ROBOTIC ARM driven by electroactive polymers may eventually be pitted against a human's in an arm-wrestling match.

Artificial Muscles

By Steven Ashley

Novel motion-producing devices—actuators, motors, generators—based on polymers that change shape when stimulated electrically are nearing commercialization

It's only a $100 toy—an aquarium of swimming robotic fish developed by the Eamex Corporation in Osaka, Japan. What makes it remarkable is that the brightly colored plastic fish propelling themselves through the water in a fair imitation of life do not contain mechanical parts: no motors, no drive shafts, no gears, not even a battery. Instead the fish swim because their plastic innards flex back and forth, seemingly of their own volition. They are the first commercial products based on a new generation of improved electroactive polymers (EAPs), plastics that move in response to electricity.

For decades, engineers who build actuators, or motion-generating devices, have sought an artificial equivalent of muscle. Simply by changing their length in response to nerve stimulation, muscles can exert controlled amounts of force sufficient to blink an eyelid or hoist a barbell. Muscles also exhibit the property of scale invariance: their mechanism works equally efficiently at all sizes, which is why fundamentally the same muscle tissue powers both insects and elephants. Something like muscle might therefore be useful in driving devices for which building tiny electric motors is not easily accomplished.

EAPs hold promise for becoming the artificial muscles of the future. Investigators are already ambitiously working on EAP-based alternatives to many of today's technologies. And they aren't afraid to pit their creations against nature's. A few years ago several individuals, including Yoseph Bar-Cohen, a senior research scientist at the Jet Propulsion Laboratory (JPL) in Pasadena, Calif., posted a challenge to the electroactive polymer research community to drum up interest in the field: a race to build the first EAP-driven robotic arm that could beat a human arm-wrestler one on one. Later, they began searching for sponsors to subsidize a cash prize for the winner.

Perhaps the most promising of the current EAP efforts is being conducted by SRI International, a nonprofit contract-research laboratory based in Menlo Park, Calif. Within a few months, SRI management hopes to complete arranging the initial $4 million to $6 million in investment funding needed to launch a spin-off company—tentatively called Artificial Muscle Incorporated—to commercialize the EAP technology it has patented. Even now, SRI is working on half a dozen R&D contracts with the U.S. government and companies

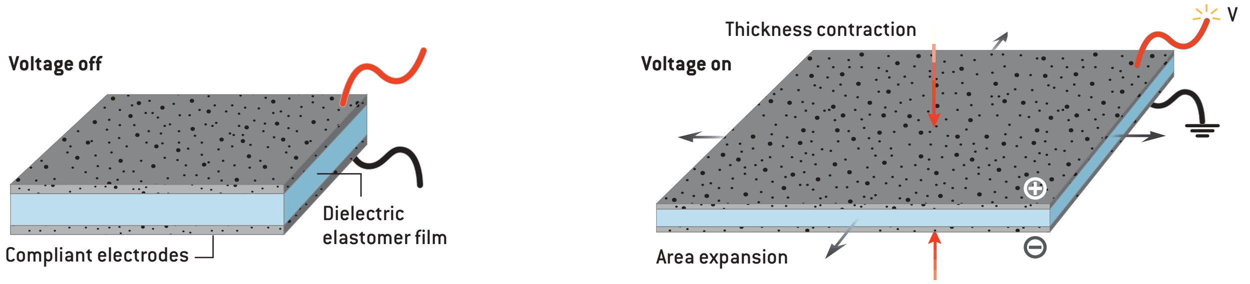
HOW ELECTRICITY MAKES A PLASTIC EXPAND

THE FUNDAMENTAL MECHANISM underlying new artificial muscle products is relatively simple. When exposed to high-voltage electric fields, dielectric elastomers—such as silicones and acrylics—contract in the direction of the electric field lines and expand perpendicularly to them, a phenomenon physicists term Maxwell stress. The new devices are basically rubbery capacitors—two charged parallel plates sandwiching a dielectric material. When the power is on, plus and minus charges accumulate on the opposite electrodes. They attract each other and squeeze down on the polymer insulator, which responds by expanding in area.

