Research News

Animating the Material World

Researchers of every stripe are joining in a quest to create intelligent structures that can warn of impending failure—in bridges, say—or adapt to a changing environment

IMAGINE A ROPE THAT BROADCASTS A BRIGHT color if there's a chance it will break, warning the rock climbers dangling from it. Or an aircraft skin riddled with fiber optic nerves, always vigilant for structural flaws that might presage catastrophic failure. How about a stealthy, propellerless submarine that moves by flexing its entire hull like a whale while its skin quiets incoming sonar probes with counteractive vibrations of its own?

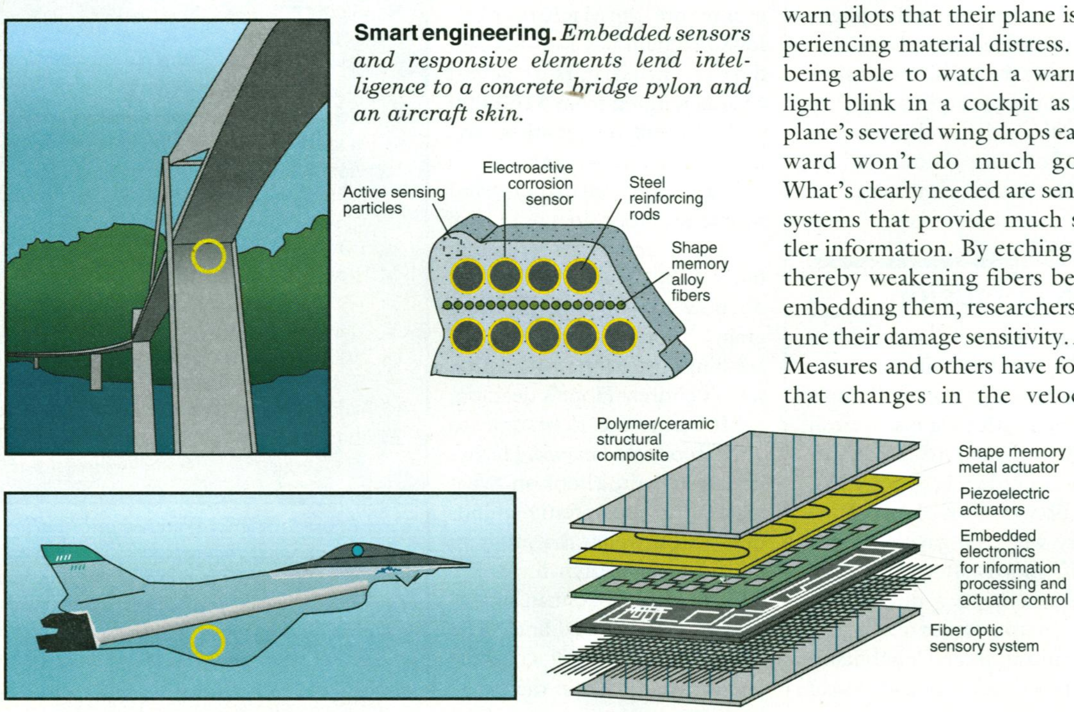
Now you're getting into the mindset of a multidisciplinary crowd of investigators who are learning to engineer "intelligence into the constructed world," as Julian Vincent of the Centre for Biomimetics at the University of Reading puts it. He is part of a growing global community of academic, industrial, and military researchers who aim to complement or replace structural brawn with smarts. The goal of their research into so-called smart or intelligent materials and structures is to animate the inanimate world, endowing it with more and more of the attributes of living things.

It isn't just on the research front that the field of "smart" materials and structures is progressing; it's also changing sociologically, as a new discipline emerges. Already a varied group of practitioners—including chemists, physicists, biologists, materials scientists, robotics aficionados, systems control experts, computer scientists, aeronautical and hydronautical engineers, among others—has enough confidence in the field's potential to identify itself as a research community. The first publication devoted to the discipline, the *Journal of Intelligent Material Systems and Structures*, is starting its third year, and the British-based Institute of Physics will launch the field's second journal in March. Conferences also are proliferating. In the same month, Japan's Science and Technology Agency will host the First International Conference on Intelligent Materials, just two months before the First European Conference on Smart Structures & Materials takes place in Glasgow, Scotland.

