Ceramics and Society
R.J. Brook (Editor)

SMART CERAMICS

Robert E. Newnham
(Pennsylvania State University)

ABSTRACT

"Smart" ceramics have the ability to perform both sensing and actuating functions. Passively smart materials respond to external change in a useful manner without assistance, while actively smart materials have a feedback loop which allows them to both recognize the change and initiate an appropriate response through an actuator circuit.

One of the techniques used to impart intelligence into materials is "Biomimetics," the imitation of biological functions in engineering materials. Composite ferroelectrics fashioned after the lateral line and swim bladders of fish are used to illustrate the idea. "Very Smart" materials, in addition to sensing and actuating, have the ability to "learn" by altering their property coefficents in response to the environment. Field-induced changes in the nonlinear properties of relaxor ferroelectrics and soft rubber are utilized to construct tunable transducers. Integration of multifunctional ferroic ceramics into compact, robust packages is a major goal in the development of smart materials.

INTRODUCTION

It has been said that life itself is motion, from the single cell to the most complex organism: the human body. This motion, in the form of mobility, change, and adaptation, is what elevates living beings above the lifeless forms [1]. This concept of creating a higher form of materials and structures by providing the necessary life functions of sensing, actuating, control, and intelligence to those materials is the motivation for studying smart materials.

Smart materials are part of smart systems - functional materials for a variety of engineering applications. Smart medical systems for the treatment of diabetes with blood sugar sensors and insulin delivery altering their shape in response to air pressure and flying speed. Smart toilets that analyze urine as an early warning system for health problems. Smart structures in outer space incorporating vibration cancellation systems that compensate for the absence of gravity and prevent metal fatigue. Smart toys like "Altered Beast" where one is awakened from the dead and must learn to survive in the hostile environment of a different age. Smart houses with electrochromic windows that control the flow of heat and light in response to weather changes and human activity. Smart tennis rackets with rapid internal adjustments for overhead smashes and delicate drop shots. Smart muscle implants made from rubbery gels that respond to electric fields, and smart dental braces made from shape memory alloys. Smart hulls and propulsion systems for navy ships and submarines that detect flow noise, remove turbulence, and prevent detection. Smart water purification systems that sense and remove noxious pollutants. A number of smart systems have already been developed for automobiles, but there are many more to come. In a recent newspaper cartoon, Blondie and Dagwood encountered a smart automobile that drives itself back to the finance company when the owner misses a payment!

In this chapter the idea of "smartness" in a material is discussed, along with a number of examples involving ferroelectric components. Some of these smart ceramics are in production, while others have great potential but are thus far limited to laboratory investigations.

To begin our discussion, we first define "smart" to set the limits for classifying smart materials.

HOW SMART IS SMART?

The short answer is "not very". Webster's dictionary gives several definitions for the word SMART, including "alert, clever, capable," "stylish," and "to feel mental distress or irritation." All three definitions are appropriate for the currently fashionable subject, "smart materials." They are "stylish," they are - in some cases - "clever," and it does cause some of us "mental distress" to think that a ceramic might somehow possess intelligence, even in rudimentary form.

There are many words in the English language denoting various degrees of intelligence. Beginning at the bottom, an intelligence scale might look like this: stupid - dumb - foolish - trivial - sensible - smart = clever - intelligent - wise. Many modern day materials have been cleverly designed to carry out useful functions and, in some cases, that we are justified in calling them "smart." They are decidedly better than "sensible" materials, but calling them "intelligent" seems rather presumptuous and self-serving. Perhaps in the future, when we are able to integrate information - processing and feedback circuitry into our sensor and actuator materials, perhaps then we will be justified in calling our materials "intelligent." As pointed out later, such a time is not far off.

To clarify the concept of smart materials, we describe a few examples of passive and active smartness.

PASSIVE SMARTNESS

A passively smart material has the ability to respond to environmental conditions in a useful manner. A passively smart material differs from an actively smart material in that there are no external fields or forces or feedback systems used to enhance its behavior. The "S" words in Table I summarize some of the meanings of passive smartness.

Table I. Some Attributes of Passive Smartness

Selectivity
Self Diagnosis
Self Tuning
Sensitivity
Shapeability
Self Recovery
Simplicity
Self Repair
Stability and Multistability
Stand-by Phenomena
Survivability
Switchability

Many passively smart materials incorporate self-repair mechanisms or stand-by phenomena which enable the material to withstand sudden changes in the surroundings. The crack-arresting mechanisms in partially stabilized zirconia are a good example. Here the tetragonal-monoclinic phase change accompanied by ferroelastic twin wall motion are the stand-by phenomena capable of generating compressive stresses at the crack tip. In a similar way, toughness can be improved by fiber pull-out or by multiple crack-branching as in the structural composites used in aircraft, or in machinable glass-ceramics.

Ceramic varistors and PTC thermistors are also passively smart materials. When struck by high-voltage lightning, a zinc oxide varistor loses most of its electrical resistance and the current is by-passed to ground. The resistance change is reversible and acts as a stand-by protection phenomenon. Varistors also have a self-repair mechanism in which its highly nonlinear I-V relationship can be restored by repeated application of voltage pulses. Barium titanate PTC thermistors show a very large increase in electrical resistance at the ferroelectric phase transformation near 130°C. The jump in resistance enables the thermistor to arrest current surges, again acting as a protection element. The R(V) behavior of the varistor and the R(T) behavior of the PTC thermistor are both highly nonlinear effects which act as standby protection phenomena, and make the ceramics smart in a passive mode.

