In Search of the Human Touch

To build robot hands that can explore and deftly manipulate objects, engineers are taking lessons from a natural marvel of biomechanical control, the human hand

SALISBURY, *ET AL.*

Strong but sensitive. Robots have feelings too.

Hands have a knowledge all their own. By feel alone, they know how to hold a piece of paper without crumpling it, get a good grip on a slippery jar, or grasp and manipulate a pen. For robotics engineers trying to build mechanical hands that, like human ones, can probe and palpate their environment, those capacities are arousing considerable envy—and a concerted effort at imitation.

Hands that could imitate the human capacity to grab, feel, and manipulate are the subject of some far-reaching hopes, notes Mandayam Srinivasan, a mechanical engineer at the Massachusetts Institute of Technology (MIT). The Department of Energy, for one, would love a staff of robotic hands sure enough to entrust the handling of radioactive materials. The prospect of telerobotic systems—robots that are controlled by humans, like high-tech marionettes—that could enable human operators sitting comfortably on Earth to pick up and probe rocks on other planets or feel the texture of objects on the ocean floor is exciting space scientists and Navy planners. And the possibility of telerobots that could convey to a surgeon working by remote control the "feel" of extracting a gall stone or give a test pilot the sensation of handling the throttle in an unbuilt fighter aircraft widens the eyes of surgeons, Air Force R&D managers, and artificial reality aficionados.

To integrate sensors of pressure, position, vibration, and strain into devices that can fulfill any of these hopes, engineers are realizing, they may have to look to the real thing. "The human sense of touch has been the inspiration," says Robert Howe, a mechanical engineer working on robotic hands at Harvard University. And that realization is building bridges between disciplines that, just a few years ago, might have had little to say to each other. Neurophysiologists would love to disentangle the ill-understood mechanisms by which we perceive and respond to an object's texture, shape, and orientation. And robot designers are watching, eager to exploit the lessons of neurophysiology. Says Susan Lederman, a psychophysicist at Queen's University in Ontario who studies the tactics people use to probe objects with their fingers and hands: "The engineers are running into the same problems that we have."

This marriage of disciplines is already bearing some early fruit, as was evident on Election Day when a handful of robot designers, mechanical engineers, neurophysiologists, and psychophysicists gathered in New Orleans for a special session on the "haptic channel" (derived from a Greek word now referring to both tactile sensation and the hand's ability to sense its position and motion) at a meeting of the Acoustical Society of America. Animating the discussion was the emergence of a unified, though sketchy, picture of how the hand senses texture and shape. And on the technology side, engineers have already exploited insights from biology to design a robotic hand that can hold an egg without breaking it and telerobotic systems that can convey to an operator the feeling of an object slipping through his fingers.

The recent meeting made clear that engineers are also devising new research tools for their neuroscientist colleagues, including one that should be able to simulate thousands of textures (see box)—an ability central to probing the patterns of neural activity underlying tactile sensing. And that's

Feelings at Your Fingertips

Engineers eager to endow mechanical grippers with some of the human hand's ability to explore and manipulate its environment by touch owe a growing debt to neurophysiology (see main text). And now technology is paying back some of that debt by offering researchers a way to address one of their chief handicaps: an inability to present controlled, reproducible stimuli to human or animal subjects.

Sure, say the researchers, you can measure how sensory nerves in the hand respond to, say, a piece of sandpaper—but how do you disentangle the complex blend of pressures, vibrations, and forces that impinge on the hand to work out what underlies the sensation of roughness? Psychologist James Craig of Indiana University sees a potential to end such doubts. With neuroscientist Kenneth Johnson of Johns Hopkins University, he has designed what they think will be one of the world's most sophisticated tactual stimulators, capable—as Craig put it—"of simulating virtually any texture" to a finger in contact with the device.

