Trends in Electromechanical Transduction

The demand for more sophisticated sensors and actuators in industrial equipment and consumer products is behind today's push for new transducer materials and geometries.

By Ilene J. Busch-Vishniac

In today's world, it is nearly impossible to avoid contact with electromechanical sensors and actuators over the course of the day, although we rarely recognize them. They drive the keyless entry systems, the light switches that respond to sound or motion, the detectors in cars that determine whether seat belts are fastened and the sound-receiving and sound-generating parts of the telephone, to name just a few examples.

Electromechanical transducers are devices in which one connection to the environment conducts electrical energy and another conducts mechanical energy. Examples include microphones, loudspeakers, accelerometers, strain gauges, resistance thermometers, solenoid valves and electric motors.

There are many ways to categorize transducers. The largest breakdown divides them into sensors and actuators. Transducers used to monitor the state of a system, ideally without affecting that state, are sensors. Transducers that impose a state on a system, ideally without regard to the system load (the energy drained by the system), are actuators. However, this division, although useful, doesn't get to the heart of what makes transducers work.

It is useful to consider transducers from the perspective of energy conversion mechanisms, an approach that also yields two broad classes of devices: those based on geometry and those based on material properties. An example of a geometry-based transducer is a condenser microphone, which is a parallel-plate capacitor with a DC voltage bias between the plates. Sound causes one of the plates to move, thus changing the gap between the plates. This change dynamically alters the capacitance and produces an output voltage. An example of a material property–based transducer is a piezoelectric accelerometer. Piezoelectric materials are those in which there is coupling between the electric field and the mechanical field so that imposed electric fields cause dimensional changes and applied material strains produce voltages. In a piezoelectric accelerometer, acceleration strains the transduction material, giving rise to an electric field that is sensed as a voltage. Of course, these two broad classes may be further refined either in terms of the function of the transducer (for example, sensing fluid flow) or in terms of narrower classes of energy conversion (for example, transduction based on piezoelectricity). The table on page 31 shows the main electromechanical transduction mechanisms. Here the definitions of "mechanical" and "electrical" are very liberal, including thermal and optical phenomena.

The 1970s and 1980s brought dramatic changes in electronics and signal processing techniques, but only modest changes in electromechanical transducers. As a result, transducers are commonly the least reliable and most expensive elements in measurement and control systems. For this reason, there is a growing emphasis on the field of transduction, and significant changes are beginning to emerge.

Pervasiveness

In the last few decades, electronics have been incorporated into products of all sorts. Their growth in consumer products has been driven by two phenomena: the public's perception that low-technology (nonelectronic) devices are not as good as high-technology devices, and the push for products with "intelligence."

Low-technology devices whose market is being overtaken by high-technology counterparts range from office equipment such as staplers and pencil sharpeners to kitchen appliances such as juice squeezers. In many cases, we are replacing purely mechanical functions performed under human control by automated electromechanical operations, leading to the introduction of sensors and actuators.

The growing market for intelligent products (those with a decision-making process) comes from the desires to automate some functions that people perform and to add functions that people cannot perform. For instance, although people can control room lights by hand, they often prefer to employ motion or sound detectors and control electronics instead. Examples of intelligent products that extend certain functions beyond standard human performance are smoke detectors, automobile airbags and clothes dryers with autodry cycles.

The growth in transducer markets has been rapid and is predicted to continue on its current pace through the turn of the century. The sensor market alone rose to become a $5 billion a year industry by 1990, with projections for a $13 billion worldwide market by the year 2000—an 8% annual growth rate over the decade.[1]

