

# From Microdevice to Smart Dust

## Learning to build, program, and control multitudes of interacting micromachines

By IVARS PETERSON

**A** swarm of surveillance mites slowly descends from the sky. Wafted by air currents, the data-collecting specks sense the presence of trace gases. Chattering incessantly among themselves in electromagnetic chirps, they assemble and process the information into a detailed picture of the state of the atmosphere.

No one has built tiny devices with such monitoring capabilities yet. However, the technology necessary for constructing a "smart dust particle" may be within reach in 5 years, says Andrew A. Berlin of the Xerox Palo Alto (Calif.) Research Center.

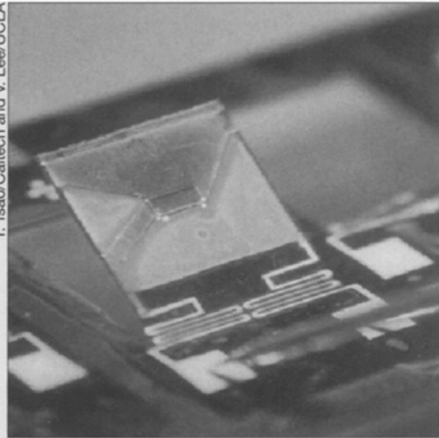
Researchers envision a pinlike unit about 1 centimeter long and 1 millimeter wide that incorporates various detectors, a power source, a microprocessor, a microphone, a transmitter and receiver, and a steerable antenna that resembles a rigid parachute. Released in the air at 2,000 feet, it would fall at about 3 cm per second, staying aloft for more than 5 hours.

"Nearly all the components exist somewhere, meaning that someone in a research lab has built the right kind of radio transmitter on a chip and someone else at another lab has built a micromachine microphone," Berlin says. "But nobody's actually trying to put it all together yet because each of the underlying technologies has a few years of development to go."

Nonetheless, combining rapidly evolving technologies—microelectronic devices, programmable, or smart, materials, micromachines, distributed computing systems, and active control mechanisms—to create smart dust and other microelectromechanical systems (MEMS) offers new capabilities that can be exploited for a variety of purposes. A cloud of smart dust, for instance, might be useful for military reconnaissance, monitoring air quality, checking ground traffic patterns, or even displaying information in the sky.

Arrays of microelectromechanical devices could also be used to handle

sheets of paper without letting them touch a surface, orient microscopic device parts for assembly, or even maneuver aircraft by making constant tiny adjustments to wing surfaces. Other potential applications include motion sensing and vehicle navigation, mass data storage, and processing optical signals on a chip for display devices.



*When arrayed on a wing, a set of microflaps like the one shown, which measures 1 millimeter square, can be used to maneuver a jet aircraft.*

"By merging sensing and actuation with computation and communication, MEMS devices can be distributed throughout the environment, coated on surfaces, or embedded within everyday objects to create distributed systems for sensing, reasoning about, and responding to events in the physical world on a scale never before possible," Berlin and Kaigham J. Gabriel of the Defense Advanced Research Projects Agency in Arlington, Va., explain in the January–March IEEE COMPUTATIONAL SCIENCE & ENGINEERING.

**A** model airplane veers sharply to the right. One-seventh the size of a jet aircraft, it lacks the conventional flaps and ailerons that an airplane normally uses to change direction, yet it

manages to perform a wide variety of maneuvers in a wind tunnel.

The secret of the plane's maneuverability is an active surface, an array of tiny flaps—like hinged lids—distributed across a small portion of each wing. Raising or lowering these miniature lids about 1 mm to interact with air flowing over the wings steers the plane from one orientation to another.

"We can roll the aircraft about 180° in 0.8 second, and we can make very sharp turns," says Chih-Ming Ho, a mechanical and aerospace engineer at the University of California, Los Angeles.

Having demonstrated the concept, Ho and his coworkers are now building a more sophisticated, robust system for controlling aircraft. Instead of little lids as actuators, they plan to use liquid-containing balloons about 1 mm across, spread over a wing surface. Heating vaporizes the liquid, inflating the plastic bubble and enabling it to interact with air. Cooling condenses the vapor, making the bubble actuator contract and get out of the way.

In addition, the researchers are trying to incorporate sensors to measure air flow and electronic circuitry to process and convey that information to the appropriate actuators.

Ho and other engineers have also been looking into using vast banks of tiny sensors and actuators to respond to air turbulence by collectively sensing vortices and interacting with them. "For drag reduction, we would need to spread these devices all across the wing," Ho says. "That's much more difficult."

For one thing, there's a limit to how much an actuator can be miniaturized and still be effective, especially if it has to stand up to air whipping across a wing at several times the speed of sound.

**B**erlin and his colleagues are focusing not on smart wings but on smart matter—building various capabilities directly into materials. Their

projects involve developing technology for embedding miniaturized sensors, computers, and actuators within materials or coating them on structures. Eventually, such smart components would be able to adjust their shape, color, stiffness, acoustic or optical reflectivity, and even strength on demand.

The trick to achieving such interaction and control lies in choosing suitable devices of the right size or scale. "It really comes down to the art of cleverly combining the appropriate technologies," Berlin says.

For example, it makes sense to use optical detectors or thermometers, devices that, when miniaturized, can still respond extremely quickly to a signal. On the other hand, a mechanical device on a microscopic scale would be too flimsy to push aside air or move anything other than itself.

"If you're thinking about pushing objects around, you have to go to a larger scale," Berlin says. That could involve coating surfaces the size of printed circuit boards with components of millimeter rather than micrometer size, while still taking advantage of the mass-production techniques used to fabricate integrated circuit chips with tiny features.

