# How Smart are Smart Materials?

Bolstered by a handful of high-volume commercial applications, smart structures and materials are experiencing a resurgence of growth and interest. In fact, many researchers in the field believe that the industry is on the threshold of achieving major technological breakthroughs that will enable additional applications in the aerospace, home-construction, automotive, and machine-tool industries.

Although people use various definitions of smart materials, the label generally applies to materials that can transform strain into an electric charge and can convert an applied electric field into a generated stress. Such materials include piezoelectric ceramics, shape-memory alloys, magnetorestrictive materials, and electrorheological and magnetorheological fluids.

Robert Crowe, program manager for advanced structural materials at the Advanced Research Projects Agency (ARPA) in Arlington, Virginia, said that smart materials have the capability to both sense and respond to environmental stimuli, as well as being capable of active control of their response. However, James Sirkis, an associate professor and director of the University of Maryland at College Park's Smart Materials and Structures Research Center, said, "These materials do not in themselves have what we would consider intelligence. In fact, they're pretty stupid."

For Sirkis, the "smartness" comes from a systematic level, where sensor and actuator components are integrated into a structure capable of achieving enhanced functionality—hence the term "smart structures." Edward Crawley, an MIT professor of aeronautics and astronautics and cofounder of Active Control Experts, Inc. (ACX) in Cambridge, Massachusetts, expanded the definition further, including the addition of highly integrated control logic and signal-conditioning and power-amplification electronics.

Although most of the basic smart materials have been around since Marie and Pierre Curie experimented with piezoelectrics in 1880, the field has evolved over the last 30 years through government-funded defense research, which developed precision control of deformable mirrors and other high-resolution optics for space-based weapons systems. Crawley identified the transition to laminated materials, which allow for easier incorporation of active elements within the structural form, as an important enabling factor for the technology, along with the development of microelectronics, switching circuitry, fiber-optic technology, information processing, and artificial intelligence.

Still, the technology did not immediately gain wide acceptance, partly because of the interdisciplinary nature of the field. "You need to be technically literate in at least two technical disciplines to work in this area," said Sirkis, who has a combined mechanical- and electrical-engineering background. Cross-training in physics and aeronautics is also common among smart-material scientists. Sirkis added that, "We had a tough time defining ourselves."

The turning point occurred around 1992, with a few minor successful applications that caught the attention of major companies, causing a resurgence of interest and investment. Today, various U.S. government agencies are providing approximately $40 million each year in support of smart materials research, with industry pitching in an additional $12 million per year. According to Crowe, ARPA alone has already invested $40 million in funding to date in development of the technology, with an additional $30 million slated for the demonstration phase of the project.

## Types of materials

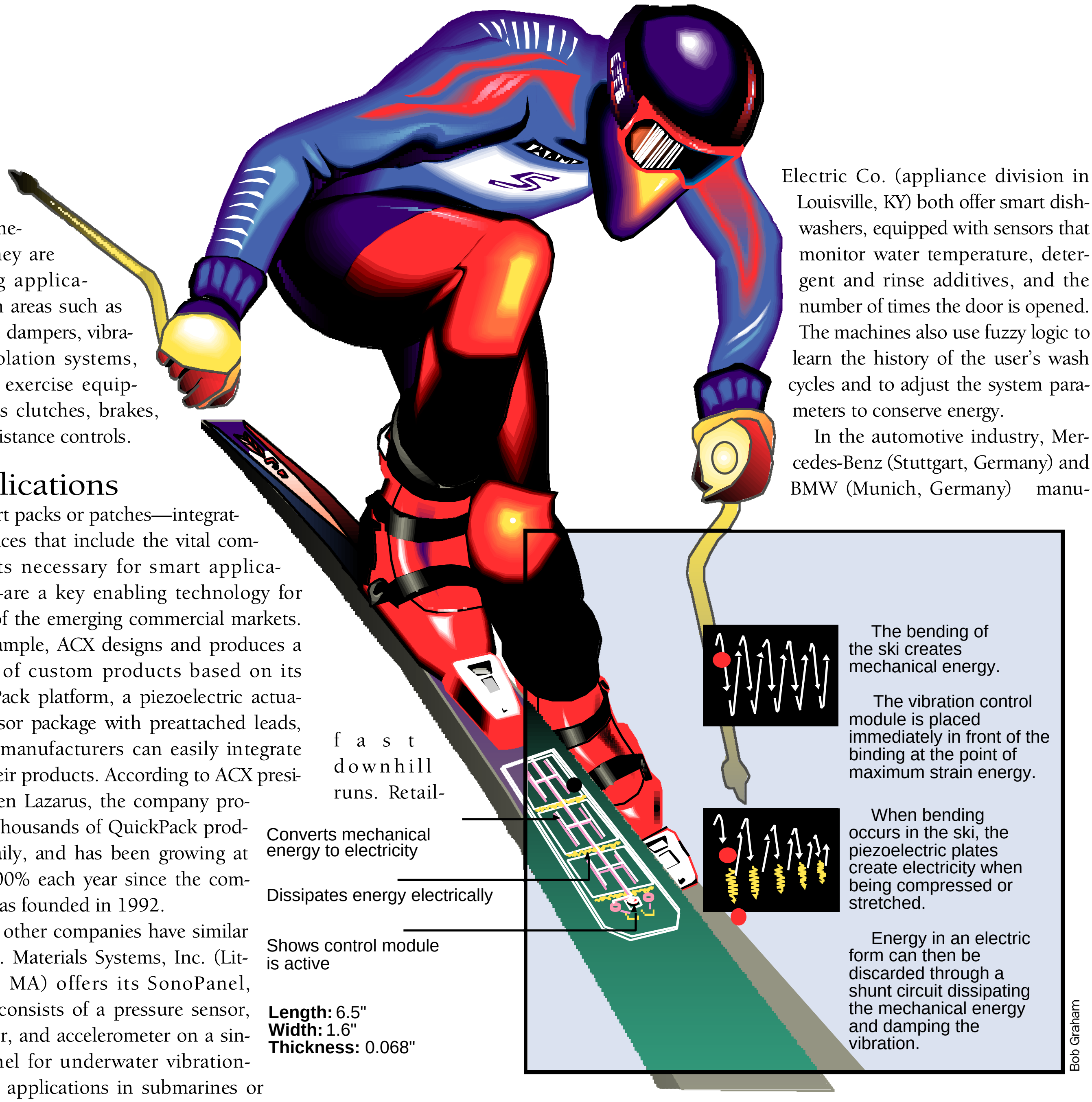
The most widely used smart materials are piezoelectric ceramics, which expand and contract when voltage is applied. Although not as forceful as shape-memory alloys, piezoelectric ceramics respond much more quickly, making them ideal for precise, high-speed actuation. In essence they are used to generate electrically stimulated movement or to record movement by providing a movement-related electric response. Demand for these materials is being fueled largely by their application as device actuators and transducers in sonar and ultrasonic systems. They can also be used in optical-tracking devices, magnetic heads, dot-matrix printers, computer keyboards, high-frequency stereo speakers, accelerometers, microphones, pressure sensors, transducers, and igniters for gas grills. The most common piezoelectric ceramic used these days is lead–zirconate-titanate.

