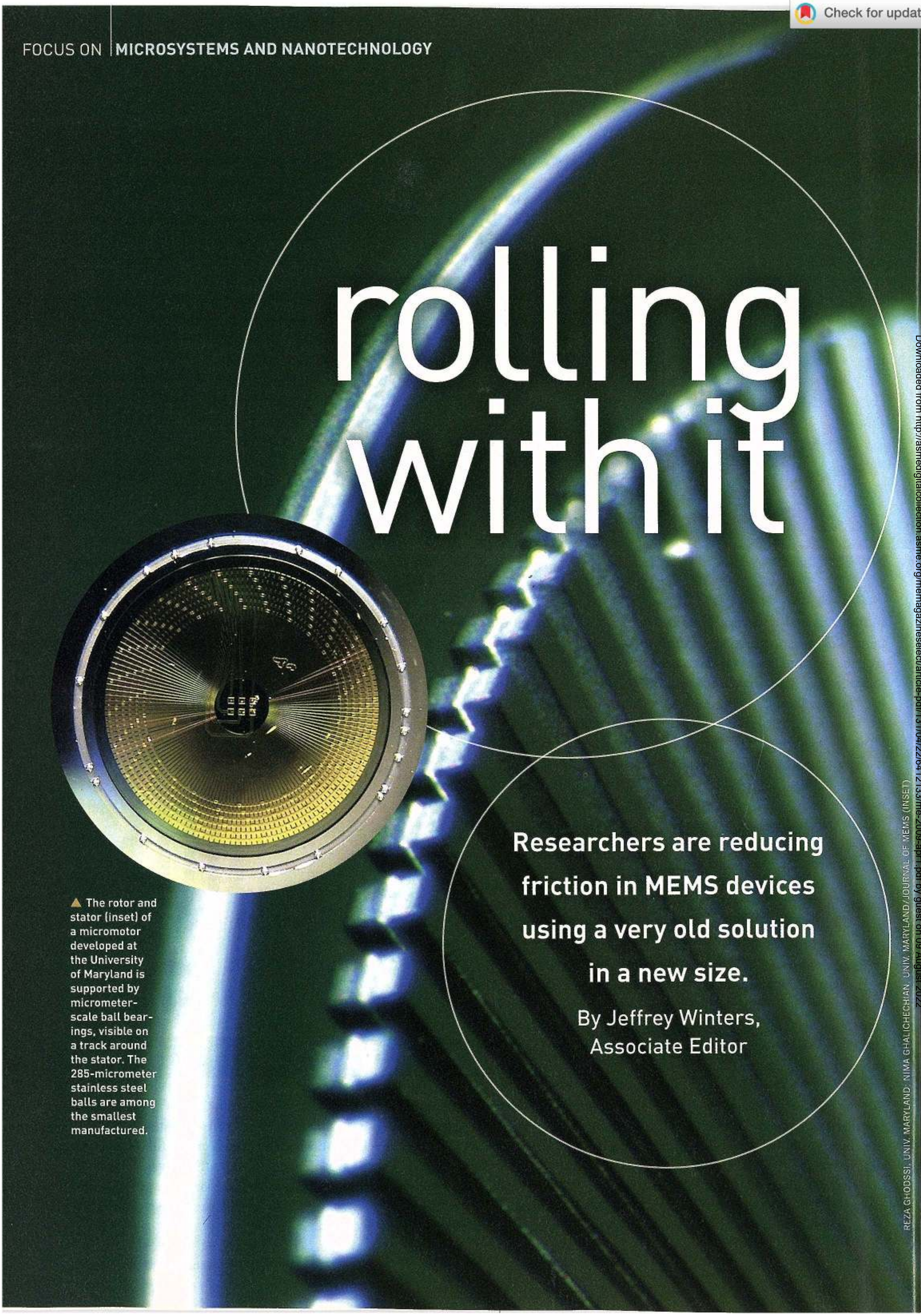


rolling with it

Researchers are reducing friction in MEMS devices using a very old solution in a new size.