Engineers laminate thin films of dielectric elastomers (typically 30 to 60 microns thick) on the front and back with conductive carbon particles suspended in a soft polymer matrix. When connected by wires to a power source, the carbon layers serve as flexible electrodes that expand in area along with the material sandwiched in the middle. This layered plastic sheet serves as the basis for a wide range of novel actuation, sensory and energy-generating devices.

Dielectric elastomers, which can grow by as much as 400 percent of their nonactivated size, are by no means the only types of electroactive materials or devices, although they represent some of the more effective examples.

The graph at the right compares the performance of various classes of actuation materials and devices. These include well-established motion-generating products driven by electric current as well as applied electrostatic and electromagnetic fields. Strain refers to the amount of displacement or travel per unit length the devices can



in the toy, automotive, electronics, medical product and footwear industries to bring artificial muscles to market.

The start-up firm's goal? Only to replace a substantial number of the myriad electric motors we use regularly, not to mention many other common motion-generating mechanisms, with smaller, lighter, cheaper products using SRI's novel actuators. "We believe this technology has a good chance to revolutionize the field of mechanical actuation," states Phillip von Guggenberg, the lab's director of business development. "We'd like to make the technology ubiquitous, the kind of thing you could pick up in hardware stores."

Materials That Move

BAR-COHEN HAS SERVED as the unofficial coordinator for the highly diverse community of international EAP researchers since the mid-1990s. Back during the field's infancy, "the electroactive polymer materials I read about in scientific papers didn't work as advertised," he recalls, chuckling slyly. "And as I already had obtained NASA funding to study the technology, I was forced to look around to find who was working in this area to find something that did." Within a few years Bar-Cohen had learned enough to help establish the first scientific conference on the topic, start publishing an EAP newsletter, post an EAP Web site and edit two books on the nascent technology.

Sitting among arrays of lab tables strewn with prototype actuation devices and test apparatus in a low-slung research building on the JPL campus, Bar-Cohen reviews the history of the field he has come to know so well. "For a long time," he begins, "people have been working on ways to move objects without electric motors, which can be too heavy and bulky for many applications. Until the development of EAPs, the standard replacement technology for motors were piezoelectric ceramics, which have been around for some time."

In piezoelectric materials, mechanical stress causes crystals to electrically polarize and vice versa. Hit them with electric current and they deform; deform them and they generate electricity.

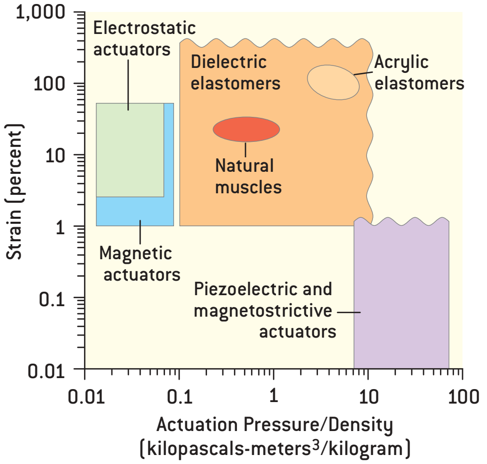
Bar-Cohen lifts a small grayish disk off one of the lab benches, saying, "This one's made of PZT—lead zirconate titanate." He explains that electric current makes the

Overview/*Electroactive Polymers*

- Physicists and chemists have long sought to develop lightweight materials that grow or shrink significantly in length or volume when subjected to electric stimulation. Such substances could serve as the drivers for novel motion-generating devices (generally called actuators)—possible replacements for the ubiquitous electric motor, which is often too bulky and heavy for smaller-scale applications.
- A new generation of electroactive polymer materials displays sufficient physical response to electrical excitation to power new classes of actuators as well as innovative sensors and energy generators. Products based on this "artificial muscle" technology are just starting to hit the market.