Nevertheless, piezoelectric ceramics have some limitations, according to Sirkis. They tend to be brittle and somewhat heavy—a problem for some advanced aerospace applications—and the piezoelectric effect disappears above material-dependent temperature thresholds. They are also difficult to scale to larger applications because of their limited stroke or displacement.

Shape-memory alloys are metals that can be deformed and then returned to their original shape by heating. In the process, they generate an actuating force. The most popular one is a nickel–titanium alloy known as Nitinol, which has a corrosion resistance similar to stainless steel, making it particularly useful for biomechanical applications. However, shape-memory alloys can respond only as quickly as the temperature can shift, which is far too slow for many advanced applications.

Magnetorestrictive materials such as Terfenol-D are similar to piezoelectrics, but these respond to magnetic rather than electric fields. They are typically used in low-frequency, high-power sonar transducers, motors, and hydraulic actuators, to name a few. Along with the shape-memory alloy Nitinol, magnetorestrictive materials are considered promising candidates for achieving active damping of vibrations.

Some researchers are experimenting with actuators made from electrorheological and magnetorheological fluids, which rapidly increase in viscosity—by several orders of magnitude—when placed in an electric or magnetic field. However, these materials often exhibit abrasiveness and chemical instability. Nevertheless, they are finding applications in areas such as tunable dampers, vibration-isolation systems, and in exercise equipment as clutches, brakes, and resistance controls.




## Applications

Smart packs or patches—integrated devices that include the vital components necessary for smart applications—are a key enabling technology for many of the emerging commercial markets. For example, ACX designs and produces a family of custom products based on its QuickPack platform, a piezoelectric actuator/sensor package with preattached leads, which manufacturers can easily integrate into their products. According to ACX president Ken Lazarus, the company produces thousands of QuickPack products daily, and has been growing at over 200% each year since the company was founded in 1992.

Two other companies have similar devices. Materials Systems, Inc. (Littleton, MA) offers its SonoPanel, which consists of a pressure sensor, actuator, and accelerometer on a single panel for underwater vibration-control applications in submarines or surface ships. The company is also developing an air acoustic transducer for controlling radiated noise in automobiles, airplanes, and power transformers. Early next year, CSA Engineering, Inc. (Palo Alto, CA) will introduce its smart-patch technology, which incorporates piezoelectric sensors, actuators, and control electronics. Initially, this product will be targeted for high-end aerospace applications.

K2 Corp. (Vashon, WA), a sporting-goods company, uses the ACX QuickPack in its Four Smart Ski to improve control on fast downhill runs. Retailing at about $625, the ski is the first high-volume commercial application of smart materials, and hence represents a significant breakthrough in their acceptance in the marketplace. Other emerging commercial applications include computer docking stations, self-diagnostic disk drives, automatic-calibration instruments, and smart handguns, which can only be fired by an authorized user wearing a special ring.