By Jeffrey Winters, Associate Editor

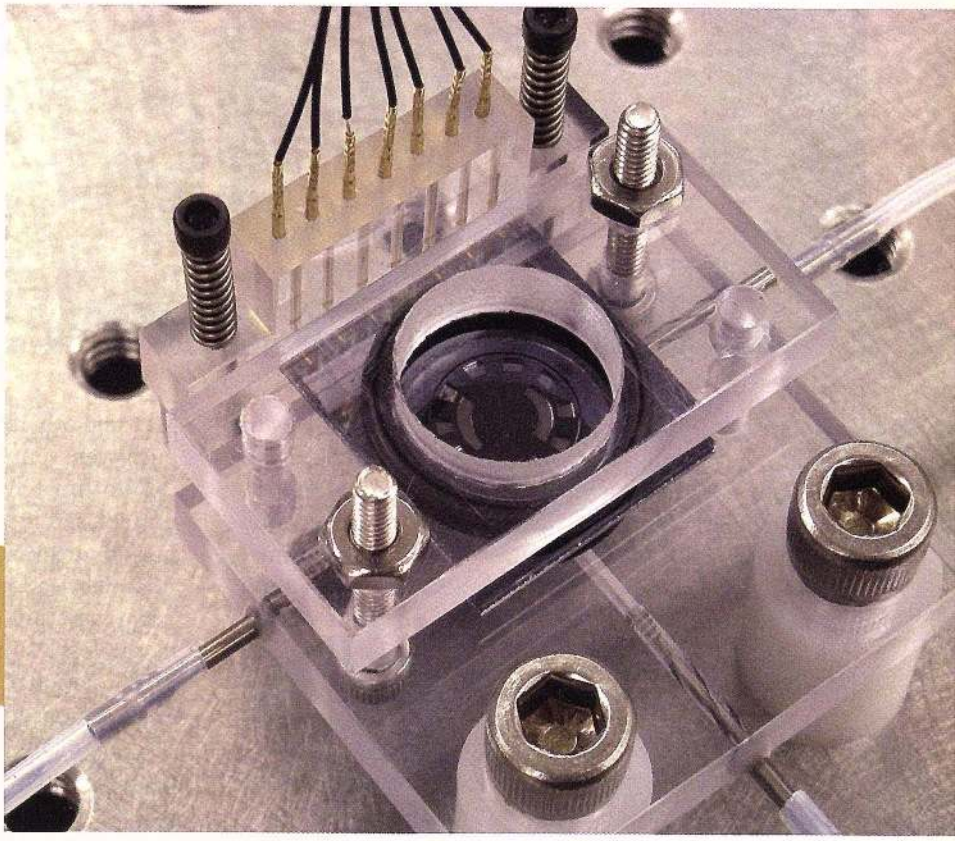
▲ The rotor and stator (inset) of a micromotor developed at the University of Maryland is supported by micrometer-scale ball bearings, visible on a track around the stator. The 285-micrometer stainless steel balls are among the smallest manufactured.

REZA GHODSSI, UNIV. MARYLAND; NIMA GHALICHECHIAN, UNIV. MARYLAND/JOURNAL OF MEMS (INSET)

How much power can be stuffed into a small package? A decade ago, two engineers at the Massachusetts Institute of Technology in Cambridge laid out a vision of millimeter-scale turbines capable of producing a few watts apiece. Such engines, each the size of a grain of rice, could power MEMS devices directly or provide an alternative to batteries for handheld electronics.

But that wasn't the most startling vision. Writing in the May 23, 1997, issue of the journal *Science*, Alan Epstein and Stephen Senturia noted that thrust-to-weight ratio of a millimeter-size jet engine would be on the order of 100 to 1, about ten times better than those found in commercial aircraft. Epstein and Senturia then provided the kicker: "1,400 of them working in parallel," they wrote, "could levitate [a] skateboard."