ACTIVE SMARTNESS

A smart ceramic can also be defined with reference to sensing and actuating functions, in analogy to the human body. A smart ceramic senses a change in the environment, and using a feedback system, makes a useful response. It is both a sensor and an actuator. Examples include vibration damping systems for outer space platforms and electrically-controlled automobile suspension systems using piezoelectric ceramic sensors and actuators.

The Piezoelectric Pachinko machine illustrates the principle of an actively smart material. Pachinko Parlors with hundreds of vertical pinball machines are very popular in Japan. The Piezoelectric Pachinko game constructed by engineers at Nippon Denso is made from PZT multilayer stacks which act as both sensors and actuators. When a ball falls on the stack the force of impact generates a piezoelectric voltage. Acting through a feedback system, the voltage pulse triggers a response from the actuator stack. The stack expands rapidly throwing the ball out of the hole, and the ball moves up a spiral ramp during a sequence of such events. Eventually, it falls into a hole and begins the spiral climb all over again.

A video tape head positioner developed by Piezoelectric Products, Inc., operates on a similar principle. A bilaminate bender made from tape-cast PZT ceramic has a segmented electrode pattern dividing the sensing and actuating functions of the positioner (Fig. 1). The voltage across the sensing electrode is processed through the feedback system resulting in a voltage across the positioning electrodes. This causes the cantilevered bimorph to bend, following the video tape track path. Articulated sensing and positioning electrodes operating at 450Hz near the tape head help keep the head perpendicular to the track.

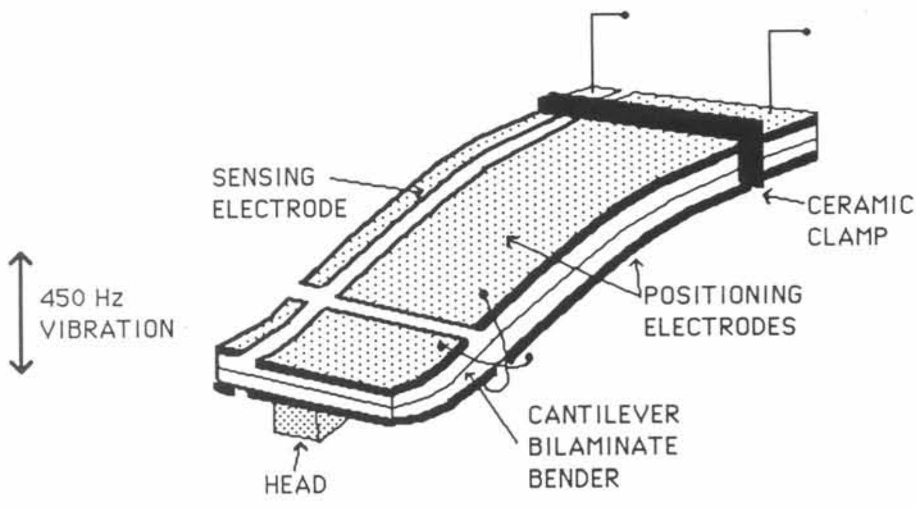

Fig. 1. Video tape head positioner made from PZT bimorph with sensor and actuator divided electrodes.

These two examples illustrate how a smart ceramic operates. Both sensing and actuating functions are involved in its performance, and while the Japanese scientists have a somewhat different perspective on "smart" or "intelligent" materials [2], the end results of efforts in this area are very similar.

RUBBER-LIKE CERAMICS

Every baseball and cricket player knows the importance of "soft hands." In catching a baseball, it is important to withdraw the hands slightly on making contact with the ball. This reduces the momentum of the ball gradually and creates a soft landing. Soft landings are achieved on ceramics in the same way, making them feel as soft as rubber.

To test the concept, controlled compliance experiments have been carried out using PZT sensors and actuators.[3] In the test set-up, one actuator is used as the external driver, and the other as the responder. Sandwiched between the two actuator stacks are two sensors and a layer of rubber. The upper actuator is driven at a frequency of 100 Hz and the vibrations are monitored with the upper sensor. The pressure wave emanating from the driver passes through the upper sensor and the rubber separator and impinges on the lower sensor. The resulting signal is amplified using a low noise amplifier and fed back through a phase shifter to the lower actuator to control the compliance.

A smart sensor-actuator system can mimic a very stiff solid or a very compliant rubber. This can be done while retaining great strength under static loading, making the smart material especially attractive for vibration control.

If the phase of the feedback voltage is adjusted to cause the responder to contract in length rather than expand, the smart material mimics a very soft, compliant substance. This reduces the force on the sensors and partially eliminates the reflected signal. The reduction in output signal of the upper sensor is a measure of the effectiveness of the feedback system. In our experiments, the compliance of the actuator-sensor composite was reduced by a factor of six compared to rubber.[3]

MODULATED SUSPENSION SYSTEMS

The automobile industry is a very large market in which smart composites and sensors are already widely used. More than fifty electroceramic components can be found in today's high-tech autos, ranging from the air-fuel oxygen sensors used in most autos to the more exotic piezoelectric raindrop sensor, which automatically senses the amount of rain falling and adjusts the windshield wipers to the optimum speed.[4]

Controlled compliance with piezoelectric ceramics is utilized in Toyota's piezoTEMS (Toyota Electronic Modulated Suspension), a system which has been developed to improve the drivability and stability of the automobile, and at the same time enhance passenger comfort.[5] The TEMS is basically a road stability sensor and shock adjustor, which detects bumps, dips, rough pavement, and sudden lurches by the vehicle, then rapidly adjusts the shock absorbers to apply a softer or firmer damping force, depending on what is necessary to minimize discomfort while maintaining control of the vehicle. The shock absorbers are continuously readjusted as the road conditions change so that rocking or wobbling on soft shocks is eliminated.