JAMIE KRIPKE (*preceding pages*); SARA CHEN (*above and opposite page*)

create. Actuation pressure/density is a measure of the force they produce. Dielectric elastomers can generate more strain and force than many of the competing technologies. Their properties in this regard are similar to those of natural animal muscle—hence the moniker "artificial muscles."



piezoelectric PZT shrink and expand by a fraction of a percent of its total length. Not much motion but useful nonetheless.

In an adjoining room, Bar-Cohen shows off foot-long impact drills driven by PZT disks that he is building with his JPL colleagues and Cybersonics. "Inside this cylinder is a stack of piezoelectric disks," he states. "When activated with alternating current, the stack beats ultrasonically on a mass that hops up and down at a high rate, driving a bit into solid rock." To one side sit piles of stone blocks into which drill bits have cut deep holes.

As a demonstration of how effectively piezoceramics can perform as actuators, it is impressive. But many applications would demand electroactive materials that grow by more than just a fraction of a percent.

Plastics That React

POLYMERS THAT change shape in response to electricity, according to Bar-Cohen, can be sorted into two groups: ionic and electronic types, each with complementary advantages and disadvantages.

Ionic EAPs (which include ionic polymer gels, ionomeric polymer-metal composites, conductive polymers and carbon nanotubes) work on the basis of electrochemistry—the mobility or diffusion of charged ions. They can run directly off batteries because even single-digit voltages will make them bend significantly. The catch is that they generally need to be wet and so must be sealed within flexible coatings. The other major shortcoming of many ionic EAPs (especially the ionomeric polymer-metal composites) is that "as long as the electricity is on, the material will keep moving," Bar-Cohen notes, adding: "If the voltage is above a certain level, electrolysis takes place, which causes irreversible damage to the material."

In contrast, electronic EAPs (such as ferroelectric polymers, electrets, dielectric elastomers and electrostrictive graft elastomers) are driven by electric fields. They require relatively high voltages, which can cause uncomfortable electric shocks. But in return, electronic EAPs can react quickly and deliver strong mechanical forces. They do not need a protective coating and require almost no current to hold a position.

SRI's artificial muscle material falls into the electronic EAP classification. The long, bumpy and sometimes serendipitous road to its successful development is a classic example of the vagaries of technological innovation.

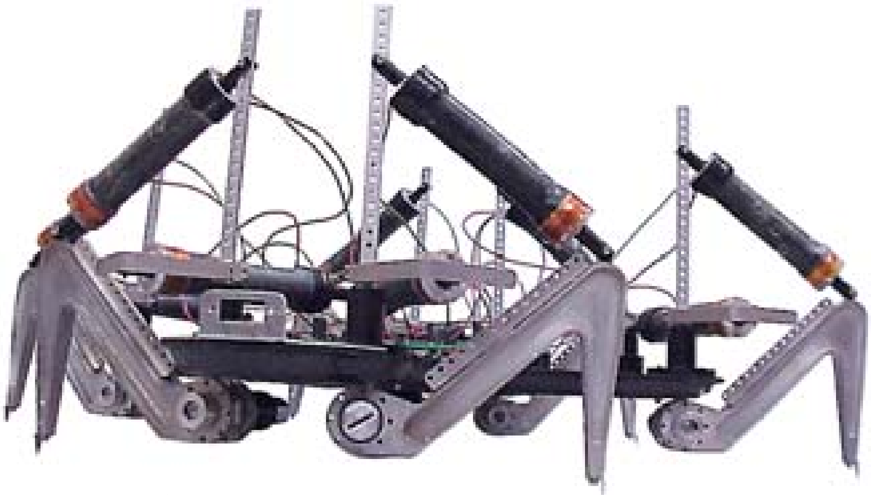
Electrifying Rubber

"SRI INTERNATIONAL began work on artificial muscles in 1992 under contract to the Japanese micro-machine program," says Ron Pelrine, the physicist-turned-mechanical engineer who leads the SRI team. Japanese officials were looking for a new kind of micro-actuator technology. A few SRI researchers started searching for a motion-generating material that resembled natural muscle in terms of force, stroke (linear displacement) and strain (displacement per unit length or area).