In the mid-1990s, the idea that microscale engines could soon be propelling flying skateboards didn't seem so far-fetched. After all, MEMS devices were quickly moving from the laboratory to the marketplace, and researchers seemed to be making the progress needed to produce millimeter-scale turbines. In the intervening decade, however, the steps toward self-powered MEMS devices have been coming much more slowly, and some of the most promising approaches look to be dead ends.



▶ This experimental micromotor using ball bearings is mounted for testing. Similar motors designed in Reza Ghodssi's lab have achieved rotational rates of 87,000 rpm.

MATT MCCARTHY, UNIV. MARYLAND/IEEE MEMS

"Some people argue that the reason that MEMS is still not a multi-billion dollar industry after so many years of research is because of problems with the long-term reliability of the devices," said Reza Ghodssi, a professor of engineering at the University of Maryland in College Park. Engineers have yet to design complex microscale machines with rotating parts that can withstand months or even weeks of wear and tear.

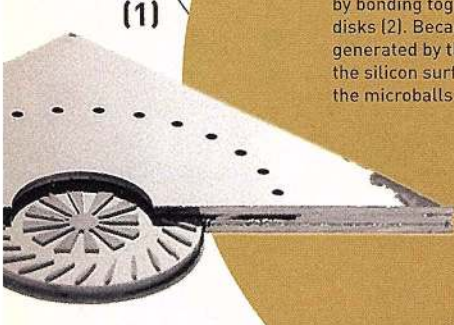
Ghodssi's research team is getting attention for using an old technology to make fresh progress in reducing wear in microscale systems. Indeed, if someday teenagers can hover on high-tech skateboards, it may well be because of something as humble as miniature ball bearings.

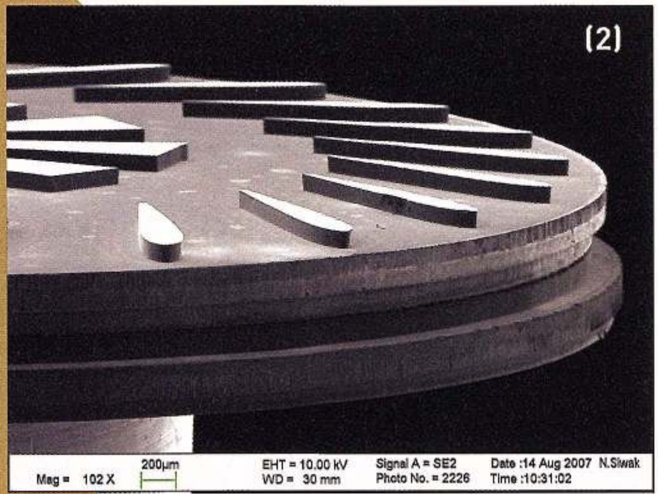
Size aside, micromachines are pretty normal objects. Micromachines are subject to adhesion, inertia, fluid dynamics, and stress, just as macroscale machines are. Perhaps the foremost force engineers need to worry about for micromachines with moving parts is friction.

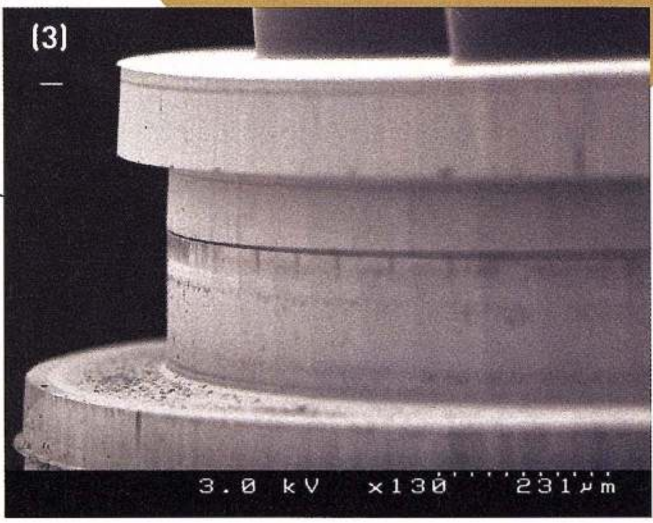
Engineers designing MEMS devices have dealt with the problem of friction in two ways. One is to design devices with very few or no parts moving while in contact with another. Cantilevers, which jut out like diving boards, can bend back and forth without touching anything. The micromirrors at the heart of Texas Instruments' digital light processing technology are set on hinges that allow a fairly constrained range of motion.