The TEMS road surface sensor consists of a five-layer piezoelectric ceramic sensor mounted on the piston rod of the shock absorber (Fig. 2). When a bump in the road is encountered, the

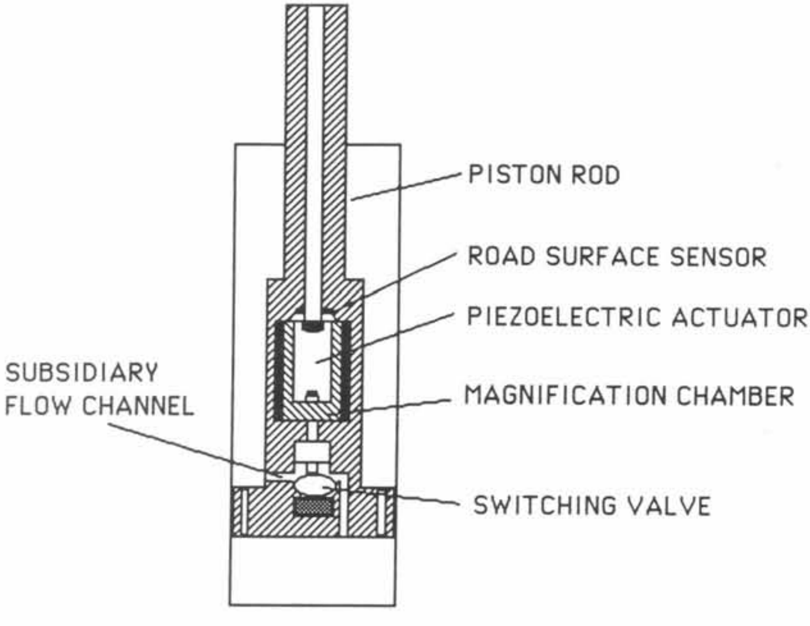

Fig. 2. Cross-section of the principal portion of the shock absorber.

resulting stress applied to the sensor produces a voltage which is fed into an electronic control unit that amplifies the signal and supplies a high voltage to the piezoelectric actuator. The 88-layer PZT actuator produces a 50 μm displacement on the oil system which is hydraulically enlarged to two millimeters, enough to change the damping force from firm to soft; the entire process takes only about twenty milliseconds (not even enough time to slam on the brakes!) Also figured into the actuator output are the vehicle speed and the driver's preference for a generally softer (American) or firmer (European) ride.

Alternatively, it is possible to damp stresses and vibrations without the need for a sensor-actuator feedback loop; materials which can perform this function are called passive damping materials. In a piezoelectric passive damper, a piezoelectric ceramic is connected in parallel with a properly matched resistor. The external stress creates a polarization in the piezoelectric, which induces a current in the resistor, leading to energy dissipation. A high piezoelectric coupling coefficient is required to induce the maximum voltage and energy dissipation.[6]

ACTUATOR MATERIALS

There are many approaches to controlling vibration and structural deformation. Actuation strain can be controlled by piezoelectric materials,[7] electrostrictive materials,[8] magnetostrictive materials,[9] shape-memory metal alloys,[10] and thermally-controllable materials.[11] Utilizing a system with distributed actuators, it is possible to design structures with intrinsic vibration and shape control capabilities. Among the most important actuator materials are shape memory metals and ceramics. The shape memory effect is exhibited by alloys which undergo thermoelastic martensite transformations. This is a first order displacive transformation in which a body centered cubic metal transforms by shear on cooling to a martensitic phase. When deformed in the martensitic low temperature phase, shape memory alloys will recover this deformation and return to the original shape when heated to a temperature where the martensite reverts back to the parent body-centered cubic structure. Unlike most ferroelectric and ferromagnetic transitions, the shape memory transformation has a large hysteresis which can be troublesome in practice.

Alloys exhibiting the shape memory effect fall into two general classes: non-ferrous and ferrous. Non-ferrous alloys currently in commercial use are Ni-Ti, Cu-Zn-Al, and Cu-Ni-Al. Ferrous shape memory alloys under development include Fe-Pt, Fe-Ni-C and Fe-Ni-Co-Ti.

Non-ferrous shape memory alloys of nickel-titanium alloy (Nitinol) have been developed by Goodyear Aerospace Corporation for spacecraft antennae.[10] A wire hemisphere of the material is crumpled into a tight ball, less than five centimeters across. When heated above 77°C, the ball opens up into its original shape--a fully formed antenna. Although it has seldom been used in service, this antenna demonstrates the magnitude of deformation and reformation possible in shape memory alloys.

While shape memory alloys are more like a solution looking for a problem, it has been suggested that transient and steady state vibration control can be accomplished with hybrid structures in which the shape memory alloy is embedded inside the material[12].

Some ceramic materials also possess a sizeable shape-memory effect; of particular interest are materials which are simultaneously ferroelectric and ferroelastic. Their ferroelasticity ensures that recoverable spontaneous strain is available for contributing to the shape memory effect, and the ferroelectricity implies that their spontaneous strain can be manipulated not only by mechanical forces but also by electric fields.

