Getting a Feel for Atoms

By IVAN AMATO

'Magic wrist' takes scientists into a new sensory realm

Whether you're learning to walk, drive a car or play tennis, you don't really know what you're doing until your entire person – your brain, nerves, bones, muscles and senses – somehow grasps the process. That's when you say: "I've got a feel for it."

In contrast to most everyday activities, scientific pursuits often focus on objects whose minuscule size would seem to exempt them from this whole-body sort of knowledge. How, for instance, could anyone possibly get to know atoms and molecules in this way?

A decade ago, that prospect might have sounded absurd. Yet scientists have already gained the ability to "see" atoms. Today, the scanning tunneling microscope (STM) routinely enables thousands of researchers to image material surfaces atom by atom (see box), and it has spawned a large and growing family of devices that empower investigators to conduct ever more sophisticated and revealing visual inspections of atomic landscapes.

But suppose there were some way to expand those inspections beyond the visual realm. Just as auto mechanics rely on a combination of their eyes, ears, noses and fingers to understand a vehicle's health or dysfunction, wouldn't scientists understand more about atoms if they could sense these diminutive objects in more ways, perhaps by even "feeling" the atoms themselves?

Three robotics engineers are now putting that conjecture to the test. Ralph L. Hollis, Septimiu E. Salcudean and David W. Abraham of IBM's Thomas J. Watson Research Center in Yorktown Heights, N.Y., say they can feel small clumps of atoms and are working toward sensing them one by one.

"If a machinist is interested in putting two precision parts together, he may eventually look at them under a microscope. But the first thing he will do is feel them, feel the parts and see if they're okay," Hollis says. "I thought it would be very interesting if one could feel individual atoms."

For the past four years, Hollis and his co-workers have been developing a versatile device they call the "magic wrist." Now, he says, they have begun using it to manually steer an STM's atom-fine probe over a sample with unprecedented precision, while simultaneously feeling the sample's atomic hills and valleys in the form of small vertical movements of the magic wrist, which correspond almost perfectly to the probe's atom-scale movements over the atomic landscape.

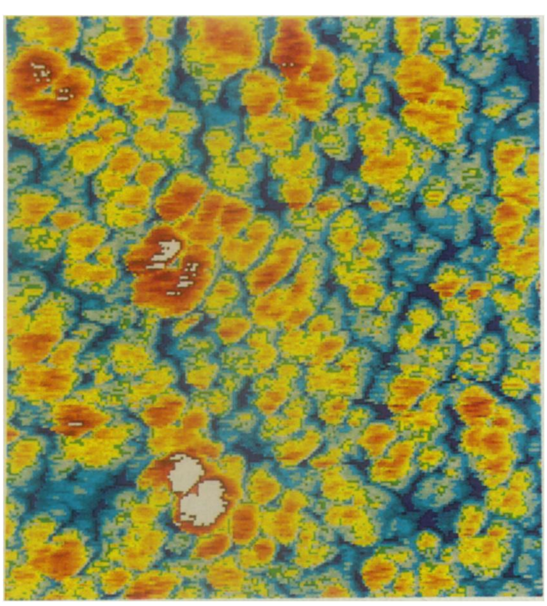
At February's Micro Electro Mechanical Systems meeting in Napa, Calif., Hollis reported using a prototype magic wrist repeatedly to find and feel the same bumps on a surface of gold atoms. He estimates that he felt clumps containing about 10 gold atoms. "And there's no reason electronically why they shouldn't be able to get to the point of feeling single atoms," says meeting organizer Kurt Petersen, who co-founded NovaSensor, Inc., a microdevice- and sensor-making firm in Fremont, Calif.

In applying the new technique to ultraflat, cleaved graphite surfaces, Hollis found that normal mechanical vibrations and electrical "noise" in the laboratory frustrated his attempts to feel the graphite's individual carbon atoms, which show up clearly in STM images. But be patient, he says.

"We are continuing to experiment with graphite and see no fundamental barrier to prevent us from achieving satisfactory operation at the level of individual atoms," the IBM researchers write in a paper that will appear in the proceedings of the meeting. To reduce mechanical vibrations, Hollis expects to move his equipment from its first-floor location to the sturdier basement of the research building.

While giving scientists a feel for the tiniest of worlds, the magic wrist could also enable them to manipulate objects formerly out of reach. The angstrom- and nanometer-scale features of atoms and molecules place them beyond the grasp of the human hand; trying to move an atom with your finger would be even harder than prodding an ant with the Washington Monument. But with the ability to steer an STM tip precisely via the magic wrist, Hollis envisions manually controlling chemical reactions by deliberately orienting specific atoms and molecules.