"We looked at a whole bunch of possible actuation technologies," Pelrine recalls. Eventually, however, they considered electrostrictive polymers, a class of materials then being investigated by Jerry Scheinbeim of Rutgers University. The hydrocarbon molecules in those polymers are arranged in semicrystalline arrays featuring piezoelectriclike properties.

When exposed to an electric field, all insulating plastics, such as polyurethane, contract in the direction of the field lines and expand perpendicularly to them. This phenomenon, which differs from electrostriction, is called Maxwell stress. "It had been known for a long time but was regarded generally as a nuisance effect," Pelrine says.

He recognized that polymers softer than polyurethane would squash more under electrostatic attraction and thus would provide greater mechanical strains. Working with soft silicones, the SRI scientists soon demonstrated quite acceptable strains of 10 to 15 percent. With further research those numbers rose to 20 to 30 percent. To distinguish the new actuator materials, silicones and other softer plastics were christened dielectric elas-



INSECTLIKE ROBOT (named Flex) walks on legs powered by extension roll-type artificial muscles.

SRI INTERNATIONAL

tomers (they are also called electric-field-actuated polymers).

Having identified several promising polymer materials, the group focused for much of the remainder of the 1990s on the nuts and bolts of building devices for specific applications. Much of the SRI team's new external funding support and research direction came at the time from the Defense Advanced Research Projects Agency (DARPA) and the Office of Naval Research, whose directors were primarily interested in using the technology for military purposes, including small reconnaissance robots and lightweight power generators.

As the elastomers began to exhibit much larger strains, the engineers realized that the electrodes would have to become expandable as well. Ordinary metal electrodes cannot stretch without breaking. "Previously, people didn't have to worry about this issue, because they were working with materials that provided strains of 1 percent or so," Pelrine notes. Eventually, the team developed compliant electrodes based on carbon particles in an elastomeric matrix. "Because the electrodes expand along with the plastic," he points out, "they can maintain the electric field between them across the entire active region." SRI International patented this concept, one of the keys to subsequent artificial-muscle technology.

Eager to demonstrate, Pelrine holds out what looks like a six-inch-square picture frame with plastic sandwich wrap stretched tautly across it. "See, this polymer material is very stretchy," he says, pushing a finger into the transparent film. "It's actually a double-sided adhesive tape that's sold at low cost in large rolls." On both sides of the middle of the sheet are the black, nickel-size compliant electrodes, trailing wires.

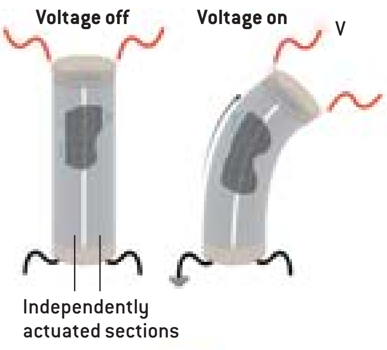
Pelrine turns a control knob on the electric power supply. Instantly, the dark circle of the paired electrodes grows to the diameter of a quarter. When he returns the knob to its original position, the disk shrinks back immediately. He flashes a grin and repeats the sequence a few times, explaining: "Fundamentally, our devices are capacitors—two charged parallel plates sandwiching a dielectric material. When the power is on, plus and minus charges accumulate on the opposite electrodes. They attract each other and squeeze down on the polymer insulator, which responds by expanding in area."

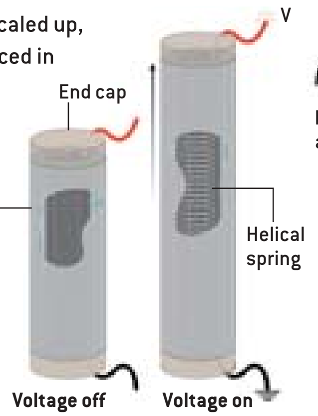
Although several promising materials had been identified, achieving acceptable performance in practical devices proved to be a challenge. A couple of breakthroughs in 1999 drew considerable interest from government and industry, however. One arose from the observation that stretching the polymers before electrically activating them somehow vastly improved their performance. "We started to notice that there seemed to be a sweet spot at which you get optimum performance," remembers engineer Roy Kornbluh, an-