Shape-memory has been demonstrated in PLZT ceramics, an important ferroelectric-ferroelastic because of the tremendous potential for applications due to the formation of microdomains smaller than the wavelength of light. In one experiment, a 6.5/65/35 PLZT helix was heated to 200°C, well above the transition temperature for recovery, T_F (= T_C), then mechanically loaded and cooled to 38°C (well below T_F) - the "brittle" PLZT helix was deformed by 30% after the load was removed. Upon heating to 180°C, above T_F, the helix transformed back to its original shape, dramatically demonstrating the shape memory effect in brittle ceramics.[13]

Researchers at Sophia University in Tokyo have created a multilayer shape memory actuator with a (Pb, Nb)(Zr, Sn, Ti)O_3 ceramic. Twenty rectangular plates of the ceramic were stacked in an MLCC-type structure; the magnitude of the strains that were induced were small by comparison to most shape memory alloys (3-4 microns) but were three times larger than the strains produced using conventional piezoelectric actuators. In this case, a ferroelectric to antiferroelectric phase change is responsible for the shape change.[14]

ELECTRORHEOLOGICAL FLUIDS

One of the criteria which separates "smart" materials from "very smart" or "intelligent" materials is the ability of the material to not only sense a change and actuate a response, but to automatically modify one or more of its property coefficients during the sensing/actuating process. In effect, this type of material not only warns the user of a change in its environmental conditions and responds to it, but can in addition adjust itself to compensate for future change.

Electrorheological (ER) fluids [15] and their magnetic analog, ferrofluids,[16] are an example of materials that have great potential for use in smart materials and systems. ER fluids are typically suspensions of fine particles in a liquid medium; the viscosity of the suspension can be changed dramatically by applying an electrical field. The electric field causes alignment of the particles in fibril-like branches in the direction of the applied field. The alignment disappears when the electric field is removed, thus creating the desired property of complete cyclic reproducibility.

ER fluids represent an advanced class of composite materials with self-tuning properties, that will find considerable use in vibration control applications. In addition, the compatibility of this technology with modern solid state electronics makes it an attractive component for integration into multifunction, self-contained smart material packages.

BIOMIMETICS - FISH EARS

The word "biomimetic" is not found in most dictionaries so it needs to be defined. It comes from the Greek words "bios," meaning "life," and "mimetikos," meaning "to imitate." Biomimetic means to imitate life, or to use the biological world as a source of ideas for device concepts.

Fish and the other inhabitants of the underwater world have some interesting ways of talking and listening which have been copied using piezoelectric ceramics.

For most fish, the principal sensors are the lateral line and the inner ear coupled to the swim bladder. The pulsating swim bladder also acts as a voice, as do chattering teeth in certain fish species.

The lateral line runs fom the head to the tail of the fish and resembles a towed array with sensing organs (stitches) spaced at intervals along the nerve fiber. Each stitch contains several neuromasts made up of gelatinous cupulae resembling pimples in shape, within each cupula are several fibers which vibrate as the fish swims through water and acts as sensors for flow noise. The hair-like fibers are extremely thin in diameter ranging from 0.5 to 10 μm. When stimulated by turbulence, the motion of the hairs produces changes in the synapses which are in turn connected to the nerve fiber. The electric signal originates from impedance changes in cell walls which modulate the flow of K^+ ions. The lateral line is especially sensitive to low frequency fluid motion parallel to the length of the fish. In the 50 Hz range, threshold signals are observed for displacements as small as 30 nm! [17,18]

The 1-3 composite hydrophones described later are patterned after the hair-filled cupulae of the lateral line. Thin PZT fibers embedded in polymer provide excellent electromechanical coupling to a liquid medium and can be used as both sensors and actuators.

DR. DOLITTLE AND FISH TALK

Among the most popular children's books of all time are the Doctor Dolittle books written by Hugh Lofting. Doctor Dolittle could talk to the animals. He started with "Pig" and went on to "Duck" and "Cow", and eventually mastered 498 languages. There is a marvelous scene in the movie where young Tommy Stebbins meets Dr. Dolittle in his laboratory and watches him talk to goldfish by blowing bubbles in the fish bowl through a rubber tube. Between bursts of bubbles, Dr. Doolittle listened intently to through a stethoscope pressed against the side of the bowl.

In recent years, great advances have been made in recording and understanding fish talk, largely because of the development of improved hydrophone arrays and high speed spectrum analyses. Much of the talk is in the form of low frequency grunts below 200Hz. Sound functions in a variety of ways for fish, both in offense and in defense, for warning and intimidation. Many fish speak differently during breeding season, and appear to use coded repetition rates to communicate. Our ability to "farm the oceans" could be greatly enhanced by learning how to talk to fish and control their movements and feeding habits.

Although they do not possess a larynx, many species of fish produce high-pitched sound by grinding their teeth, but the vibration of the swim bladder wall provides the greatest repertoire of noises or calls. The croakers of Chesapeake Bay make tapping noises like a woodpecker, by contracting their drumming muscles attached to the swim bladder, and the twilight choruses of sea robins caused great confusion among the operators of antisubmarine echo-location devices during World War II.[19]

INNER EARS AND SWIM BLADDERS

The nature of sound transmission in water has had a great influence on the evolution of hearing in fish. Sound, especially low frequency sound, travels faster and farther than in air. "Near-field" sound consists of small fluid motions or vibrations and are characterized by a displacement direction. They are detected by the inner ear or by the lateral line. The hydrostatic component or "far-field" sound is detected best through the swim bladder.

The inner ear is made up of inertia-sensing chambers resembling accelerometers. Within each chamber is a dense ear stone (otolith) which vibrates in a near-field sound wave. The inertia of the ear stone causes it to lag behind the motion of the fish, and to push against hair cells which line the chamber (sacculus). On bending, the hair cellular membranes deform, stimulating neural transmissions to the brain. Connections to the swim bladder improve the sensitivity to far-field sound.