Maytag Corp. (Newton, MA) and General Electric Co. (appliance division in Louisville, KY) both offer smart dishwashers, equipped with sensors that monitor water temperature, detergent and rinse additives, and the number of times the door is opened. The machines also use fuzzy logic to learn the history of the user's wash cycles and to adjust the system parameters to conserve energy.

In the automotive industry, Mercedes-Benz (Stuttgart, Germany) and BMW (Munich, Germany) manu-

**Users have reported that because vibration is dampened, the skis are more in contact with the snow; thus, for example, turning is a lot easier, putting less pressure on the skier's legs and back.**

facture high-end models that feature autonomous stability control. Sensors monitor steering angle, position of the accelerator pedal, braking pressure, lateral acceleration, and wheel rotation, while linear controllers monitor engine torque and individual brake pressure.

Anderson Electronics, Inc. (Madison, WI) markets Smart House automation systems, which employ motion and light sensors for controlling lighting, security systems, heating and air conditioning, and most audio/video and telephone equipment. The systems provide a central location for operation, control, and programming of those household functions, and it can interface with doorbells, personal computers, and other peripheral devices.

Allied Signal Aerospace (Kansas City, MO) licenses a piezoelectric traveling-wave motor, which is suitable for automotive, camera-lens, and fractional-horsepower applications. It can also be used in computer technology and as a replacement for solenoid and electromagnetic drivers. Piezo Systems, Inc. (Cambridge, MA) manufactures piezocomposite transducers, many of which find applications in various types of pressure valves. One of the most popular applications of Continuum Dynamics, Inc.'s (Princeton, NJ) smart-memory-alloy devices is in antiscald valves for showers, according to senior associate Todd Quackenbush.

Advanced Cerametrics (Lambertville, NJ) specializes in supplying the lead zirconate–titanate fibers used to manufacture piezocomposites for ultrasonic devices and hydrophones. A prototype for the latter has just been completed by investigators at Rutgers University (New Brunswick, NJ) and will be tested in underwater environments by the U.S. Navy. Unlike more rigid ceramic materials, the fiber allows enormously expanded capabilities for complicated shapes, uses, and architectures, according to company president Bud Cass. "We think the commercial markets for this aren't far away," he said.

## The future

Most industry insiders agree that the next generation of viable smart-structure technology will be in applications for monitoring structural integrity, noise reduction, and vibration suppression. "The end applications are there, it's just a matter of meeting them with something that's cost-effective," said Craig Near, director of new business development for Materials Systems, who predicts systems demonstrations in key areas will be completed in the next year or two.

Sirkis said that applications of smart materials are emerging in civil engineering to monitor the integrity of bridges, dams, offshore oil-drilling towers, and wooden utility poles. These applications use fiber-optic sensors embedded in the structures to identify problem areas. Smart structures are also being developed to monitor structural integrity in aircraft and space structures. In addition, Carrier Corp. (Syracuse, NY) is investigating the use of piezoelectric materials in an effort to reduce noise in air conditioners.

According to David Martinez of Sandia National Laboratories (Albuquerque, NM), he and his colleagues are exploring smart-structure systems to improve precision and increase productivity by controlling chatter in machine tools. These studies could result in more flexible robotics, which in turn would enable faster motion with greater accuracy. For example, embedding smart structures in lithography machines would enable the manufacture of smaller microelectronic circuits by controlling vibrations in the photolithographic circuit-printing process. Other projects include using an active material to implement precision shape control of solar reflectors and the integration of active-device technologies with structures for vibration suppression in high-precision manufacturing and machining operations.

Applications in biomedicine and medical diagnostics are also under investigation. Investigators at Sandia—along with MIT's David Brock and a host of Japanese researchers—have experimented with polyelectrolyte gels for artificial-muscle applications: a polymer matrix swollen with a solvent that can expand or contract up to 500% when exposed to an electric field or other stimulation. In addition, the material's biodegradable properties may make it useful as a drug-delivery system.

McDonnell Douglas Corp. (St. Louis, MO) and the Boeing Company's Defense and Space Group (Seattle, WA) are separately developing smart materials to suppress vibrations and change shape in helicopter rotor blades. Continuum Dynamics is also a collaborator in this area and hopes to have an on-blade control device operating on a full-scale rotor by the end of 1997. The company is also developing shape-memory-alloy devices capable of achieving accelerated breakup of vortex waves of submarines.

Northrup-Grumman Corp. (Los Angeles, CA) and Lockheed-Martin Corp. (Bethesda, MD) are developing adaptive-control surfaces for airplane wings, although ARPA's Crowe believes a working implementation of such a technology is at least 10 years away. SRI International (Menlo Park, CA) is focusing on new control technologies for smart materials and design methods for placement of sensors and actuators. However, "I think we're just scratching the surface right now," Lazarus said of these emerging applications.

Craig Rogers, former director of the Center for Intelligent Materials Systems and Structures at Virginia Polytechnic Institute and State University (Blacksburg), now dean of engineering at the University of South Carolina (Columbia), sees smart materials as having a revolutionary impact on materials science. "Intelligent materials systems will ultimately enable inanimate objects to become more natural and lifelike," he said. "They will be manifestations of the next engineering revolution, and the dawn of a new materials age.