SPRING ROLLS, SNAKES AND ROBOT ARMS

POLYMERS THAT EXPAND in response to electricity make possible roll actuators that extend—or bend—on command. Engineers first roll up two layers of dielectric elastomer sheet (laminated on both sides with flexible electrodes) into compact cylinders. Often the film materials are wrapped around a compressed helical spring that holds a high circumferential prestrain on the films, thereby enhancing device performance. So-called spring rolls can serve in many applications, such as actuators for robotic and prosthetic mechanisms, valves and pumps, and wherever simple linear motion is required. To date, roll actuators have produced up to 30 newtons of force (about 6.6 pounds), linear displacements (strokes) up to about two centimeters and cyclic speeds of more than 50 hertz. To increase the mechanical output, the technology can be scaled up, or multiple actuators can be placed in series or in parallel.

Relatively simple modifications can yield devices that bend on command. Researchers spray specially patterned electrodes onto the dielectric elastomer film in such a fashion that the roll incorporates two independently energized actuators on either side (split lengthwise). If only the left half receives voltage, the right one inhibits the resulting motion and causes the device to bend toward the right (*below*). If only the right half is activated, the roll bends left. If both halves are energized, the roll extends. More complicated arrays of independent electrodes can create more complex motion. Applications for bending rolls include snakelike robots and manipulators, steerable catheters and endoscopes, legged robots, and pointing mechanisms for antennas.





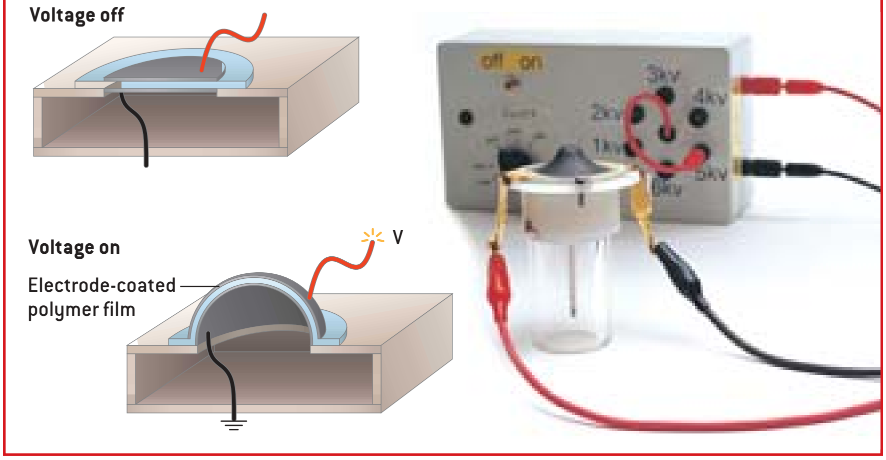
SARA CHEN (*illustrations*); JAMIE KRIPKE (*photographs*)

other team member. “No one was sure exactly why, but prestretching the polymers increased breakdown strengths [resistance to the passage of current between electrodes] by as much as 100 times.” Actuation strains improved to a similar degree. Although the reason is still unclear, SRI chemist Qibing Pei believes that “prestretching orients the molecular chains along the plane of expansion and also makes it stiffer in that direction.” To achieve the prestraining effect, SRI’s actuator devices incorporate an external bracing structure.

The second key discovery came about primarily because the researchers “were testing every stretchy material we could find—what we call an Edisonian approach,” Pelrine says with amusement. (Thomas Edison systematically tried all kinds of materials for suitability as lightbulb filaments.) “At my home, we had placed a polymeric door lock on the refrigerator to keep my toddler from getting in. As he got older, we didn’t need the lock anymore, so I removed it. But since it was made of a stretchy material, I decided to test its strain properties. Surprisingly, it gave very good performance.” Tracking down the material and determining its composition took no small effort, but in the end the mystery polymer “turned out to be an acrylic elastomer that could provide tremendous strains and energy output—as much as 380 percent linear strain. These two developments allowed us to start applying the dielectric elastomers to real-world actuator devices,” the researcher says.