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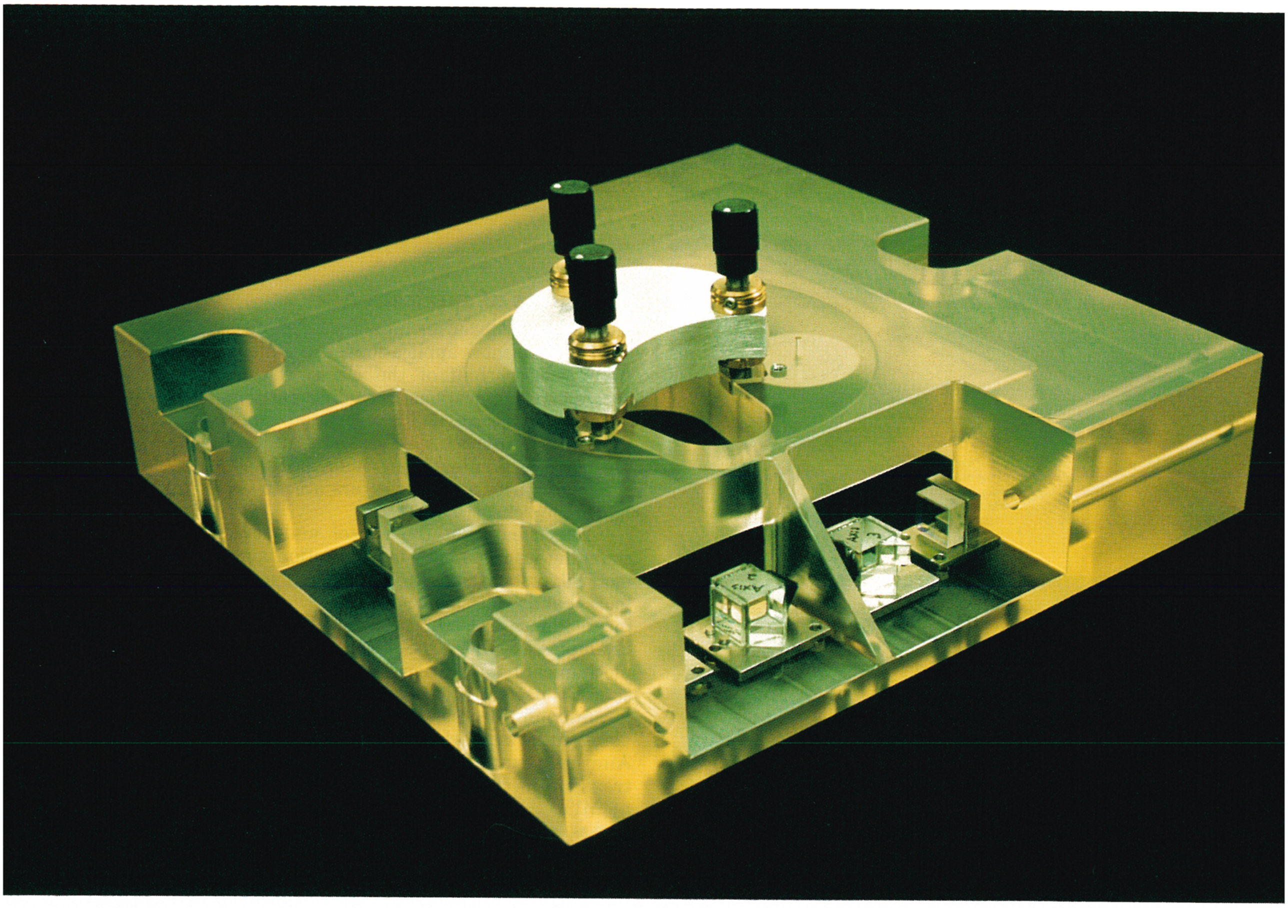

FIGURE 1. LONG-RANGE SCANNING STAGE. This positioner can travel 25 mm × 25 mm in the horizontal plane and 100 μm vertically. The goals are positioning resolution of 0.1 nm, repeatability of 1 nm and accuracy of 10 nm. The stage's actuator uses magnetic bearings with neutrally buoyant oil flotation, interferometric optical sensors for planar motion control and capacitive sensing for short-range vertical motion control. (From ref. 3.)

In search of design context

Product performance demands increase over time. In electromechanical transduction, the recent trend in product demands has led to goals that are mutually exclusive.

On the one hand, proponents of modularity view complicated mechanical systems as conglomerations of smaller components in much the way that circuit designers see circuits as sets of connected resistors, capacitors and inductors. The modular view calls for creating just a few standard types of a particular component. This limitation poses a need for great flexibility in transducer performance—wide ranges of operation, adjustable sensitivities, standardized shapes and so on. Of course, such flexibility normally is achieved through compromise on specific performance characteristics—a sort of design for the mean.