The primary function of the gas-filled swim bladder is to provide buoyancy, but it is also used for sound and pressure reception and in some species is equipped with drumming muscles for sound production. The flexible swim bladder responds to hydrostatic pressure waves by changing volume. Fish with swim bladders can perceive relative pressure changes equivalent to less than 0.5% of the ambient hydrostatic pressure. Direct or indirect linkages from the swim bladder to the inner ear promote the hearing sensation. Fish with no connections perceive low frequency sound (less than 500 Hz), while those with good connections have an upper frequency response of 5000 Hz. As might be expected, the swim bladder is reduced in size with depth, and loses much of its sensitivity as a sensor.

HYDROPHONE MATERIALS

The knowledge which comes from the understanding of "fish talk" can be directly applied to research in materials destined to someday "sleep with the fishes". Hydrophones are underwater listening devices made from piezoelectric materials which respond to hydrostatic pressure waves. Among the applications for hydrophones are sonar systems for submarines, off-shore oil platforms, geophysical prospecting equipment, fish finders, and earthquake monitors.

As the earth's population continues to increase, mankind must continue to search for new and efficient sources of food and nutrition. The world's oceans may provide a solution to this problem, not only through fish farming but through the use of new and varied salt water vegetation that could provide an abundant source of food, especially for third world countries in which poor soil and harsh climates prohibit conventional farming. Smart hydrophone transceivers will receive and transmit fish talk and monitor the growth of underwater vegetation.

The figure of merit for hydrophone materials is the product of the hydrostatic piezoelectric charge coefficient (d_h) and the piezoelectric voltage coefficient (g_h). While good piezoelectric materials such as PZT have high d_{33} and d_{31} piezoelectric coupling coefficients, the d_h value is only about 45 pC/N because d_{33} and d_{31} are opposite in sign, and $d_h = d_{33} + 2d_{31}$. $d_h g_h$ is also inversely related to the dielectric permittivity, e_{33}, so that low dielectric constants are desirable as well.

Rather than abandon PZT in search of the ultimate hydrophone material, avoiding this problem is often a matter of appropriate engineering of existing materials. Too often in the field of materials research we put too much emphasis on the synthesis of new materials and too little emphasis on new and unique designs for old materials.

A composite design with 1-3 connectivity is similar in design to the hair-filled gelatinous cupula with thin PZT rods embedded in a polymer matrix. The 1-3 piezocomposites have excellent sensitivity to pressure waves in water [20,21]. The large d_{33} is maintained because the parallel connection results in stress transfer from polymer to piezoceramic, while the d_{31} is destroyed because of series connection in the lateral dimension where the mechanical load is absorbed by the polymer and not transferred to the PZT rods. Finally, ε_{33} is minimized due to the large volume of low ε_{33} polymer present. The $d_h g_h$ values are improved by more than an order of magnitude when very thin rods are used.

Another piezoelectric hydrophone composite maximizes d_h by simply redirecting the applied stresses using specially shaped electrodes [22]. These are flextensional transducers which mimic the motions of the swim bladder. Shallow air spaces are positioned under the metal electrodes while the PZT ceramic plays the role of the muscle lining the swim

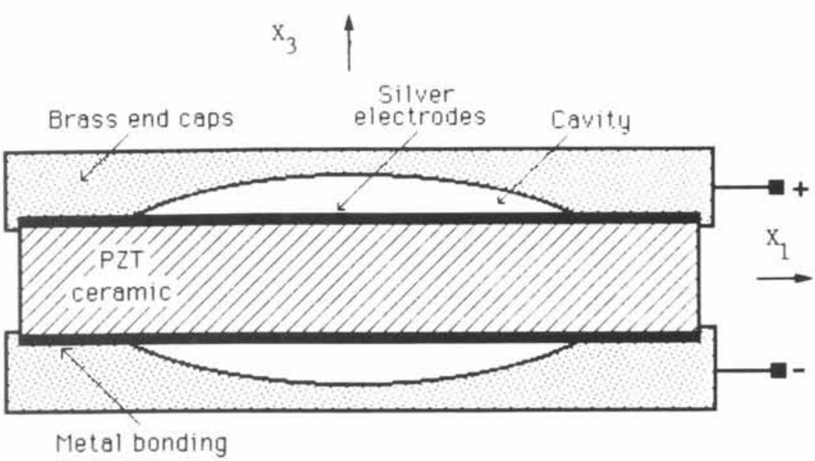

Fig. 3. Composite moonie actuator.

bladder (Fig. 3). When subjected to a hydrostatic stress, the thick metallic electrodes convert a portion of the z-direction stress into large radial and tangential stresses of opposite signs. The result is that d_{31} changes from negative to positive, so that its contribution now adds to d_{33} rather than subtracting from it. The $d_h g_h$ of these composites is approximately 250 times that of pure PZT.

VERY SMART COMPOSITES: THE TUNABLE TRANSDUCER

By building in a learning function, the definition of a smart material can be extended to a higher level of intelligence:

A very smart material senses a change in the environment and responds by changing one or more of its property coefficients. Such a material can tune its sensor and actuator functions in time and space to optimize future behavior. With the help a feedback system, a very smart material becomes smarter with age, something even human beings strive for. The distinction between smart and very smart materials is essentially one between linear and nonlinear properties. The physical properties of nonlinear materials can be adjusted by bias fields or forces to control response.

To illustrate the concept of a very smart material, we describe the tunable transducer recently developed in our laboratory. Electromechanical transducers are used as fish finders, gas igniters, ink jets, micropositioners, biomedical scanners, piezoelectric transformers and filters, accelerometers, and motors.