Now being built by engineer Wolfger Schneider of the Johns Hopkins Applied Physics Laboratory, the device will consist of a 20 by 20 arrangement of 400 pins spaced as little as 0.4 mm apart, each controlled by its own microprocessor. Each pin in the device, called the "dense array," will be capable of vibrating up to 400 times a second, at a variety of amplitudes. Depending on the pattern of pin vibrations, the device could give you a tour of all the silks, cotton, and polyesters of a fabric shop, says Craig, who likens the tactual display to a visual one. "The frequency, amplitude, and separation of the stimulator tips permit the dense array to match or exceed the sensory capabilities of the skin," Johnson says.

By sometime next year, Schneider expects to deliver a pair of the universal tactile stimulators to Craig and Johnson. "The dense array will be a nice improvement" for experimenters, remarks psychophysicist Susan Lederman of Queens University in Ontario. She points out, though, that the device will only be able to stimulate a small patch of skin at once—about 64 square millimeters, or roughly the area of a fingertip. But that's a great improvement over present capabilities—and, of course, it raises expectations of much bigger and better simulations in the future. Perhaps even something approximating the "feelies" that Aldous Huxley portrayed in *Brave New World*—a cinema for the body as well as the eyes. Keep in touch.

–I.A.

great news, because at the moment, "we know pretty near zip" about the way the brain perceives realistic, complex inputs, sighs Robert LaMotte, a sensory physiologist at Yale University who is collaborating with Srinivasan in studying the perception of softness and hardness.

LaMotte may be overstating a little; his colleagues do know the scale of the challenge. "Twenty kinds of nerve fibers innervate the human hand," says Kenneth Johnson, a neurophysiologist who studies tactile sensation at the Johns Hopkins School of Medicine. To make things worse, "most of these [20] are firing simultaneously during complex haptic perception," Johnson notes. Of the 20 types, eight are motor fibers that control skeletal muscles, blood vessels, and sweat glands. But a dozen kinds of sensory fibers convey information about pain, temperature, texture, muscle length, and joint angles. By tapping into the chatter of individual neurons with microelectrodes, Johnson says, neuroscientists experimenting with animals and humans have made progress in mapping specific tactile functions, such as the recognition of texture and certain kinds of vibrations, to specific neuron types.

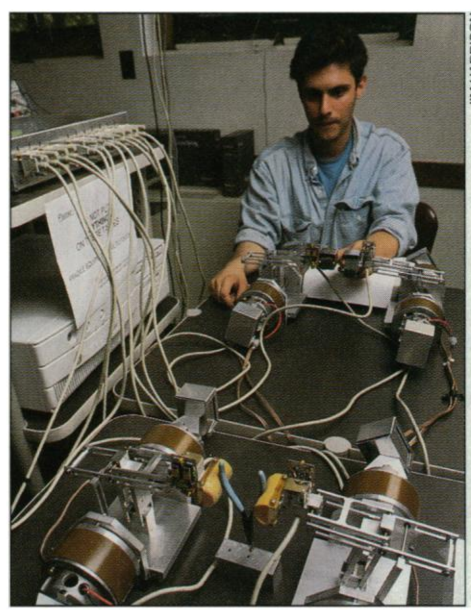
A gentle hand

That riot of cellular activity would seem to offer little guidance to a robotics engineer. But some general principles of tactile sensation are already clear. As a person uses a screwdriver, Lederman says, position- and strain-sensing neurons in the muscle and tendon fibers of the hand, fingers, and wrist keep the brain informed about the overall spatial arrangement of the hand and the forces it is applying. Many clues about an object's material properties—its stiffness and strength, for example—emerge from these kinds of senses.

That's roughly the level of tactile sensibility that mechanical engineer Kenneth Salisbury of MIT's artificial intelligence laboratory is aiming to bestow on the articulated, three-fingered robotic hand he designed more than a decade ago, which has become a well-known research tool in the robotics community. "When you grab something, you often first touch it and incrementally sneak up on it" by moving your fingers and hand around the object, Salisbury says. "I want a robot that knows it has touched something, what that thing is, and if it is about to lose a grip on it." With that kind of sensibility, the robotic hand ought to be able to catch an object tumbling in space or explore the world with gentle, probing fingers.