PUMP UP THE MEMBRANE

DIAPHRAGM ACTUATORS are made by stretching dielectric elastomer films over an opening in a rigid frame. Typically the diaphragm is biased, or pushed up or down, by a spring, light air pressure, foam or other means. Biasing makes the diaphragm actuate in one direction (up or down) rather than simply wrinkling randomly when voltage is applied. Diaphragm actuators can displace volume, making them suitable for pumps or loudspeakers. Alternative drive technologies such as piezoelectric materials have long been in use, but dielectric elastomer diaphragms offer larger displacements. Some designs can deflect from an initial flat position to a convex shape (*below*).



SARA CHEN (*illustrations*); JAMIE KRIPKE (*photograph*)

Making It Real

THE SRI TEAM’S general approach is flexible, encompassing many designs and even different polymers. As Pei says, “This is a device, not a material.” According to Pelrine, the team can produce the actuation effect using various polymers, including acrylics and silicones. Even natural rubber works to some extent. In the extreme temperatures of outer space, for example, artificial muscles might best be made of silicone plastics, which have been demonstrated in a vacuum at –100 degrees Celsius. Uses that require larger output forces might involve more polymer or ganging up several devices in series or in parallel.

“Because the dielectric elastomers can be purchased off the shelf and we’d use at most only a few square feet of material in each device, the actuators would be very low cost, particularly in volume production,” SRI’s von Guggenberg estimates.

The voltages required to activate dielectric elastomer actuators are relatively high—typically one to five kilovolts—so the devices can operate at a very low current (generally, high voltage means low current). They also use thinner, less expensive wiring and keep fairly cool. “Up to the point at which the electric field breaks down and current flows across the gap [between the electrodes], more voltage gives you greater expansion and greater force,” Pelrine says.

“High voltage can be a concern,” Kornbluh comments, “but it’s not necessarily dangerous. After all, fluorescent lights and cathode-ray tubes are high-voltage devices, but nobody worries about them. It’s more of an issue for mobile devices because batteries are usually low-voltage, and thus additional electric conversion circuits would be needed.” Moreover, at Pennsylvania State University, Qiming Zhang and his research group have managed to lower the activation voltages of certain electrostrictive polymers by combining them with other substances to create composites.

When asked about the durability of SRI’s dielectric elastomer actuators, von Guggenberg acknowledges a need for more study but attests to a “reasonable indication” that they continue to work sufficiently long for commercial use: “For example, we ran a device for one client that produces moderate, 5 to 10 percent strains for 10 million cycles.” Another generated 50 percent area strains for a million cycles.

Although artificial-muscle technology can weigh significantly less than comparable electric motors—the polymers themselves have the density of water—efforts are ongoing at SRI to cut their mass by reducing the need for the external structure that prestrain the polymers. Pei, for instance, is experimenting with chemical processing to eliminate the need for the relatively heavy frame.

Building Products

HAVING DEVELOPED a basic mechanism, the SRI team soon began work on a flood of application concepts:

Linear actuators. To make what they call spring rolls, the engineers wrap several layers of prestrained laminated dielectric elastomer sheet around a helical spring. The tension spring supports the circumferential prestrain, whereas the lengthwise prestrain of the film holds the spring compressed [*see illustration on page 56*]. Voltage makes the film squeeze in thickness and relax lengthwise so that the device extends. The spring rolls can therefore generate high force and stroke in a compact package. Kornbluh reports that automakers are interested in these mechanisms as replacements for the many small electric motors found in cars, such as in motorized seat-position controls and in the valve controls of high-efficiency camless engines.

Bending rolls. Taking the same basic spring roll, engineers can connect electrodes to create two or more distinct, individually addressed sections around the circumference. Electrically activating that section makes its side of the roll extend, so the entire roll bends away from that side [*see illustration on page 56*]. Mechanisms based on this design could engage in complicated motions that would be difficult to accomplish using conventional motors, gears and linkages. Possible uses would be in steerable medical catheters and in so-called snake robots.