The field is finding some permanent homes, too. Last February in Glasgow, the University of Strathclyde (home of the self-diagnosing rope) launched a Smart Structures Research Institute, following the institutional lead of the Center for Intelligent Material Systems and Structures (CIMSS) at Virginia Polytechnic Institute and State University and the Intelligent Materials and Structures Laboratory in Michigan State University. Many aerospace and automotive companies have their own smart structures programs. And the military has taken a more than passing interest, funding work in its own laboratories and those of contractors.

One of the hallmarks of the new field is that it weds high-tech sensors and responsive elements with traditional structural materials, blurring the seams between mechanism and material. As a first step, much of the ongoing research effort is aimed at designing materials that can sense their own condition—monitoring their own integrity. Checking for signs of imminent failure in airplane wings, bridges, and other critical structures, after all, is one of the tougher challenges in engineering. The answer, argues Raymond Measures, director of the Fiber Optic Smart Structures Laboratory at the University of Toronto, is to endow the material with a kind of sensory system. "We have senses that tell us if we feel pain, hot, or cold," he notes. "When you start building into structures a resident sensing system, and even an intelligence to interpret the sensory signals, the structure can know itself." When the structure is hurt, it will in effect feel pain and let someone know.

What should the sensory system of an airplane wing be made of? One answer—an approach being taken by Measures and other workers, including Eric Udd of McDonnell Douglas—is optical fibers embedded in high-performance composite materials. The composites are often constructed from polymers such as epoxy or kevlar reinforced with particles, flakes or fibers of stronger but more brittle substances such as graphite. Criss-crossing the composite, the optical fibers can act as what Measures calls "nerves of glass." In the simplest case, an optical fiber that snaps and stops sending an otherwise constant light signal to a detector might warn pilots that their plane is experiencing material distress. But being able to watch a warning light blink in a cockpit as the plane's severed wing drops earthward won't do much good. What's clearly needed are sensory systems that provide much subtler information. By etching and thereby weakening fibers before embedding them, researchers can tune their damage sensitivity. And Measures and others have found that changes in the velocity,

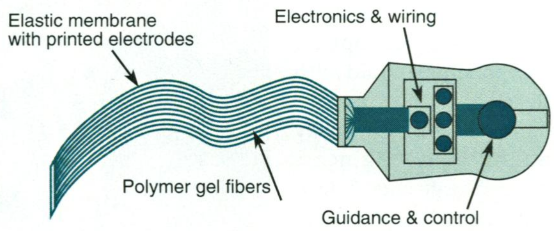


Smart engineering. *Embedded sensors and responsive elements lend intelligence to a concrete bridge pylon and an aircraft skin.*

phase, and frequency of light traveling down fibers can serve as indicators of subtle mechanical and chemical changes in the material, before overt damage occurs. "If you can know ahead of time that your aircraft's skin is about to come apart, you might have time to change your altitude [to equalize pressure between the aircraft's inside and outside] or decide not to take off," Udd says.

These varied sensory abilities suggest to Udd that a fiber-optic network could serve as a cradle-to-grave self-monitoring system for a composite material. Incorporated during manufacturing, the fibers could monitor temperature and water content to maintain the optimal conditions for production; once the composite had cured, the fibers would keep track of its health as it was assembled into planes, bridges or spacecraft. Perhaps most important, they would keep track of the material's structural integrity during its service lifetime. Finally, when the material could no longer serve its structural role reliably, the optical fibers would signal as much.

