Small Things Considered

Scientists craft machines that seem impossibly tiny

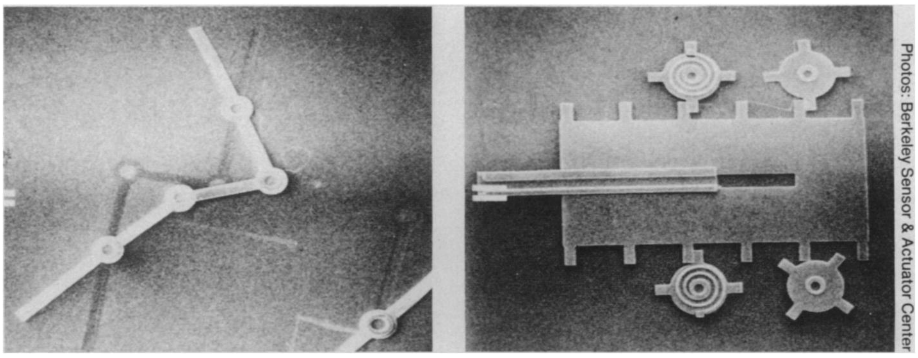
By IVAN AMATO

A cadre of scientists and engineers is preparing for the next Machine Age by thinking small — very small. For several years, these "micromechanics" have been exploring a diminutive *terra incognita* measured in thousandths and millionths of meters—a scale at which scientists are gargantuan, cells are people-sized and mechanical principles such as friction assume new meaning.

Micromechanics are learning how to fashion materials into ultrasmall nozzles, valves, channels, springs, levers, cantilevers and motors, some as thin as a human hair. Minuscule devices crafted from such wee components should aid in a number of diverse ventures, among them microsurgery, sorting cells and making sub-featherweight instruments for mini-spacecraft. Most applications, say the researchers, have yet to be imagined. "We're in the process of discovering what is possible," explains Stephen Senturia, a microdevice maker at the Massachusetts Institute of Technology.

Although much of their work remains in the training-wheel stage, micromechanics are building up know-how by making admittedly crude and poorly understood microdevices — dust-speck-sized motors and barely visible tweezers, for example—and then studying how they work and why they fail. Some scientists say these fledgling efforts could evolve into a wide-ranging technology as socially transforming as microelectronics has been in recent decades. Already, some microfabricated devices have been married to well-established microelectronics technology to yield chip-sized pressure sensors that track engine pressure in millions of automobiles.

Last February, dozens of researchers from the United States, Europe and Japan converged in Salt Lake City, Utah, for the second Workshop on Micro-Electro-Mechanical Systems. At the conference, held by the Institute for Electrical and Electronic Engineers, they talked about micromotors, new ways of fabricating silicon, tungsten and other materials into tiny shapes, and how fabrication processes affect the mechanical properties of these materials on sub-lilliputian scales.


Photos: Berkeley Sensor & Actuator Center

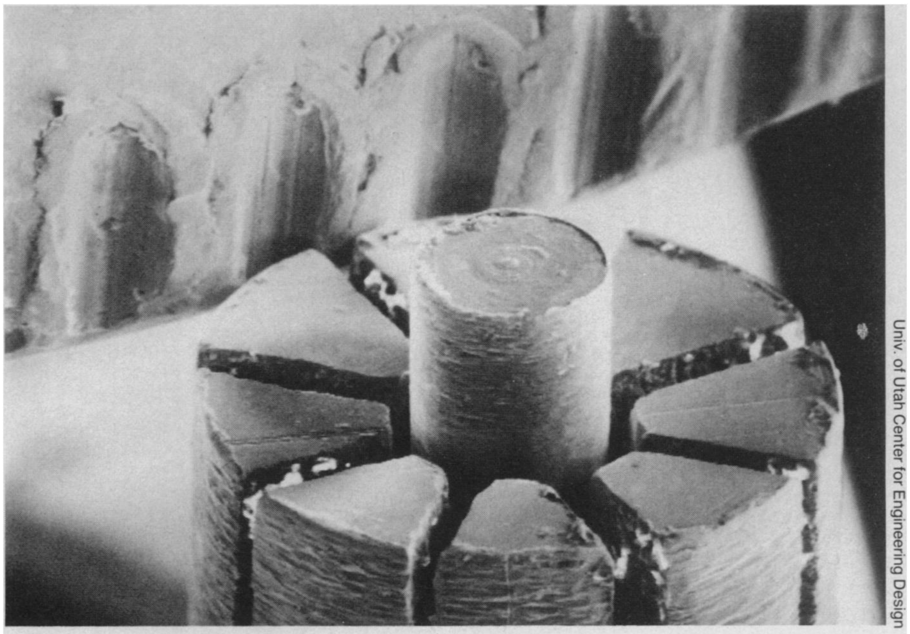
The microcrank on the left has a fixed point at each end and two rotating joints. The microscopic contraption on the right has functional springs visible on two of the circular objects and a movable bar that slides in a track.