Five important properties of a transducer are the resonant frequency f_r, the acoustic impedance Z_A, the mechanical damping coefficient Q, the electromechanical coupling factor k, and the electrical impedance Z_E. The resonant frequency and acoustic impedance are controlled by the elastic constants and density, as discussed in the next section. The mechanical Q is governed by the damping coefficient (α) and is important because it controls "ringing" in the transducer. Definitions of the coefficients are given in Table II.
Electromechanical coupling coefficients are controlled by the piezoelectric coefficient which, in turn, can be controlled and fine-tuned using relaxor ferroelectrics with large electrostrictive effects. The dielectric "constant" of relaxor ferroelectrics depends markedly on DC bias fields, allowing the electrical impedance to be tuned over a wide range as well. In the following sections we describe the nature of nonlinearity and how it controls the properties of a tunable transducer.

ELASTIC NONLINEARITY: TUNING THE RESONANT FREQUENCY

Information is transmitted on electromagnetic waves in two ways: amplitude modulation (AM) and frequency modulation (FM). There are a number of advantages to FM signal processing, especially where lower

Table II. Important characteristics of an electromechanical transducer.

Fundamental resonant frequency, f, of the thickness mode

$$f = \frac{1}{2t}\sqrt{c/p}$$

t = thickness dimension

c = elastic stiffness

r = density

Acoustic Impedance Z_A

$$|Z_A| = \sqrt{pc}$$

Mechanical Q

$$Q = \pi/\lambda_a \alpha$$

λ_a = acoustic wavelength

α = damping coefficient

Electromechanical coupling coefficient k

$$k = d\sqrt{c/\varepsilon}$$

d = piezoelectric charge coefficient

ε = electric permittivity

Electrical impedance Z_e

$$|Z_e| = t / \omega\varepsilon A$$

ω = angular frequency

A = electrode area

---

noise levels are important. Atmospheric static is considerably lower in FM radio than in AM.

Signal-to-noise ratios are also important in the ultrasonic systems used in biomedical and nondestructive testing systems, but FM-modulation is difficult because resonant frequencies are controlled by stiffness (c) and transducer dimensions (t). Neither c, t, nor the density (ρ) can be tuned significantly in ceramics and most other materials, but rubber is an exception. To tune the resonant frequency of a piezoelectric transducer, we designed and built a composite transducer incorporating thin rubber layers exhibiting nonlinear elasticity.[23]

Rubber is a highly nonlinear elastic medium. In the unstressed compliant state, the molecules are coiled and tangled, but under stress the molecules align and the material stiffens noticeably. Experiments carried out on rubber-metal laminates demonstrate the size of the nonlinearity. Young's modulus ($E = 1/s_{1111}$) was measured for a multilayer laminate consisting of alternating steel shim and soft rubber layers each 0.1 mm thick. Under compressive stresses of 200 MPa, the stiffness is quadrupled from about 600 to 2400 MPa.[24] The resonant frequency f is therefore doubled, and can be modulated by applied stress.

Rubber, like most elastomers, is not piezoelectric. To take advantage of the elastic nonlinearity, it is therefore necessary to construct a composite transducer consisting of a piezoelectric ceramic (PZT) transducer, thin rubber layers, and metal head and tail masses, all held together by a stress bolt.

The resonant frequency and mechanical Q of such a sandwich structure has been measured as a function of stress bias. Stresses ranged from 20 to 100 MPa in the experiments. Under these conditions the radial resonant frequency changed from 19 to 37 kHz, approximately doubling in frequency as predicted from the elastic nonlinearity. At the same time the mechanical Q increases from about 11 to 34 as the rubber stiffens under stress.

The changes in resonant frequency and Q can be modeled with an equivalent circuit in which the compliance of the thin, rubber layers are represented as capacitors coupling together the larger masses (represented as inductors) of the PZT transducer and the metal head and tail masses. Under low stress bias, the rubber is very compliant and effectively isolates the PZT transducer from the head and tail masses. At very high stress, the rubber stiffens and tightly couples the metal end pieces to the resonating PZT ceramic. For intermediate stresses the rubber acts as an impedance transformer giving parallel resonance of the PZT - rubber - metal -radiation load.

Continuing the biomimetic theme, it is interesting to compare the change in frequency of the tunable transducer with the transceiver systems used in the biological world. The biosonar system of the flying bat is similar in frequency and tunability to our tunable transducer. The bat emits chirps at 30 kHz and listens for the return signal to locate flying insects. To help it differentiate the return signal from the outgoing chirp, and to help in timing the echo, the bat puts an FM signature on the pulse. This causes the resonant frequency to decrease from 30 to 20 kHz near the end of each chirp. Return signals from the insect target are detected in the ears of the bat where neural cavities tuned to this frequency range measure the time delay and flutter needed to locate and identify its prey. Extension of the bat biosonar principle to automotive, industrial, medical and entertainment systems is underway.

PIEZOELECTRIC NONLINEARITY: TUNING THE ELECTROMECHANICAL COUPLING COEFFICIENT

The difference between a smart and a very smart material can be illustrated with piezoelectric and electrostrictive ceramics. PZT (lead zirconate titanate) is a piezoelectric ceramic in which the ferroelectric domains have been aligned in a very large poling field. Strain is linearly proportional to electric field in a fully poled piezoelectric material which means that the piezoelectric coefficient is a constant and cannot be electrically tuned with a bias field. Nevertheless it is a smart material because it can be used both as a sensor and an actuator.