One potential application is a paper mover that uses sensors and tiny air jets to shift and position sheets of paper. "There would be all sorts of new things you could do in printing if you could move paper without touching it," Berlin says.

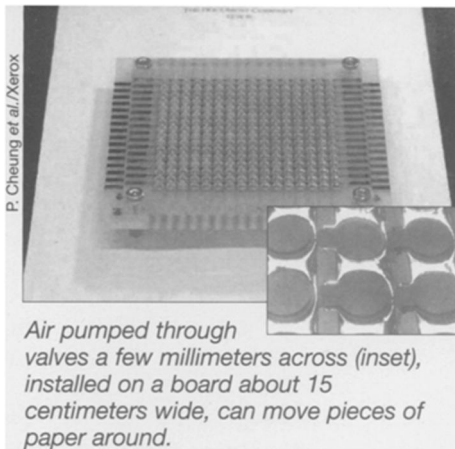
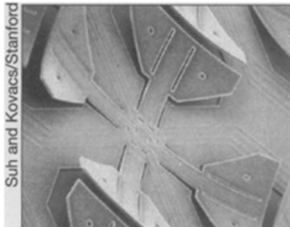
The researchers have built a prototype array that incorporates a number of sensors and valves to operate about 50 air jets on which a sheet of paper rides. Programming the array so that it responds appropriately to a sheet's instantaneous position and moves it to the next orientation presents a considerable challenge, Berlin remarks.

Another smart matter project is incorporating stress sensors and actuators that would stiffen or strengthen a beam to prevent buckling or collapse. "There's a whole range of interesting applications," Berlin contends.

**S**ome researchers are studying ways to position and orient not paper but microscopic parts—a task that human workers or even conventional robots on an assembly line find increasingly difficult as electronic devices keep shrinking.

One possible mechanism is a chip equipped with microarms modeled on the hairlike cil-

*Each of the four fishtail actuators comprising a motion pixel is 430 micrometers long and bends up to 120  $\mu$ m above the surface.*



*Air pumped through valves a few millimeters across (inset), installed on a board about 15 centimeters wide, can move pieces of paper around.*

ia that bacteria use to move themselves around. Hiroyuki Fujita and his co-workers at the University of Tokyo pioneered the development of ciliary motion systems, and other groups are following up with more sophisticated designs.

At Stanford University, Gregory T.A. Kovacs and John W. Suh have fabricated ciliary arrays in which each microscopic actuator looks like the tail of a fish, curling upward from the surface. These actuators, less than 0.5 mm long, have been designed to lie flat in response to an electrostatic force or heat.

Four actuators, arranged in a cross with tails pointing away from the center, work together as a unit, or motion pixel, about 1 mm wide. By activating different actuators in sequence, it's possible to propel a part across an array of motion pixels. Properly programmed, such arrays could act as miniature conveyor belts or as micromanipulators with an extensive repertoire of movements.

Experiments with a prototype array of 1,024 cilia showed that it is possible to move silicon chips at speeds up to 200 micrometers per second with an accuracy of a few micrometers. In the latest work, Suh is fabricating a much more complex array, in which each pixel can be individually programmed.

"That's never been done before," Kovacs says. "When you have individually controlled pixels, you can move several components on different trajectories and put them together in various kinds of assembly tasks."

"Now that we can move things around, there's a lot of interest in what you would use these arrays for," says computer scientist Bruce R. Donald of Cornell University.

One potential application of a ciliary device is as a microscope stage—a surface on which a sample can be moved with high accuracy for magnified view-

ing. In an optical or electron microscope, "we can replace a big, clunky mechanical unit with something more compact and less expensive to produce," Kovacs says.

Manipulating silicon chips in an industrial setting, how-

ever, is still fairly far off, Donald remarks. Indeed, much preliminary work remains to be done on designing efficient strategies for precisely orienting variously shaped parts.

Micromanipulation may eventually play a role in biological research—perhaps for moving and sorting cells, Donald says. "That would be pretty exciting."

The recent development of functioning motion arrays also makes it possible to test various strategies for programming the devices. Donald and Karl F. Böhringer of the University of California, Berkeley have developed what they call the theory of programmable force fields to model the actions of a ciliary array. In essence, they describe the forces generated by the actuators as vectors, which can be represented as arrows giving the strength and direction of the field at various points. A radial field, for example, can be used to center a part.

Peter Will and his colleagues at the Information Sciences Institute of the University of Southern California in Los Angeles have adopted a similar approach. They have created a software tool kit that allows researchers to program ciliary arrays to perform a variety of functions.

"We've done a whole lot of work exploring the use of different fields for different purposes, including centering, rotation, and other actions," Will says.

**T**he development of microelectromechanical systems is still in its infancy. Researchers face a host of obstacles in their efforts to design, build, program, and control such devices. In particular, coordinating large arrays of devices to perform reliably while continuously adapting to the physical environment in real time poses serious computational difficulties.

"How do you program a cloud of dust?" Berlin asks. Should all the smart dust particles run the same program, or should they specialize? How do units synchronize their activities when they are in motion relative to each other and spread over large distances? How can communication be established and maintained in such a system? How can it build a global view of a situation using many small pieces of information that are gathered in different places at different times?

"There are a lot of hard problems here," Berlin says.

Nonetheless, the vision of distributing sophisticated electromechanical systems of all sorts throughout the environment is a compelling one for many researchers. "In essence, the challenge that MEMS places on information technology is not merely to coordinate lots of tiny computers," Berlin and Gabriel note, "but rather to add a bit of computational behavior to materials and the environment." □