About a year ago — and just seven months after the first such workshop — the National Science Foundation issued a report on what it called "the emerging field of microdynamics." This report, coupled with the actual devices described at the workshops, has helped establish microdevices as a *bona fide* research pursuit.

The goal of such research, according to the report, "is to make fully assembled devices and systems that do what large-scale electromechanical systems cannot do as well, as cheaply or at all." For example, electromechanical motors of the type used in household appliances are ill-suited for powering arrays of micropositioners, which researchers hope will one day control minuscule mirrors in optical communications systems. Precisely controlled mirrors might help guide information flow by shunting light signals from an incoming optical fiber originating at the White House to several outgoing fibers reaching to the Kremlin and Beijing, for example.

"Like microelectronics, microdynamics could lead to products as advanced beyond present ones as a compact disk is beyond a long-playing record, and as fundamentally different," states the report. A case in point is the work of Iwao Fujimasa at the University of Tokyo's Research Center for Advanced Science and Technology. If he succeeds in his attempts to build a minuscule robot surgeon that navigates within a patient's vascular labyrinth, carrying drugs or microtools to treat diseased tissues, he could render the 1966 sci-fi film "Fantastic Voyage" more forecast than fantasy.

Researchers at the workshop reported similarly staggering ideas, some in the early stages of realization. But electrical engineer and teensy-tweezer maker Noel C. MacDonald of Cornell University says the collective message of the meeting is more down-to-earth. To usher microdynamics through its present infancy to a more mature status, he asserts, micromechanics need a better understanding of the properties and behavior of materials at these fine dimensions. Micromotor builder Richard S. Muller concurs, but he points out that the lack of a full understanding need not curtail creative explorations. If Edison had not tinkered with numerous materials for filaments before fully understanding what he was doing, the world might have waited far longer for light bulbs, suggests Muller, who works at the University of California's Sensor and Actuator Center in Berkeley.



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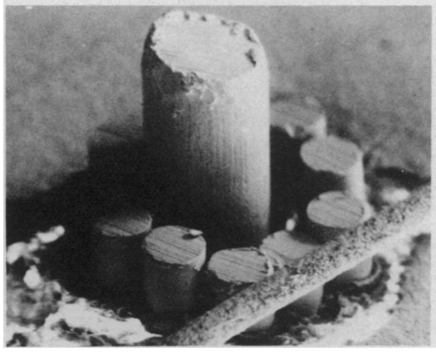


The "wobble motor" above appears near the front edge of a dime for size comparison. Approximately 20 hair-widths in diameter, it has already completed billions of revolutions in tests at the University of Utah. Its designers say the motor might power tiny surgical tools, scientific instruments and robot limbs. On the left is a smaller design with a metal-coated human hair in the foreground.

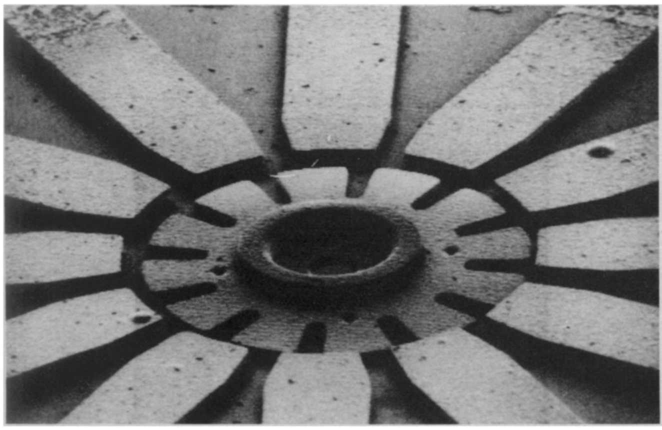
Microdevices fall largely into two categories – sensors and actuators. Tiny sensors sculpted in silicon chips, for instance, respond to pressure, humidity, motion and other physical conditions with an electronic signal that on-chip circuitry can then amplify, process and use. In one device, called an accelerometer, researchers position a superthin, supersmall silicon strip over a micropit chemically etched in a chip. The strip responds to motion by bending, initiating transient electrical currents. Additional chip circuitry can use these currents to help steer a missile or "decide" if a car's collision air bag system should be activated.

Sensors have dominated the field of microdynamics so far, but actuators are gaining ground, says Kurt E. Petersen, president of NovaSensor, Inc., a microsensor company in Fremont, Calif. Unlike sensors, which gather and relay information, actuators move and do things. Micromotors spin or slide; teensy tweezers clasp.