Some elements of self-monitoring may already have been built into the composite skins of military aircraft—stealth bombers, suggests Craig Rogers, director of CIMSS—although any details would be classified. The next advance—a "brain" that can harvest and interpret the signals from such a sensory network, giving the system a kind of self-awareness—remains on the lab bench. But when it emerges, it will probably be made up of embedded microprocessors, connected to form brain-like neural nets. Edward Crawley of the Massachusetts Institute of Technology and his co-workers have done preliminary studies showing that the kinds of electronic chips that would host this "intelligence" can survive and perform even when embedded within candidate materials for smart structures. In order to be commercially attractive, however, these material "brains" will have to be small, lightweight, and localized, Crawley argues. "No one is going to be interested in these systems if there's a big rack of electronics that goes with them."



Robofish. *An electroactive polymer gel would serve as swimming muscles, imitating a fish's motion* (right).

SOURCE: MO SHAHINPOOR. ILLUSTRATION: J. CHERRY

Other researchers are taking the biological metaphor further by equipping their material systems with components that are the equivalent of muscles or the immune system, reacting to stimuli and helping the structure protect itself from damage. Civil engineering structures such as bridges that could detect and counter corrosion before a pylon gives way or buildings that could brace themselves against seismic waves are some of the potential payoffs of this strategy of "active damage control."

In one version, materials researcher Carolyn Dry of the University of Illinois has been equipping concrete with substances that can sense and chemically respond to corrosion of steel reinforcing rods or cracks in the surrounding concrete. "The main problems with standard concretes are that they are brittle, porous and very dumb," Dry says. To remedy these shortcomings, at least in part, she adds polypropylene fibers filled with calcium nitrite, an anti-corrosion chemical, and sealed with polyol, a polymeric alcohol. When the alkalinity near the fibers rises high enough to corrode steel, the polyol coating dissolves, releasing the calcium nitrite onto the steel reinforcing bars. Dry's crack-arresting strategy is even simpler: She loads the concrete with fibers filled with an adhesive filler such as methyl methacrylate. When a crack forms, it breaks open the fibers, spilling the contents into the crack, where they can polymerize and in effect glue the crack into quiescence.

Those reactions are relatively slow, though, and CIMSS director Rogers and his colleagues are developing structures that could react much faster, averting damage before it occurs. The workers have been experimenting with high-performance composite slabs, cylinders, or beams fitted with actuators made of piezoelectric ceramics—

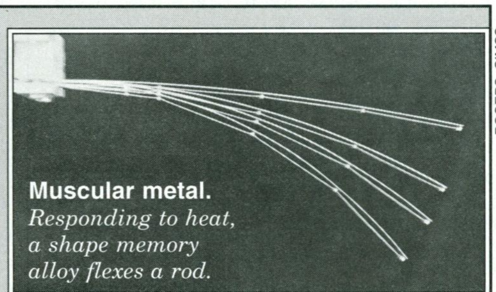
What It Takes to Smarten a Material

Smart materials are really materials systems, combining structural materials such as concrete and high-performance composites with other components that can sense the environment or respond to it. Here is a gallery of the sensors and actuators that could boost the IQ of tomorrow's smartest constructions.

■ ***Piezoelectric Ceramics and Polymers.*** These substances—lead zirconium titanate and polyvinylidene fluoride are two examples—can act either as pressure sensors or as mechanical actuators. Thanks to the electrical polarity of their crystal or molecular structures, they can swiftly transform the mechanical forces that impinge on them into electrical current or, conversely, turn electrical stimuli into vibrations.

■ ***Shape Memory Alloys.*** When slower, stronger responses are called for, these alloys (nitinol, a nickel-titanium alloy, is the best known) often fill the role of actuators. Below a certain transition temperature, a shape-memory wire will take any shape it is bent into. But when the wire is heated beyond the transition, it returns to its original shape—or tries to. Thus, when a shape-memory metal is incorporated into a smart system in its low-temperature shape, it exerts a force whenever it is heated. The force-generating transition takes place as the atoms in the alloy's crystal grains toggle between different geometric arrangements.