At a nanotechnology conference last fall, physicist John Foster of the IBM Almaden Research Center in San Jose, Calif., reported some preliminary molecule-manipulating feats achieved with an STM. In one case, he and his collaborators used the instrument to slice a long organic molecule in two. In another, they

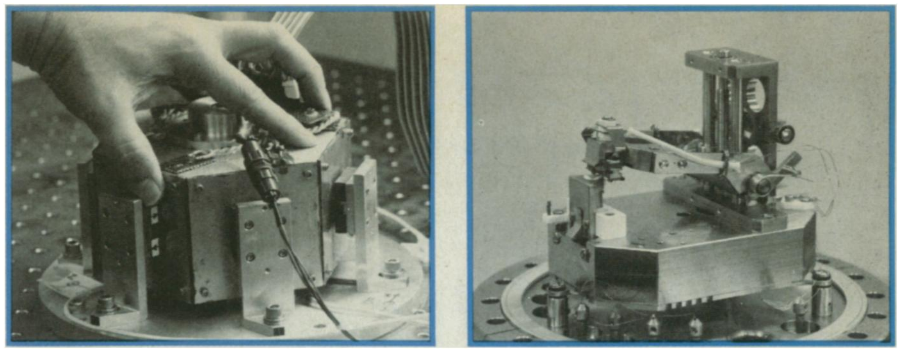


Hollis/IBM

Clumps of gold atoms appear as yellow, orange, red and white areas in this STM image. White spots represent the tallest peaks of the landscape and blue areas depict the valleys between the hills of gold.

"corralled" molecules by encircling them with a computer-controlled STM tip. Such manipulations could become even more precise with the help of a magic wrist, Hollis says.

And the possibilities aren't limited to steering STMs. Hollis notes, for instance, that an eye surgeon in Memphis, Tenn., is considering using a magic wrist to manipulate minuscule scissors for delicately removing retinal scar tissue from diabetic patients and vision-obscuring tissue from the eyes of some infants.



Hollis et al.

By carefully moving the hexagonal magic wrist (left) within its frictionless magnetic cushion, a researcher can precisely steer the STM tip over a sample's surface (right). A computer immediately translates the tip's subtle vertical movements into humanly perceptible vertical movements of the magic wrist.

The magic wrist started out as an experiment in robotics. From the beginning, the IBM researchers saw their device as a way to refine a process called teleoperation, or the ability to control specific actions from a distance – the same principle underlying the use of tongs to retrieve an ear of corn from boiling water. To accomplish tasks in the inhospitable conditions of radioactive environments, the deep sea and outer space, human workers often must remain far away, relying on robots to do the manual labor through teleoperation.

But tasks that are simple for human hands can be daunting for a robot. When a person grabs an egg from a carton, for instance, tactile information from the hands feeds back to motor-control centers in the brain, which orchestrate the finger muscles to hold the egg without breaking it. Most industrial robots lack such precise feedback and control.

"The motivation of our work was to provide robots with a soft touch," says Hollis.

The magic wrist consists of a hexagonal box called a flotor, which hovers within a stationary frame (the stator) on a magnetic "cushion" formed between the stator's six permanent magnets and the flotor's electromagnetic coils. A set of light-emitting diodes and light sensors keeps track of the flotor's position and feeds this information to a powerful computer designed specifically for the magic wrist.

In robots, the stator attaches to an arm and the magnetically imprisoned flotor carries a gripper or some other tool. Lacking a direct mechanical connection to the arm, the flotor endows the robotic assembly with a delicate, cushiony touch, Hollis explains. A robotic arm positions the tool-equipped wrist near an object to be worked. Then the computer-guided magic wrist fine-tunes the placement and moves the tool. By distributing the magnetic forces according to mathematical algorithms formulated for different tasks, Hollis says he can control the wrist's position the way a pilot controls an airplane, specifying the roll, pitch, yaw and spatial location with a precision of one-millionth of a meter along any line and one-thousandth of a degree in rotation.

The researchers expect the wrist to expand the versatility of many standard industrial robots. "We have, in a sense, a universal mechanism," Hollis says. "We can change the mechanical properties [of the magic wrist] at will." To transform the wrist action from gripping to plunging, for instance, an operator would simply press a key on the computer keyboard.