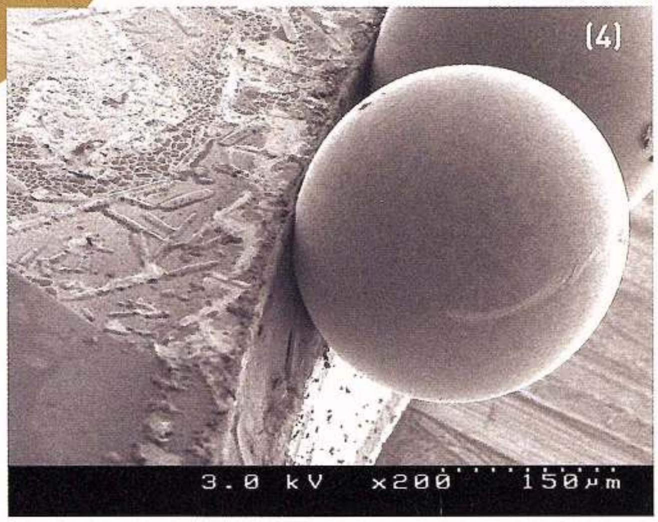
Researchers at the University of Maryland have developed an experimental air-powered turbine (1) supported by microball bearings. The microballs are contained in a notch in the edge of the turbine, which is created by bonding together a sandwich of silicon disks (2). Because of the low level of friction generated by the steel microballs rolling over the silicon surface, neither the turbine (3) nor the microballs (4) show much wear after use.

(1)









The first MEMS motors were built in research labs in the late 1980s and they were electrostatically driven, with rotating parts jumping forward around a ratchet. The moving parts had contact bearings: In essence, one part would just slide over the other. It was not an optimal solution. At rest, there was a danger that the parts would be subject to atomic forces that would bind them together, thus resisting any force trying to move the parts. The unlubricated pieces would be stuck, if temporarily.

Of more importance to high-speed applications such as turbines, however, was that no matter how low the bearing friction was, heat would build up, requiring elaborate cooling mechanisms. Friction would also cause wear on the parts, leading to failure. These early motors had a lifetime measured in a few hours.

In the years before Epstein and Senturia wrote their article in *Science*, researchers had realized that they needed a more robust way for enabling MEMS-scale parts to rotate at great speed. By the mid-1990s, researchers at MIT had built the first air bearing on the microscale. This was a huge advance: It held out the promise of virtually zero friction as the rotating parts were supported on a cushion of air. Experimental microturbines built by MIT and others during an intensive decade-long research push were spun at more than two million rpm.

Unfortunately, the air bearing introduced as many problems as it solved. The design specs for devices relying on air bearings were incredibly exacting, involving microfabrication with tolerances of about a micrometer. "Any variation or tapering in the sidewalls could result in the loss of the microturbine," Ghodssi said. At such high rotational speeds even the slightest contact carries an enormous force.

To maintain the cushion that separated the moving parts, a steady stream of air had to be introduced into the device. This support apparatus could be many times the size of the MEMS device itself. And while it was excellent at spinning miniature turbine parts at millions of rpm, it was less effective with slower speeds or when turning a rotating piece by a few degrees, Ghodssi said.

There were other problems being encountered by researchers working on power MEMS, to be sure, but the lack of a sensitive, durable bearing has helped slow the progress toward pumps, turbines, and other rotating machinery at the microscale. The microengine research program at MIT was phased out last year.