On the other hand, the demands for performance within any particular system in terms of quality, reliability and cost are becoming more stringent. This trend has spawned "mechatronics," a view that the design process ought to include models of sensors, actuators and controlling electronics as well as the mechanical system itself. The premise is that only through considering the mechanics and the electronics in an integrated fashion can one produce a product that performs as desired. Taken to its natural limit, this notion suggests that there is an optimum transducer for a given set of system performance characteristics and could lead to custom transducers.

Although there is merit in both views, there are compelling reasons to favor mechatronics. They have been articulated by Daniel Whitney, who argues that the modular approach to electronic system design will never apply to mechanical systems.[2] Among his reasons: Mechanical components typically perform multiple functions rather than just one, and, unlike electrical components, they perform differently in a system than they do in isolation. If one accepts that the mechatronic view will prevail, then the main implications are that it is important to continue to design, discover and create new sensors and actuators that push the envelope of performance characteristics, and that it is important to develop modeling approaches that permit sensor and actuator models to be integrated with conventional models of physical systems.

Scores of research programs are under way to produce electromechanical transducers that have previously unachieved levels of performance. Among the most interest-

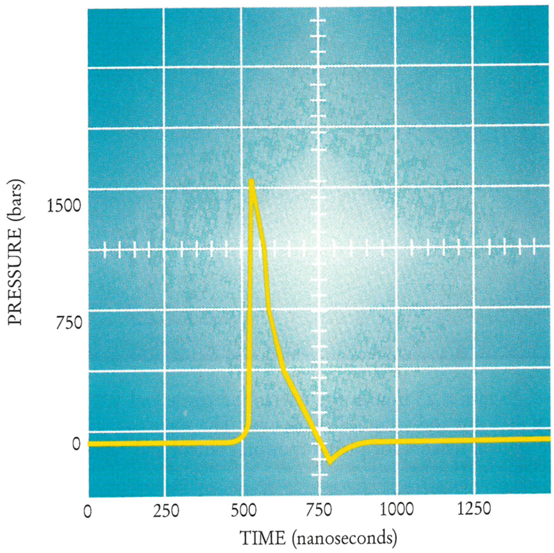

FIGURE 2. LITHOTRIPTER sound source (a) and output trace (b). **a:** Piezoelectric actuator head for production of high-intensity sound in a lithotripter. An array of piezoelectric sources line a parabolic dish so that the sound produced is focused on the site of a kidney stone. **b:** The pressure produced at the focus has an amplitude of over 1500 bars and a pulse width of about 125 nanoseconds. (Courtesy of EDAP Technomed SA, Lyon, France.)

ing goals are actuators that push the limits of resolution—that is, the smallest detectable change. An example is the work of Robert Hocken and his coworkers at the University of North Carolina at Charlotte, to produce a long-range scanning stage.[3] (See figure 1.) The goals are positioning resolution of 0.1 nm, repeatability of 1 nm and accuracy of 10 nm. These are to be achieved using active feedback control with capacitive and interferometric sensing.

Modeling transducers in a manner that fosters integration with other models is challenging, because there are multiple forms of energy, but here, too, progress is being made. For instance, work on piezoelectric transducers has led to a strategy for simultaneous consideration of thermal, mechanical and electrical energy through a model that is compatible with computer programs that use finite elements.[4] Using this modeling approach, it is possible to predict the thermal drift in system parameters and to design an underwater sound source that drifts into resonance, rather than drifting off of resonance.

New areas of application

Most of the transducer industry's expansion is due to the emergence of new applications, especially for sensors. In 1990, roughly half of the US sensor market was for automotive applications, including position, temperature, emission, pressure and acceleration sensors.[1] And one-third of the market was for industrial applications, and the rest was dominated by biomedical applications. Consumer products other than cars accounted for only about 1% of the sensor market.

It is clear that the sensor and actuator market is changing its focus both in application and in scale. With medical costs rising rapidly, the impetus for diagnostic tools that are less invasive and provide information earlier in an illness is leading to more biomedical applications. Examples abound. One device that makes use of electromechanical transduction is the lithotripter. In lithotripsy, sound is used to break up kidney stones in a process that is minimally invasive. The sound waves are created by using either a spark or a piezoelectric actuator (figure 2). Another example of the biomedical application of transducers is found in the recent work of Harry Asada at MIT. He has produced a prototype finger ring that senses a patient's vital statistics and uses telemetry to send the information to a central monitoring location. The hoped-for result is an ambulatory home patient who can be monitored for dangerous physiological changes such as a rapid rise in blood pressure.