PMN (lead magnesium niobate) is not piezoelectric at room temperature because its Curie temperature lies near 0°C. Because of the proximity of the ferroelectric phase transformation, however, and because of its diffuse nature, PMN ceramics exhibit very large electrostrictive effects.

Electromechanical strains comparable to PZT can be obtained with electrostrictive ceramics like PMN, and without the troubling hysteretic behavior shown by PZT under high fields. The nonlinear relation between strain and electric field in electrostrictive transducers can be used to tune the piezoelectric coefficient and the dielectric constant.

The piezoelectric d_{33} coefficient is the slope of the strain-electric field curve when strain is measured in the same direction as the applied field. Its value for $Pb(Mg_{0.3}Nb_{0.6}Ti_{0.1})O_3$ ceramics is zero at zero field and increases to a maximum value of 1300 pC/N (about three times larger than PZT) under a bias field of 3.7 kV/cm .

This means that the electromechanical coupling coefficient can be tuned over a very wide range, changing the transducer from inactive to extremely active. The dielectric constant also depends on DC bias. The polarization saturates under high fields causing decreases of 100% or more in the capacitance. In this way the electrical impedance can be controlled as well.

Electrostrictive transducers have already been used in a number of applications including adaptive optic systems, scanning tunneling microscopes, and precision micropositioners [8].

To summarize, two types of nonlinearity are utilized in the fully tunable transducer: elastic nonlinearity and piezoelectric nonlinearity. By incorporating thin rubber layers in an electrostrictive transducer several important properties can be optimized with bias fields and bias stresses. Electromechanical coupling coefficients and electric impedance are tuned with electric field, and mechanical damping, resonant frequency, and acoustic impedance with stress bias.

SMART ELECTROCERAMIC PACKAGES

Up to this point, our discussion has focused primarily on piezoelectric transducers in which the sensing and actuating functions are electromechanical in nature. But the idea of a smart material is much more general than that. There are many types of sensors and many types of actuators, and many different feedback circuits (Fig. 4).

Many of these sensors and actuators can be fabricated in the form of multilayer ceramic packages. Until recently multilayer packages consisted of low permittivity dielectric layers with metal circuitry printed on each layer and interconnected through metallized via holes between layers. Buried capacitors and resistors have now been added to the three-dimensional packages, and other components will follow shortly. Smart sensors, adaptive actuators, and display panels, together with thermistors and varistors to guard against current and voltage overloads, are next in line for development.[25]

Integration and miniaturization of electroceramic sensors and actuators is an ongoing process in the automotive and consumer

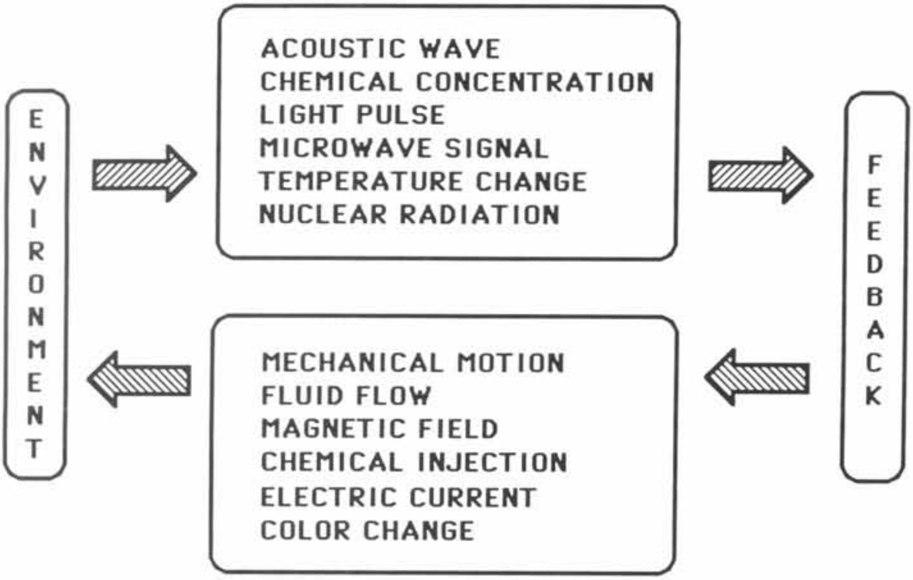

Fig. 4. Schematic of smart possibilities for smart electroceramic packages. Smart devices bring together a number of sensor-actuator combinations.

electronics areas. Multilayer packages containing signal processing layers made up of low-permittivity dielectrics and printed metal interconnections are in widespread production. Further integration with embedded resistors and capacitors are under development, and its seems likely that intelligent systems will make use of the same processing technology. Tape casting and screen printing are used most often. Varistors, chemical sensors, thermistors, and piezoelectric transducers can all be fabricated in this way, opening up the possibility of multicomponent, multifunction ceramics with both sensor and actuator capabilities (Fig. 5). Silicon chips can be mounted on these multifunctional packages to provide all or part of the control network. Processing is a major challenge because of the high firing temperatures of most ceramics, typically in the range 800°C to 1500°C. Differences in densification shrinkage and thermal contraction, together with adverse chemical reactions between the electroceramic phases, create formidable problems. Nevertheless, the rewards for such an achievement