As the field matures, researchers say, sensors and actuators will share the same real estate on a chip to make hybrid microelectromechanical devices. At MIT's Artificial Intelligence Laboratory, Anita M. Flynn and her colleagues are taking steps toward this long-term goal by learning how to integrate motors, sensors, computation and power supplies onto a single inch-square piece of silicon. The advantages include "mass producibility, lower costs and the avoidance of the usual connector problems encountered in combining discrete subsystems," she says. At the Salt Lake City workshop, Flynn's group introduced "Squirt," an autonomous, cubic-inch working robot "that acts as a 'bug,' hiding in dark corners and venturing out in the direction of last heard noises, only moving after noises are long gone." The MIT scientists say they already know how to shrink the sensing and computing components even more. But they call on the micromachining community to come up with micromotors for propelling the flea-sized robots they envision.

That's where people like Muller of the University of California and Stephen C. Jacobsen of the University of Utah's Center for Engineering Design in Salt Lake City enter the picture. To date, most micromotor builders have used silicon micromachining techniques to fashion flat, gear-like motors, some small enough to fit inside a hair shaft. Muller reported the first freely rotating micromotor of this sort last August. At the moment, such motors can't do much. They spin for a minute or so before the rotor sticks to the hub or the nearby silicon substrate. Moreover, they are so thin and flat that hooking microtools or propulsion mechanisms to them will take some new ideas, Jacobsen says. Such motors could be ideal, though, for less strenuous jobs such as splitting light into segments to send optical messages, suggests MacDonald.

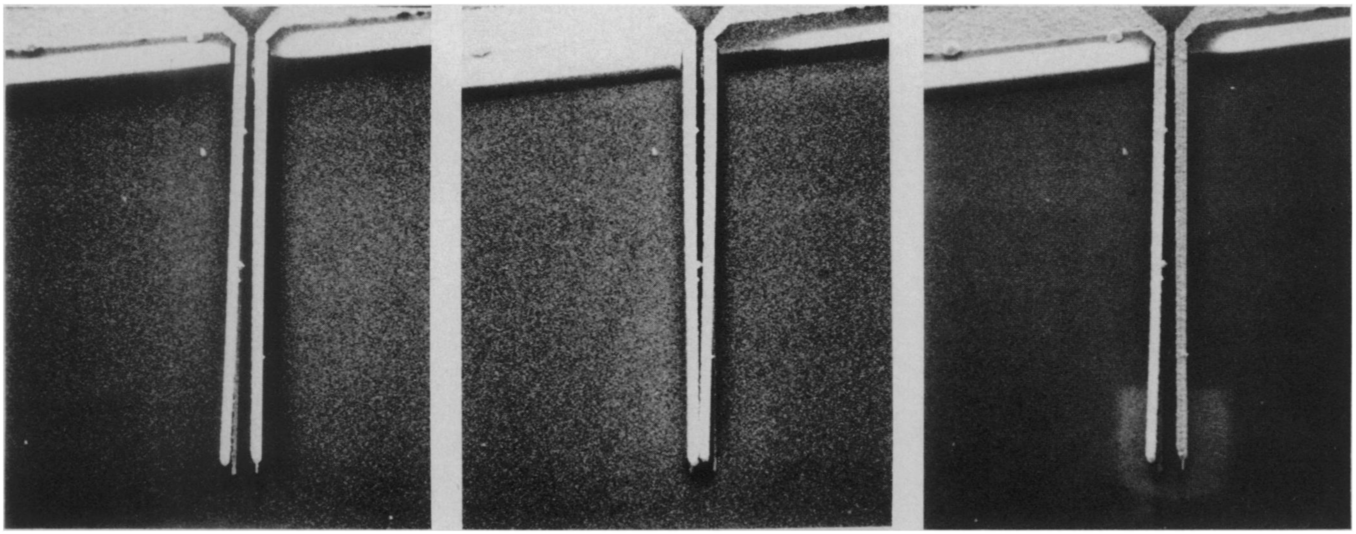
And despite their limitations, Muller says these short-lived devices enable his research team to study how friction and electrostatic forces affect motors thousands of times smaller than those powering household appliances. "Initial tests on the [micro]motors show that friction plays a dominant role in their dynamic behavior," he reports. Although engineers know what concepts such as material strength, friction and air resistance mean for larger-scale machines, these concepts pose new problems at shrunken scales.



Berkeley Sensor & Actuator Center

The teeth on this micromotor are about the size of red blood cells, and the entire rotor spans about two hair-widths, or 100 microns. Electrostatic forces between the rotor and surrounding stator poles send the rotor spinning.