(1) MATT MCCARTHY, UNIV. MARYLAND/JOURNAL OF MEMS; (2-4) REZA GHODSSI, UNIV. MARYLAND

Ghodssi worked on the microengine program at MIT in the mid-1990s and faced the problem of air bearings. But prior to that, he had researched the potential for using another kind of bearing in MEMS. "In fact, my master's thesis was the first demonstration of measuring the mechanical properties of ball bearings in MEMS," Ghodssi said. After leaving the microengine program, he returned to the ball bearing.

Ball bearings and other roller-type bearings have been in the mechanical bag of tricks for centuries. It's believed that tree trunks underlying sleds helped Egyptians move the heavy blocks used to build pyramids. Wooden ball bearings were discovered in the remains of ancient Roman ships.

The modern ball bearing was patented by a 19th century bicycle manufacturer, and from that point on, it became an integral part of machinery. So critical were these bearings that Allied bombers repeatedly attacked German ball bearing plants during World War II.

Unlike contact bearings, such as bushings, ball bearings minimize the amount of contact between the moving parts. When the balls are rolling in their tracks, the small amount of contact area means that friction is minimal.

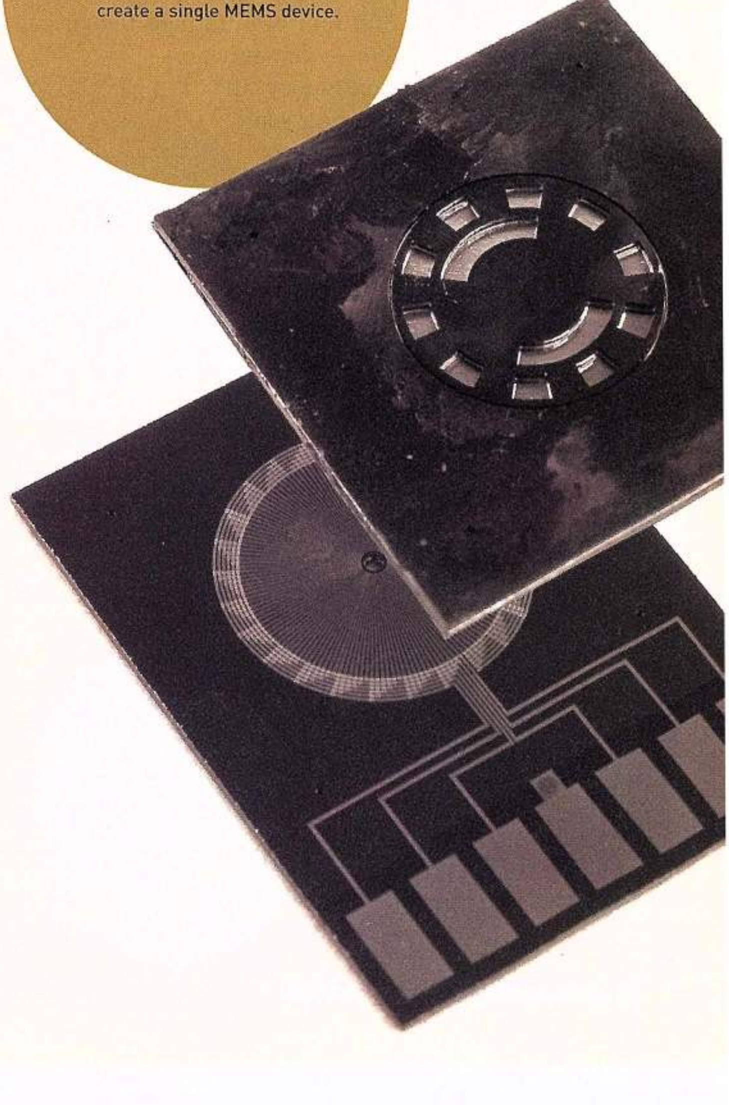
"Over the years, ball bearings have shown themselves to be a reliable platform," Ghodssi said. He added that he was surprised that no one else in the MEMS community had investigated integrating ball bearings into MEMS, since it seemed to be a very obvious solution.