Push-pull actuators. Pairs of dielectric elastomer films or of spring rolls can be arranged in a "push-pull" configuration so that they work against each other and thus respond in a more linear ("one input yields one output") fashion. Shuttling voltage from one device to the other can shift the position of the whole assembly back and forth; activating both devices makes the assembly rigid at a neutral point. In this way, the actuators act like the opposing bicep and tricep muscles that control movements of the human arm.

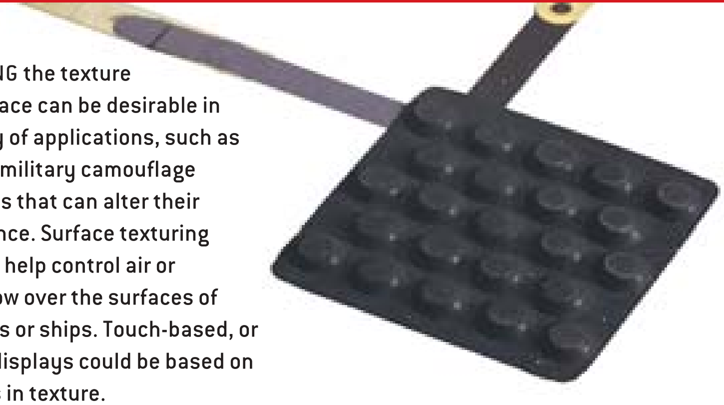
Loudspeakers. Stretch a dielectric elastomer film over a frame that has an aperture in it. Expanding and contracting rapidly according to the applied voltage signal, the diaphragm will then emit sound. This configuration can yield a lightweight, inexpensive flat-panel speaker, whose vibrating medium is both the driver and sound-generating panel. Current designs offer good performance in the mid- and high-frequency ranges. The speaker configuration has not yet been optimized as a woofer, although no obstacle prevents it from operating well at low frequencies [*see illustration on preceding page*].

Pumps. The design of a dielectric elastomer diaphragm pump is analogous to that of a low-frequency loudspeaker to which engineers have added a fluid chamber and two one-way check valves to control the flow of liquid. Artificial muscles are well suited to powering microfluidic pumps, for example, on the lab-on-a-chip devices prized by medicine and industry.

Sensors. Because of their nature, all SRI's dielectric elastomer devices exhibit a change in capacitance when they are bent or stretched. Thus, it is possible to make a sensor that is compliant and operates at low voltage. According to Kornbluh, the team came close to getting an automaker to adopt the technology as a sensor for measuring the tension of a seat belt. Such sensors could similarly be incorporated in fabrics and other materials as fibers, strips or coatings, he says.

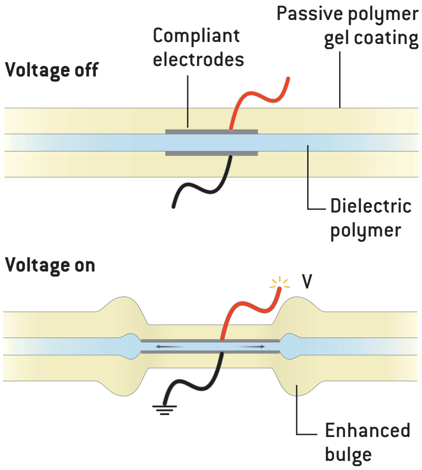
Surface texturing and smart surfaces. If the polymers are imprinted with patterns of electrodes, arrays of dots or shapes can be raised on a surface on demand. This technology might find use as an active camouflage fabric that can change its reflectance as desired or as a mechanism for making "riblets" that improve the aerodynamic drag characteris-

CONTROLLABLE SURFACE TEXTURES



CHANGING the texture of a surface can be desirable in a variety of applications, such as "active" military camouflage materials that can alter their reflectance. Surface texturing can also help control air or water flow over the surfaces of airplanes or ships. Touch-based, or haptic, displays could be based on changes in texture.