While most microdevice research has focused on how to adapt silicon – the material mainstay of microelectronics – several micromotor makers are trying nonsilicon materials. Jacobsen has used metals and


Photos: MacDonald/Cornell

Scanning electron micrographs of microtweezers. At left, the tweezers are open in the absence of a voltage difference across the arms. Applying enough voltage closes the tweezers (center), which reopen (right) when the voltage is reduced. For three-dimensional control, the arms can also be moved in a plane perpendicular to the page.

plastics to fashion what he calls a "wobble motor," in which a stationary electric field induces a torque that makes the rotor move.

"The reason there is interest in these two alternative strategies is to address two different ends," remarks MIT's Senturia. The silicon-based motors are smaller and spin faster but pack a lower torque. They're best suited for jobs that require little or no work beyond spinning – such as chopping a beam of light into millions of bits of information. Wobble motors spin more slowly but have higher torque and are better suited for governing movements of tiny robotic components or manipulators.

Jacobsen and his colleagues have designed and built a variety of wobble motors. A few of them would fit easily inside this "o." One has been running steadily since Feb. 3, he says. Had it been rolling along a road, its 10 billion or so revolutions would have brought it nearly halfway around the world by now.

Like the more familiar motors in fans and coffee grinders, wobble motors consist of parts that move – rotors – and parts that stay put – stators. In some of Jacobsen's designs, a cylindrical rotor sits within the stator's cylindrical hollow, which is slightly larger in diameter and formed by several electrically isolated metal pie wedges. By sequentially applying voltages to the stator segments, the engineers can induce the rotor to roll inside the stator so that it appears to wobble in place. This arrangement overcomes the friction and sticking problems that continue to plague silicon versions.

To see why the rotor wobbles, put a pen in your palm and lightly wrap your fingers around it so that you make a loose fist. With the pen pointed up, use your other hand to push it around inside your fist. You'll notice that the pen wobbles around the center of your fist several times faster than it spins around its own center. This wobble-to-spin reduction serves as a built-in transmission that could make wobble motors more practical for robotic applications than the silicon micromotors, which would spin at dizzying rates, Jacobsen says.

In one design, his team makes a stator out of 32 circularly arranged copper rods, each about two hair-widths in diameter. The circle of rods, which are insulated and anchored in epoxy, spans 20 hair-widths. The metal rotor, about 18 hair-widths, fits inside the circle. Jacobsen and his co-workers have observed the rotor wobbling around the copper sleeve at a rate of about 250 wobbles per minute.

In an even smaller design, the Utah engineers assemble a plastic rotor with a stator made from 10 stainless steel wires. Although this design has yet to yield a working motor, its simplicity makes for a potentially economic way of manufacturing "wobble motors by the meter," Jacobsen says. Hundreds or thousands of wobble motors could be mass-produced simply by slicing the assembly like a salami, he suggests.

Most promising, Jacobsen says, are wobble motors made by the "electrodischarge machining" method. He and his colleagues assemble the stator from eight steel pie wedges sliced from a thin sheet with a tiny electrified wire used like a band saw. Thin films of epoxy hold the wedges together and keep them electrically isolated from each other. Again, applying voltage sequentially to the wedges makes the rotor roll around the stator cavity. The researchers have clocked such motors at more than 100,000 wobbles per minute.

Still other nonsilicon-based materials are auditioning for roles in microdevices, says Cornell's MacDonald. He uses a technique called chemical vapor deposition to lay thin layers of tungsten into silicon molds. Residual strain causes most ultrathin materials to fold up like potato chips when freed from their supports, MacDonald notes. "Tungsten," he says, "stays very straight."

He and his colleagues have created the smallest lab-made tweezers in the world – a couple of hair-widths long and no wider than a cell. By applying voltages to different parts of the tweezers, he can move the arms together or apart and move the entire assembly in three dimensions. MacDonald envisions such dwarf tweezers someday helping biologists to manipulate individual cells for microscopy or other studies. But for now, he says, the tweezers serve as a way to study the micromechanical properties of tungsten. He wants to know how the strength, hardness and other properties of the metal vary with the conditions of processing. As he builds up a database on such properties, he hopes to develop sophisticated, computer-aided design systems to help engineers perfect micromechanical devices without actually having to make and test hundreds of individual designs.

MacDonald's immediate goal is to show that the tungsten/chemical vapor deposition technology can build just about anything that silicon microfabrication techniques can. "If we could get a toolbox of four or five different materials that have good friction, hardness and fatigue properties," he remarks, "we could start designing things the way a mechanical engineer does" – by determining a device's mechanical requirements, then picking and choosing from the available materials. But one big difference would remain: MacDonald and his fellow microengineers would be building in a realm that seems lilliputian even to the Lilliputians. ☐