In reaching toward that goal, he and his co-workers have already built robotic fingertips with six-way strain gauges that can determine the locations of contact with the fingertips, the orientation of the contact plane, and the components of force and torque acting on the fingertips. The result is a hand sensitive enough to its own force to hold an egg without cracking it. But the sensor-equipped hand still can't "perceive" shape. It can't tell, for example, whether it's holding an egg or a can. That ability would require robot fingers that could systematically probe the whole surface of an object and then integrate the sensory input into a tactile picture.

And that isn't simply a matter of equipping the mechanical hand with more capable sensors. Also needed are computer control algorithms that could combine sensor input into a coherent picture, which in turn would enable the robot to plan and carry out the probing motions needed to identify an object by touch. For that Salisbury and his colleagues need detailed guidance from biology. "While humans make good use of tactile sensing in manipulation, it is not yet clear how to implement, let alone use, this capability in a robot hand," Salisbury warns.


JIM HARRISON

Being there. A teleoperated hand can tell its human controller when it's losing its grip.

But the wait may not be hopelessly long. Despite the sensory system's complexity, Johnson says, enough principles have emerged from the corpus of research to rough out a neural mechanism for perceiving the details of shape and texture. In the 1992 *Annual Review of Neuroscience*, he and coauthor Steven Hsiao, a neuroscience colleague at Johns Hopkins, distilled their own findings and many other researchers' work into a "working hypothesis" for the neural events accompanying the use of an instrument such as a screwdriver. A class of sensory neurons known as the SA-I (slowly adapting-I) system, which is arranged under the skin in a two dimensional grid like the photoreceptors in a retina, gets credit as the primary means of perceiving the screwdriver's shape. It is also good at detecting the low-frequency vibrations that signal when the screwdriver has made contact with other surfaces, such as the groove on the head of a screw.

A separate, denser grid of neurons—the RA (rapidly adapting) system—apparently relays spatial information with about one-third of the clarity of the SA system, but it can pinpoint much subtler movements between skin and surfaces, such as the vibrations that occur when a turning screwdriver slips slightly in a hand. That neural information presumably is the key to perceiving fine textures and adjusting the forces applied to tools during their use, Johnson surmises. Yet another class of sensory fibers, the Pacinian system, whose specialized encapsulation shields them from low-frequency stimuli, respond to transient high-frequency vibrations generated, for example, when the screwdriver slips in the groove.

Lessons from nature

Howe, the Harvard mechanical engineer, is already taking these lessons to heart. Last May at a robotics and automation conference in Nice, France, he reported experiments with a two-fingered telerobotic hand—linked via wire and computer to a controller manipulated with thumb and index finger by a human operator—rigged with tiny accelerometers that pick up the tiny rapid vibrations caused when something slips in its grasp. A controller immediately relays those signals to the operator's fingers, in the form of a rapid tweak that triggers his own RA system as though it had been stimulated by the slip.

"This kind of force feedback makes robotic manipulation more reliable," Howe says. "If someone is going to use a telerobotic hand to pick up radioactive waste, you would like to trigger the same physiological events in the operator that would normally kick in" if the container were slipping in his own human hand, Howe says. Howe's two-fingered hand, he admits, is a long way from leaving the laboratory. But he and his colleagues are now working on more complicated telerobotic hands that can, for example, relay an object's shape to the hand of a human operator.

Ultimately, Howe and other engineers trying to design sensitive robotic hands picture their research coming full circle to biology—by restoring tactile sensibility to people who have lost it. Deeper insight into how the human hand works and how machines can imitate it, MIT's Srinivasan says, opens "the possibility of limb prostheses whose built-in sensors could convey tactual information through the intact sensory nerves in the stump of an amputee." At that point in the field of haptics, engineering and nature will be meeting on equal terms.

–Ivan Amato