Beginning in the early 2000s, Ghodssi and a research team at Maryland's MEMS Sensors and Actuators Laboratory that included Matthew McCarthy and Mike Waits began investigating just how to incorporate ball bearings into MEMS devices. The bearings themselves were made conventionally because photolithography and other microscale fabrication techniques can't make objects smooth enough. At 285 micrometers, they are near the extreme of what's commercially available. Ball bearings as small as 150 micrometers are now available, though the Maryland group is not using those at the moment.

"When you start working on a new area, you don't want to scale down too much," Ghodssi said. "You want to develop the concept first and understand the limitations."

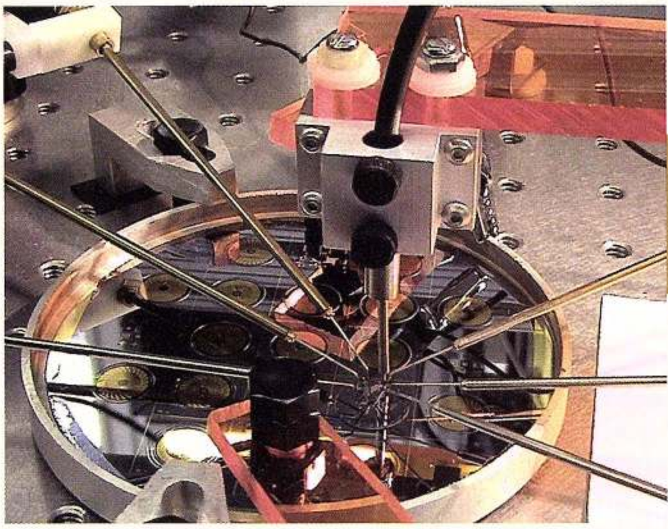
The trick, however, was figuring out how to incorporate these ball bearings into a microfabricated device. After a couple of false starts, the research team hit upon an elegant solution. The balls are placed by hand onto a track etched into a silicon wafer. Another wafer is bonded over the top of the balls, encapsulating them in a racetrack. The wafer is then etched so that a central rotor is cut away from the rest of the wafer and can turn freely, supported only by the bearings. Of course, no fabrication method that relies on graduate students is ready for mass production. But Ghodssi said that since this technique is fairly straightforward, it has the potential to scale up cheaply.

Supported on ball bearings the size of dust particles, the disks are part of a new approach to MEMS turbines. Unlike air bearings, which operate best at very high speeds, ball bearings do best at lower rotational rates. Ghodssi estimates that rotors supported by ball bearings could run at speeds between 10,000 to

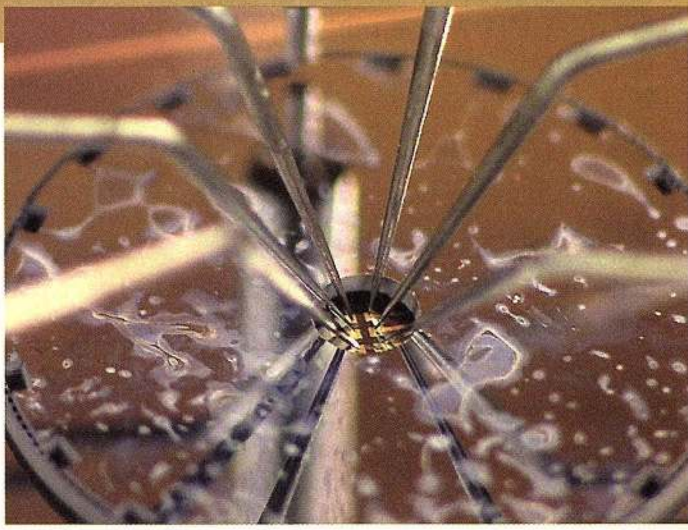


▼ The stators and rotors of the micromotors are fabricated separately and then bonded together to create a single MEMS device.