By connecting the magic wrist to an STM, Hollis and his co-workers have converted their device into what they call a "tele-nanorobotic manipulation system." Using an algorithm that transforms human-controlled horizontal motions of the magic wrist into the horizontal positions of the STM's platinum tip, millimeter movements of the magic wrist downscale into nanometer-scale movements of the tip over an atomic landscape. A nanometer is one-billionth of a meter, and a typical atom spans several tenths of a nanometer.

But without some immediate feedback from the physical features of the landscape, a scientist operating the magic wrist would have a hard time guiding the STM tip to specific locations on a sample. To remedy this, the researchers formulated another algorithm, which magnifies the tiny vertical motions of the STM tip as it scans over the sample surface into a humanly perceivable vertical motion of the magic wrist.

"With this system, it is possible to manually probe surfaces at atomic scale, while feeling the atomic-scale topography back in the operator's hand," the researchers write in their proceedings paper. "It [the magic wrist] feels like it's floating on a very slippery block of ice," Hollis told Science News.

To help scientists correlate the feel of atomic landscapes with the visual appearance of STM images, the IBM team plans to program an auxiliary computer to display images of sample surfaces that also show the path of the tip as it was steered by the teleoperator. Other possible extensions of the system include controlling the tip's vertical position by moving the wrist vertically, and using an atomic force microscope (an STM cousin) to "feel" atomic forces such as van der Waals forces. And by making the system responsive to sideways (as opposed to vertical) forces on the tip, researchers might get a feel for the tip as it automatically "slides off" a hillside, Hollis suggests. This feature could give an operator the sensation of gravity within the atomscape. In the present system, wrist operators feel no resistance or falling sensation as the STM tip ascends and descends over sample surfaces.

The IBM researchers are not alone in their pursuit to "manhandle" minute objects formerly off-limits

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Visualizing atomic terrain

When an STM performs its usual image-producing role, its tip sweeps back and forth over the atomic-scale hills and valleys of a sample's surface. A computer monitors the so-called tunneling current – a tiny flow of electrons that jumps the minuscule gap between the tip and the sample according to quantum mechanical rules. The tunneling current changes in proportion to the gap distance. As the tip scans, a computer controls micropositioners that slightly raise or lower the tip over the sample to maintain a constant level of tunneling current. A computer plots the tip's varying vertical positions, yielding a three-dimensional image of the surface. *– I. Amato*

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even to remote-controlled probing. Ian W. Hunter of McGill University in Montreal, working with colleagues from MIT and the University of Aukland in New Zealand, reports using a tele-microrobot system to grip and manipulate individual muscle cells while viewing the microscopic operation with a three-dimensional vision system. As with Hollis' system, an operator may literally get the feel of an object, Hunter and his collaborators suggested at last year's Institute of Electrical and Electronics Engineers conference on robotics and automation, held in Scottsdale, Ariz.

And at the February meeting in Napa, mechanical engineers Yotaro Hatamura and Hiroshi Morishita of the University of Tokyo described a prototype "nanomanipulator" for ultraprecise manufacturing tasks of the future. Although they say the ideal nanomanufacturing environment would enable a human teleoperator to experience even the sounds and smells of the ultra-Lilliputian operations, the Japanese researchers have set their sights for now on a "nanorobot system," which would enable workers to see and feel what the nanorobot is doing on submicron scales.

So far they have built and used a prototype robot to make millionth-of-a-meter scratches in aluminum with a fine tungsten needle. A stereoscopic scanning electron microscope helps the operator watch the actual process. A strain sensor monitors the tiny forces between the aluminum and the needle and provides feedback so the operator can better control the depth of the scratch. Hatamura and Morishita envision using improved versions of the technology for such applications as microsurgery, storing data as etched surface features, and modifying and testing tiny regions of microelectronic circuits, thin films and other materials.

Though nanomanipulation promises a wealth of practical uses, touch has its limits as a purely exploratory sense – as anyone who has groped and stumbled through a dark, unfamiliar room will agree. Hollis and his co-workers concede that the more conventional way of surveying microscopic terrains – converting them into a visual display – may be more reliable and revealing than tactile sensing alone. Nevertheless, they conclude in their proceedings paper, "we may learn something by trying to 'connect our own neurons' with atomic-scale phenomena using real-time teleoperation."

The direct experience of touch, Hollis adds, could give scientists a kinesthetic sense of atomic surfaces – and an exhilarating new realm of control – the way children get a whole-body feel for riding a bike. □