There is also a shift in the types of transducers used in manufacturing. The most successful industrial control systems have focused on continuous processes such as oil refining. They usually rely on the low-speed monitoring and control of chemical characteristics using electrochemical sensors and electronically controlled heaters, mixers and prime movers such as motors. In recent years, attention has shifted toward unit (or discrete) industrial processes and operations performed by individual machines. In discrete processes such as drilling, grinding, turning and mechanical assembly, one normally monitors mechanical variables such as vibration and tool wear and senses and actuates on short timescales for the purpose of process control. These more challenging industrial transduction needs are reflected in the transducers now being developed and sold commercially.

Another industrial change relates to scales of operation. A growing segment of industry is concerned with very small dimensions. For instance, the microelectronics industry is constantly pushing toward smaller feature sizes, and is now at about the 0.1 μm level. Small-scale features have created a market for sensors with higher sensitivity, and actuators with greater positioning accuracy and resolution. These characteristics normally are achieved by compromising performance in another area, such as range. The piezoelectric actuators used for positioning in microscopy are a good example of this compromise. Consider, for instance, piezoelectric actuators sold for atomic force microscopy. The standard piezoelectric

Major Electromechanical Transduction Mechanisms

Transduction mechanism	Description	Examples
Capacitive—geometric	Quadratic—energy stored in electric field varies as geometry changes	Microphones, static pressure sensors, humidity sensors
Electrostriction	Quadratic—material coupling between electric and mechanical fields	Positioning actuators
Inductive—geometric	Quadratic—energy stored in magnetic field varies as geometry changes	Motors, linear variable differential transformers (position sensors)
Magnetostriction	Quadratic—material coupling between magnetic and mechanical fields	Sound sources, positioners
Eddy current	Nonlinear—material-dependent surface electrical resistance	Flaw detectors, proximity sensors
Piezoelectric	Linear—material coupling between electric and mechanical fields	Accelerometers, microphones
Pyroelectric	Nonlinear—material coupling between thermal and mechanical fields	Thermal imaging
Charged particle interactions	Linear—charged particles moving nonparallel to a magnetic field cause forces	Loudspeakers, computer disk head positioners
Hall effect	Linear—material coupling between nonparallel magnetic and electric fields	Position sensors
Variable conductivity	Nonlinear—conductivity changes through a fixed volume as material varies	Liquid-level sensors
Potentiometric	Linear—changes in energy dissipated due to motion of a potentiometer slide	Position sensors
Piezoresistive	Linear—material coupling between resistivity and mechanical field	Strain gauges
Thermoresistivity	Nonlinear—material coupling of electrical resistivity and temperature	Resistance temperature detectors, thermistors (temperature sensors)
Thermoelectricity	Linear—coupling of electric field and temperature differences (Peltier and Seebeck effects)	Thermocouples
Magnetoresistivity	Nonlinear—material coupling of resistance to magnetic field strength	Magnetic disk heads
Shape memory alloys	Nonlinear—material undergoes phase and shape change as temperature varies	Springs, biomedical actuators
Photoconductivity	Linear—material conductivity depends on light intensity	Position sensors
Photostriction	Linear—material coupling involving photovoltaic and piezoelectric effects combined	Light-driven relays

positioner components tout ranges of up to 0.2 mm and resolutions of nanometers or less. Thus the tradeoff is clearly high resolution for small range. One commercial actuator uses three piezoelectrics to move in steps of about 50 nm; it can achieve much greater ranges (up to hundreds of millimeters) but is slower than standard positioners because it repeats a clamping, extension, clamping and release operation.

Miniaturization

A clear trend in transduction is the extreme miniaturization of devices. Further, miniaturization is taken to be synonymous with the use of microelectronic fabrication techniques. The logic driving the production of silicon sensors and actuators deserves careful consideration, especially because the special electrical properties that silicon offers are not always relevant.

Sensors. To monitor a system without affecting it, one wants a sensor with a small footprint—that is, a small size and low power use. For sensors then, the push for extreme miniaturization has some compelling logic. A remaining question is whether miniaturization must lead to silicon sensors fabricated using very large scale integration (VLSI) approaches. In general, the arguments for solid-state sensors focus on three points: One can make features with smaller dimensions; electronics can be integrated with the sensors; costs can be cut by using mass production. However, it is not clear that these points resolve the miniature-sensor question in favor of silicon-based approaches, as opposed to electric discharge machining or ultrasonic machining, which work on a broader range of materials, including metals and ceramics. It is true, though, that compared to VLSI approaches, electric discharge machining and ultrasonic machining are slower, more costly and restricted to somewhat larger feature sizes.