Most dielectric elastomer actuators take advantage of large-scale deformations in the plane of the film. Alterations in the thickness of the film, on the other hand, are barely perceptible. By coating the thin-film sheets and patterned compliant electrodes with a much thicker and softer layer of polymeric gel, however, thickness changes can be greatly amplified so that they are readily apparent. As the film grows in the plane, the gel spreads out along with the expanding film and bunches up at the points at which the film compresses.



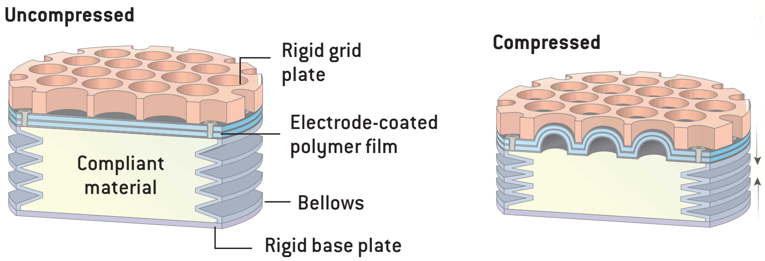
SARA CHEN (*illustrations*); JAMIE KRIPKE (*photograph*)

ELECTRIC BOUNCE IN EVERY STEP

DIELECTRIC ELASTOMERS can produce electric power. In generator mode, a voltage is applied across the dielectric elastomer, which is deformed by external force. As the shape of the elastomer changes, the effective capacitance of the device also alters and, with the appropriate electronics, electrical energy is generated. The energy density of these materials when used as a generator is high, which means that they can be made lighter than other technologies.

Dielectric elastomers are well suited to applications in which electrical power comes from relatively large motions, such as those produced by wind energy, waves and human activity. Capturing the compression energy of a shoe heel when it strikes the ground during walking or running is a good way to generate portable electrical power. This energy is free in the sense that it does not place an additional burden on the wearer. The heel-strike generator effectively couples the compression of the heel to the deformation of an array of multilayer diaphragms.

SRI engineers expect that, with further development, a device will be able to generate about a watt during normal walking. A unit in each shoe should provide enough electricity to power a cellular phone, for example. Such a device is being developed for the U.S. military to supply power to soldiers in the field, but the technology has civilian uses as well.



tics of airplane wings [*see illustration on preceding page*].

Power generators. Again, because these materials act as soft capacitors, variable-capacitance power generators and energy harvesters can be built from them. DARPA and the U.S. Army funded development of a heel-strike generator, a portable energy source that soldiers and others in the field could use to power electronic devices in place of batteries. An average-size person taking a step each second can produce about a watt of power using a device now under development [*see illustration above*]. Von Guggenberg says this concept has caught the interest of footwear companies. The devices could similarly be attached to backpack straps or car-suspension components. In principle, this approach could also be applied to wave generators or wind-power devices.

SRI researchers recently tested a more radical concept—"polymer engines." Propane fuel was burned inside a chamber, and the pressure from the resulting combustion products distorted a dielectric elastomer diaphragm, generating electricity. Such designs might eventually lead to efficient, extremely small generators in the centimeter-or-less size range.

But truly marketable products are still to come. "At this point we're building turnkey devices that we can place in the hands of engineers so they can play with them and get comfortable with the technology," von Guggenberg notes. "We hope it's just a matter of time before every engineer will consider this technology as they design new products."

Bar-Cohen says that he is impressed by the progress the SRI group has made on its actuator technology. But success has also created problems in one regard: the arm-wrestling challenge. "We expected it would take 20 years or so for anyone to develop a mechanical arm that would be strong enough to compete against a human," he laughs. "Now SRI says they're ready to build one, and we haven't raised the prize money yet!" SA

Steven Ashley is a staff writer and editor.

MORE TO EXPLORE

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Simple muscle demos are available online at **www.erg.sri.com/projects/muscle/recipe** and **ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-recipe.htm**

The WorldWide ElectroActive Polymer Newsletter is at **ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html**

SARA CHEN (*illustrations*); JAMIE KRIPKE (*photograph*)