MATT MCCARTHY, UNIV. MARYLAND/IEEE MEMS



Micromotors supported by ball bearings are shown during testing. Current to the stator is provided through the 2 mm opening in the rotor.



200,000 revolutions per minute. "In this speed range, you can do all sorts of things, including power generation," he said. The higher speed possible with air bearings promises more power, but in Ghodssi's eyes the ball bearings compensate by offering more simplicity.

In research reported last year in the *Journal of Microelectromechanical Systems*, Ghodssi and students Nima Ghalichechian, Alireza Modafe, and Mustafa Beyaz built a six-phase micromotor just 14 millimeters across and capable of more than 300 microwatts of mechanical power. In proof of concept experiments, the rotor turned at more than 500 rpm even though the air gap was only 10 micrometers—a feat only possible because of the consistency and reliability of the ball bearing supports. The experimental motors were tough enough to survive many hours of continuous operation at low speed. Other experiments have run at faster speeds, up to 87,000 rpm for shorter periods.

The hope is to use these turbines as the heart of miniature pumps, motors, and generators in applications where tiny amounts of power can do an enormous amount of good. Researchers at the Army Research Laboratory in Adelphi, Md., are pursuing the use of microscale components to supply power to electronic devices on the battlefield. Microscale pumps, for instance, could feed hydrogen or alcohol to miniaturized fuel cells, or fingernail-size turbines could directly power micro-generators.

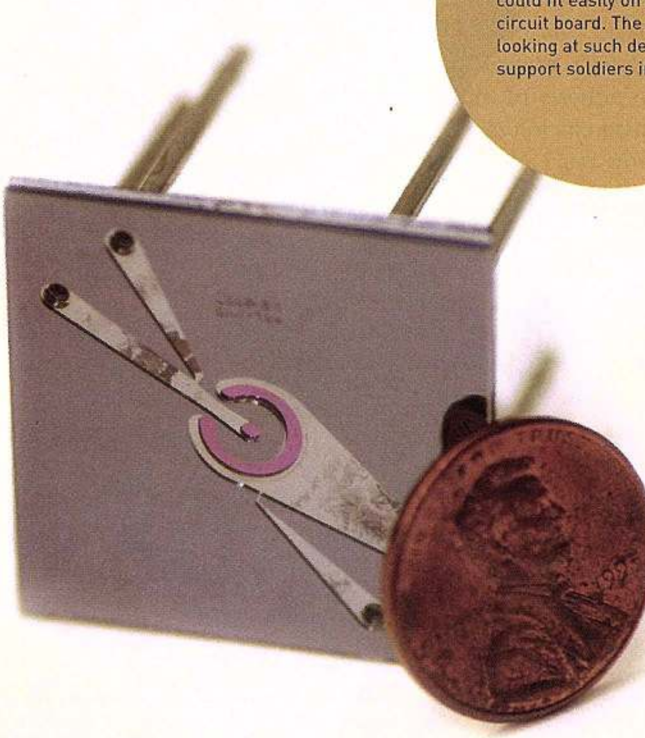
"You can integrate the ball bearing mechanism in a more compact form, because you don't require external components to operate it," said Mike Waits, an engineer now at the Army Research Laboratory.

Ghodssi is also interested in using ball bearings to support rotating MEMS involved in precision applications. The bearings can provide low-friction support to devices such as sensors that need to rotate just a few degrees at a time. His team is currently pursuing a grant from the U.S. Defense Advanced Research Projects Agency to create microscale platforms to support a sensor array for high-risk environments.

"The devices we're currently working on toward that proposal would be wirelessly powered and then demonstrate precision movement," Ghodssi said.

It's the kind of application that could help turn MEMS into the sort of ubiquitous technology that experts had always predicted it would be. For those hoping for flying skateboards, however, their wait will continue. ■

▼ A MEMS pump created using microball bearings could fit easily on a standard circuit board. The Army is looking at such devices to support soldiers in the field.



REZA GHODSSI, UNIV. MARYLAND