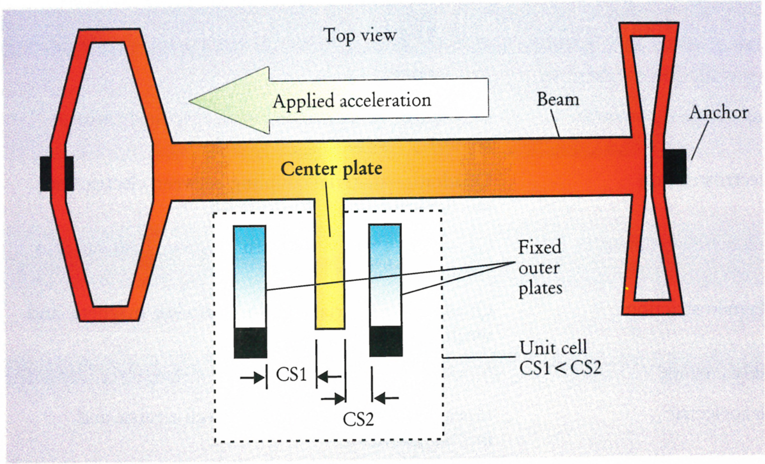

FIGURE 3. ACCELEROMETER SCHEME. This solid-state device is used as a crash sensor for airbag deployment in many automobiles. The actual sensor uses 46 unit cells (one is shown) and a common mechanical beam. Each cell contains two capacitors connected in series with a common, movable center plate. The two capacitors are driven by square voltage pulses 180 degrees out of phase so that there is no net signal when the center plate is midway between the fixed plates. A rapid deceleration causes a differential capacitance and a corresponding voltage signal. (Courtesy of Analog Devices Inc, Norwood, Mass.)

Microelectronic fabrication techniques do offer features of a size that is difficult or impossible to achieve by conventional methods. However, the range of dimensions they offer is small. In conventional processes, it is common to have features that are smaller than largest part dimensions by a factor of 10^5. For instance compact disks, which are made in a stamping process, are roughly 10 cm in diameter, while the features that encode information are roughly 1 μm in size—a size ratio of 10^5. Using microelectronics approaches, the same ratio is limited to between 10^3 and 10^4. Since range of operation tends to relate to sensor size while resolution relates to feature size, sensor performance can be negatively impacted by the more severe size ratio constraint.

Integrating electronics with a sensor on a single chip is a challenge. Microelectronic circuitry is two-dimensional, existing on the surface of a silicon substrate. By contrast, electromechanical transducers require a greater dimensionality, and hence different manufacturing techniques have been developed. Unfortunately, the fabrication techniques for transducer structures and for electronics are not wholly compatible. Thus, a desire to integrate the two on a single chip requires making compromises in each component that may not be acceptable in terms of performance or device yields. There is significant investment in research on new processing chemicals and techniques that offer greater sensor/electronics compatibility, and a few notable successes are emerging. A promising alternative to single-chip integration is multimodule integration, in which the sensor and electronics are on separate but electrically connected chips. Although this approach solves the compatibility problem, it is much more expensive than single-chip fabrication.

It is true that mass production of microelectronic circuits has greatly reduced the cost of electronics. Unfortunately, the same savings are not available for all sensors. Consider, for instance, the silicon microphone. This microphone must compete with the miniature electret microphone. An electret microphone is similar to a condenser microphone, but we replace the externally supplied DC bias voltage across the plates with a permanently polarized polymer film such as Teflon, which makes up one of the plates. This design means that electret microphones can operate without a power supply and with lower mass than their condenser microphone cousins. Estimates of the worldwide annual production of electret microphones are about 800 million devices. Sizes down to a couple of millimeters in diameter and costs as low as $5 including amplification are commercially available. Against this backdrop, solid-state microphones generally offer poorer performance in terms of signal-to-noise ratio and frequency response, and yet it is not clear that they can be made price competitive even when mass produced.[5] On the other hand, many sensors do benefit from mass production. For instance, the accelerometers used in airbag deployment are more than an order of magnitude less expensive than the smallest similar devices made using conventional techniques.