■ ***Electrorheological Fluids.*** Instead of generating a force, these actuator materials change their mechanical properties more dramatically by reversibly transforming from a liquid to a solid. When subjected to strong electric fields, such fluids—which consist of fine polarizable particles of ceramic or polymer suspended in a liquid such as silicone oil—organize themselves into filaments and networks, stiffening the material into a gel-like solid. When the electric field is removed, the organization dissipates, and the material becomes fluid again.



Muscular metal. *Responding to heat, a shape memory alloy flexes a rod.*

ROGERS, CIMSS

■ ***Optical Fibers.*** By transmitting light signals through a smart material, these sensor materials act as glass "nerves." Changes in temperature, pressure, strain or other physical or chemical conditions within the material can affect the properties of these hair-thin fibers. The optical signals provide a readout of those changes, yielding an intimate picture of the material's internal health.

■ **Second String.** Engineers mixing and matching components to create smart materials systems can also draw on a number of somewhat less studied sensor and actuator materials. Like piezoelectric materials, electrostrictive or electromechanical materials such as lead magnesium niobate respond to electrical stimuli with subtle shape changes; magnetostrictive materials such as terfenol (terbium difluoride) undergo similar changes, but in response to magnetic rather than electric fields; and electroactive and chemoactive polymers undergo changes in volume in response to electrical or chemical stimulation.

■ **I.A.**

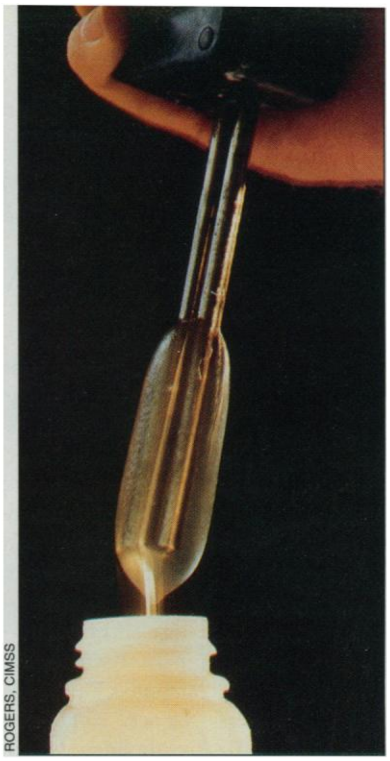
substances that twitch each time they are electrically stimulated (see box). The idea is to damp out damaging vibrations in a structure by inducing countervailing vibrations. In one study, the researchers tested the ability of a composite joined to an aluminum plate to withstand a regimen of vibrations with and without the help of the piezoelectrics. The composite/aluminum joint lasted 10 times longer when it was equipped with piezoelectric vibration control.

Smart materials researchers sometimes liken piezoelectric materials to fast-twitch muscle fibers, capable of reacting rapidly to stressful conditions. But Rogers has also been equipping his composites with the equivalent of slow-twitch fibers, which can exert a greater force but are slower and need more power to operate. These take the form of shape-memory metal wires, which return to former shapes as they are heated (see box). By embedding shape-memory metals in a composite, together with a control system that selectively heats them depending on the pattern of stresses the material is experiencing, designers can shunt stresses away from weak spots to avert material failure. "The whole idea is to redirect energy," Rogers says.

The damage-resisting bridges or airplane wings that might grow from such work would be not only more reliable than current, inert versions, says Rogers, they might also be more efficient. "Structures are currently designed to withstand extreme worst case scenarios," says Rogers. That translates into "overdesigning," with tons of extra mass and reinforcement for strength and stiffness or redundancy—features that are little more than extra baggage under ordinary conditions. By incorporating active damage control into their structures, Rogers hopes, engineers can tailor the structures more closely to the routine stresses and mechanical challenges they will face. "This can save us a lot in terms of mass and energy," he says. "For those rare instances in which you need additional stiffness or strength [during earthquakes, for example], we could input thermal or electrical energy [into piezoelectric or shape memory metal actuators, for example] to modify the structural performance."