Using microelectronics fabrication for sensors requires accepting a paradigm in which the design is limited by options available in manufacture. This is distinctly different from conventional designs, in which fabrication alternatives are sufficiently rich that it is possible to focus on manufacturing *after* the design has been established. The distinction suggests that very different skills are needed for designing sensors on conventional scales and on microscopic scales.

There are certainly examples of successful microsensors. For instance, successful airbag deployment depends on operation of a crash sensor that responds very quickly. Virtually all of these automotive sensors are solid-state devices. Figure 3 is a schematic diagram of an accelerometer used in General Motors Corp and Honda Motor Co cars for airbag deployment. This device monitors the capacitances between a movable center plate and two fixed electrodes. In rapid deceleration, capacitance CS2 is much greater than CS1, and the airbag is deployed.

Actuators. Now consider miniaturization of electromechanical actuators. Driving a system suggests a device with a large footprint: large size and high power. Thus, miniaturization is not logical unless there are compelling geometric or application-specific constraints. Given this, the case for solid-state actuators is made by arguing in favor of large numbers of small actuators put into arrays. Historically, the question of single large actuators versus arrays of smaller actuators has been called the staging problem. The classic example is the problem of the analog watch, which could use either a separate motor to turn each of the hands, or a single motor with gearing. In general, which approach will prevail ought to be compelled by the specific application. Of course, even for those cases favoring multiple small actuators, it is not clear that fabrication in silicon is advisable.

There are two additions to the categories of difficulties already mentioned: delivering power and providing interconnections. The interconnection problem for power delivery and signal processing is challenging at the level of tens or hundreds of array elements. At the level of

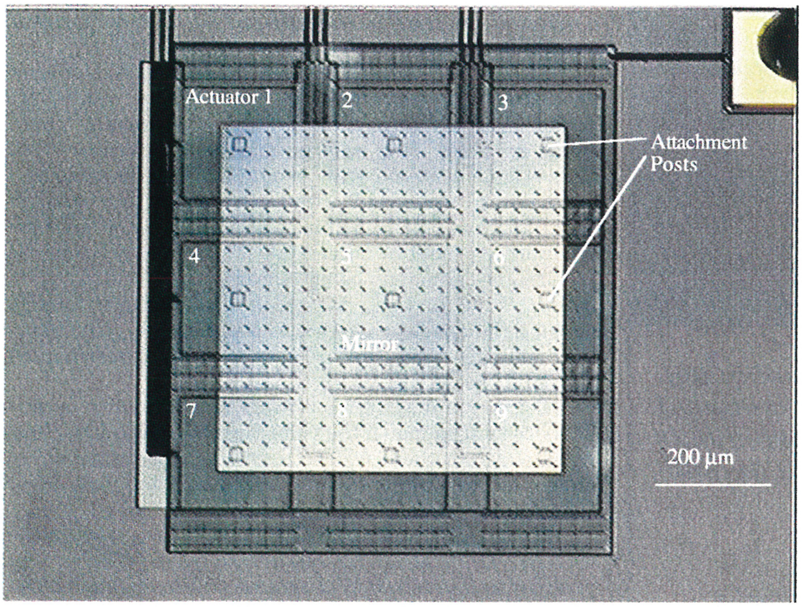

FIGURE 4. CONTINUOUS-MEMBRANE deformable mirror suitable for adaptive optics applications, made using microelectromechanical systems. This prototype is a nine-element square array of actuators attached to a single mirror 560 × 560 × 1.5 μm. Posts are used to suspend the mirror roughly 2 μm above the nine actuators. Using this approach and simple control systems, it is possible to correct for significant time-varying optical aberrations in real time.

thousands to millions of elements, this problem poses fundamental difficulties in reliability, speed and real estate. The power delivery issue poses additional complications of heat dissipation.

Despite the difficulties posed by microscopic actuators, a few compelling successes are emerging. For instance, Thomas Bifano and his coworkers at Boston University have developed a continuous-membrane deformable mirror suitable for adaptive optics applications.[6] Their prototype, shown in figure 4, is a nine-element square array of actuators attached to a single mirror (560 × 560 × 1.5 μm). The mirror is suspended roughly 2 μm above the nine actuators by posts. The small size of the actuators could make adaptive optics more tractable.