In aerospace engineering, where weight is at a premium and repairs are impossible or prohibitively expensive, the benefits Rogers describes would be multiplied. If the arms that support the Hubble Space Telescope's solar panels included active vibration controls, for example, wobbles like the ones currently threatening the telescope might be quelled without any need to send repairmen into orbit at astronomical hourly rates. Adaptive optics—systems in which piezoelectric or other kinds of actuators alter a mirror's surface or the precise placement of other optical components—could also serve as a kind of active damage control. They might help engineers build "forgiveness" into superexpensive and hard-to-access space hardware, making it possible, in effect, for flaws like the one marring the Hubble's mirror to heal themselves.

While such efforts to endow material systems with lifelike properties aim to make them more durable and efficient in familiar applications, others researchers are looking well beyond that horizon. They are envisioning materials that, equipped with nervous systems and motive powers, are ready for jobs no existing materials can fill.



ROGERS, CIMSS

Responsive fluid. *An electrorheological fluid changes from liquid to gel in a double exposure.*

Given the military's love affair with high techology, it's no surprise that many of the researchers who see the most dazzling possibilities in smart materials and structures are working for the military, as a meeting last November in Alexandria, Virginia, made clear. Sponsored by the American Defense Preparedness Association, the meeting, called Active Materials and Adaptive Structures, brought together research managers and officials from virtually all U.S. defense agencies as well as academia and industry.

Among the smart structures programs outlined at the meeting were visions like that of Admiral W.C. Miller, chief of Naval Research. "One might envision a submarine with an array of sensors and actuators" embedded in a deformable hull, he told his audience. The object: quieting the turbulence created by an ordinary submarine, which both slows the vessel's progress and creates a din that "sounds like rain on a tin roof," he remarked. A sufficiently smart and responsive skin, he said, could detect the turbulence and nudge the chaotic water into quieter laminar flows making the submarine both swifter and more stealthy to sonar.

Mechanical engineer Mo Shahinpoor of the University of New Mexico, who participated in the Alexandria conference, takes visions of muscular submersibles even further. Taking inspiration from whales and dolphins, he said in an interview, he and coworkers at Sandia National Laboratory are trying to design polymeric swimming muscles for stealthy submarines. Their current efforts rely on "smart polymeric gels" made from a combination of polyacrylic acid and polyvinylic acid. The gels can dilate and contract like muscles when their polymer backbones are charged or neutralized—driving apart neighboring molecules or allowing them to draw together—a feature first discovered by Israeli researchers in the 1940s.

But Shahinpoor sees plenty of nonmilitary applications for his research. By forming the polymer into filaments and attaching them to miniaturized heads filled with guidance and control electronics and batteries, he hopes to make autonomous swimming robotic "fish." Besides an aquarium filled with exotic artificial fish of his own design, he envisions polymer-powered underwater robots that might be useful for jobs such as cleaning hulls without expensive drydocking. In the medical arena, he thinks the polymers, which can generate forces as strong as natural muscle and can flex as fast or faster, might serve well in an artificial heart.

Before electroactive polymers or any other smart structures develop into on-the-shelf, in-the-air, or underwater technologies, though, researchers will have to wrestle with some vexing problems. Many of the sensors and actuators available to researchers today fall short of their dreams. No artificial muscles yet exist, for example, that could exert enough force to control an airplane's flight surfaces. Another major concern is the increase in cost and complexity that comes when sensors and actuators are built into structural materials. If smartened structures end up weighing and costing more or living shorter lives than the designs they are supposed to replace, the concept easily could join the junk heap of nice ideas that didn't quite work.

But Vincent of the University of Reading predicts that the researchers working on intelligent structures "will eventually do better" than even the ultimate smart structures already among us, namely, the masterpieces of biology's own engineering. And when that happens, the concept of intelligence, which has already expanded beyond human beings to apply to complex electronic devices such as computers, will take another expansive step to include the most inert and least likely category of all: the world of materials. ■ IVAN AMATO