Focus on actuators

Controlling a system is generally more difficult than monitoring it. Hence, it is typically more challenging to design and build an actuator than a sensor. As a consequence, the progress in electromechanical sensors has outstripped that in actuators in the last decades. For instance, consider electric motors. Of the various types of electric motors available, the squirrel cage induction motor is the most common found in industry. In such a motor, the stator (fixed position) and rotor (rotating part) both use AC drives. The stator currents result from magnetic induction as the rotor conductors cut the magnetic field lines of the stator poles. Thus, there is no need for physical connection to the stator conductors. Because of its dominance in industry, the motivation for improving squirrel cage motors is substantial. However, the modern specifications—starting current of 480–900% of running current, starting torque of 100–300% of running torque, efficiency of 80–92%—match those given in texts back in the 1950s.

Modern improvements in electromechanical actuators have been few and far between, and so there is a growing focus on actuators, aiming to improve their speed, efficiency, size, reliability and cost. To date, most of this research has focused on either new materials for standard actuator geometries or slight modifications to geometries used in actuators. Unfortunately, significant improvements have not materialized from this work. Thus, researchers are now considering more dramatic changes. They include new actuation materials (for example, taking advantage of phase transitions to produce large forces), and radically different geometries that may offer some mechanical advantage over purely cylindrical or rectangular designs (for example, replacing the piezoelectric array in figure 2 with a single bowl-shaped actuator).

Rapid change

The pace of change is escalating dramatically. Consider, for example, the history of the piezoelectric effect in quartz. Jacques and Pierre Curie reported the phenomenon in 1880,[7] but it was not until 1921 that Paul Langevin produced the first patent for a transducer using it.[8] By contrast, consider the more recent creation of Terfenol, a rare earth magnetostrictive material. In magnetostrictive materials, the magnetic permeability is a strong function of the mass density, thus coupling mechanical and magnetic fields. The key US patent on Terfenol was granted in 1981.[9] Excluding the inventors, the first US patent to mention Terfenol in a device was applied for in 1984, just three years after the materials patent was issued.[10]

There are a few obvious reasons for the rapid change in the field of transduction: Technology is improving quickly, free information is accessible nearly instantaneously and the amount of money at stake is enormous. In general, the effects of rapid change on the field of transduction are the same as those seen in all sectors of industry: Design times are growing shorter, there is a rise of small and medium-sized companies to address niche needs and there is a growing variety in the transducers that are commercially available.

The future

Based on current trends, one can reliably make six major predictions about the future. First, the markets for sensors will continue to expand, particularly for sensors that are coupled with electronic controls. For example, current concern over the inappropriate activation of automobile airbags is resulting in the installation of turnoff switches, but only as a short-term solution. For the long term, significant research is already under way to develop additional sensors that will automatically determine whether a seat near an airbag is occupied and whether deployment should be initiated.

Second, the current tension between proponents of modularity and proponents of mechatronics will be resolved, probably with mutually exclusive areas of application for each. It is easy to imagine, for example, that high-volume products with noncritical specifications will move toward standard transducers that are purchased in bulk. Toys are classic examples of products in which such an approach could be successful. On the other hand, the performance demands being placed on high-end products will continue to rise. As those demands are already pushing the envelope of what is feasible, it is quite likely that meeting them will require a move toward more custom devices.

Third, the market for sensors and actuators is very likely to shift to match the changing world economy. This trend suggests there will be a growing concentration on biomedical applications and on consumer products other than the automobile.

Fourth, eventually there will have to be a more logical view prevailing about the role of size scales. The current push for miniaturization of sensors will undoubtedly continue, and rules will emerge for when the staging problem is best solved by one actuator, or by many, small actuators.

Fifth, it is clear that progress in electromechanical actuation is stalled. Given that the history of transduction is steeped in the exploitation of new materials and geometries, one may anticipate that advances will be achieved through the collaborative efforts of materials scientists and transducer designers. This approach led to the creation of Terfenol, one of the first new and significantly useful transducer materials to emerge in decades.

Finally, there will be a continuing reduction in the time that elapses between new technologies and materials being developed and the production of sensors and actuators incorporating them. Particularly as the market for transducers moves more toward the high-volume consumer market, one can anticipate that being first with a new device will become increasingly important.

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