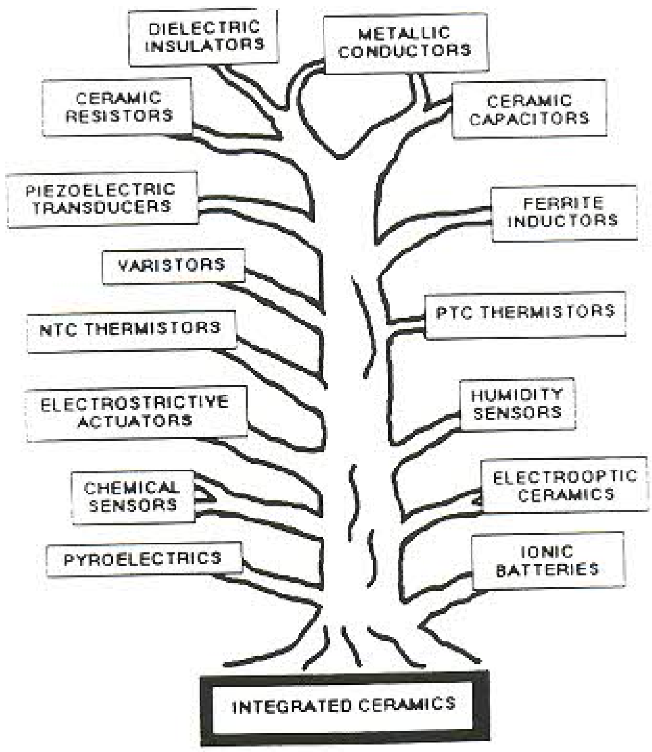

Fig. 5. Integrated ceramic packages of the future will incorporate many different components.

are substantial. An all-ceramic multifunction package would be small, robust, inexpensive, and sufficiently refractory to withstand elevated temperatures.

Electrodes are both a problem and a challenge. At present, precious metals such as palladium and platinum are used in multilayer ceramic components, greatly adding to the cost of the device. Copper and nickel electrodes require that the ceramic be fired in a reducing atmosphere, which may reduce the electroceramic layers and adversely affect the electrical properties. Copper and silver have high electrical conductivity but the melting points (~1000°C) require lower firing temperatures and make it necessary to alter the ceramic compositions and fabrication procedures. Some headway has been made on this problem, but further work is needed. One interesting approach to the problem is ceramic electrodes. There are a number of ceramic phases with excellent conductivity which could be used, including the copper-oxide superconductors. In actuator devices, there are some special advantages in having electrodes and piezoceramics with matched elastic properties.

Composites are another approach to making sensor-actuator combinations. These can be formed at lower temperatures using low-firing ceramics and high temperature polymers such as polyimides. Sol-gel and chemical precipitation methods are helpful in preparing ceramic powders with low calcining temperatures, but further work on composite fabrication is required to obtain reliable and reproducible electrical behavior.

To miniaturize the sensors and actuators, and to obtain complex shapes, we recommend the use of photolithography and other processing methods employed in the semiconductor industry. Ultraviolet curable polymers incorporated into the tape-casting process make photolithographic processing comparatively easy and should find wide use in preparing ceramic or composite packages for intelligent systems.

The next logical step is to combine the sensor and actuator functions with the control system. This can be done by depositing electroceramic coatings on integrated circuit silicon chips. Electroceramics have a vital role to play in intelligent systems, and many new developments will take place in the coming decade and the next century.

REFERENCES

1. C.A. Rogers, "From the Editor," *Journal of Intelligent Material Systems and Structures* **1**, 3 (1990).

2. T.Takagi, "The Concept of Intelligent Materials and the Guidelines on R&D Promotion", Japan Science and Technology Agency Report, 1989.

3. R.E. Newnham, Q.C.Xu, S.Kumar, and L.E.Cross, "Smart Ceramics," *J.Wave-Matl. Int.* **4**, 3-10 (1989).

4. M.Taguchi, "Applications of High-Technology Ceramics in Japanese Automobiles," *Adv.Ceram.Mat* . **2**, 754-762 (1987).

5. H.Tsuka, J.Nakomo, and Y.Yokoya, "A New Electronic Controlled Suspension Using Piezoelectric Ceramics," IEEE Workshop on Electronic Applications in Transportation, 1990.

6. A.R.Ramachandran, Q.C.Xu, L.E.Cross, and R.E.Newnham, "Passive Damping with Piezoelectric Ceramics," presented at the 7th International Symposium on Applications for Ferroelectrics, June 6-8, Urbana, Illinois, 1990.

7. S.Burke, and J.E.Hubbard, "Active Vibration Control of a Simply-Supported Beam Using a Spatially-Distributed Actuator," *IEEE Control Systems Magazine* **7**,25-30 (1987).

8. K.Uchino,"Piezoelectric/Electrostrictive Actuators," Morikita Publishers,Tokyo,1986.

9. J.L.Butler, "Application Manual for Design of Magnetostrictive Transducers," Edge Technologies, Extrema Division, N.Marshfield, MA (1988).

10. L.Schetky, "Shape Memory Alloys,"*Scientific American* **241**, 74-82 (1979).

11. D.L.Edberg, "Control of Flexible Structures by Applied Thermal Gradients," *AIAA Journal* **25**, 877-883 (1987).

12. C.A. Rogers, C.Liang, and D.K.Barker, in "Smart Materials, Structures, and Mathematical Issues," ed.by C.A.Rogers, Technomic Publishers, Lancaster, PA, 1989, 39-62.

13. V.K.Wadhawan, M.C.Kernion, T.Kimura, and R.E.Newnham, "The Shape Memory Effect in PLZT Ceramics," *Ferroelectrics* **37**, 575-578 (1981).

14. A.Furuta, K.Oh, and K.Uchino, "Mechanical Clamper Using Shape Memory Ceramics," presented at the 7th International Symposium on Applications for Ferroelectrics, June 6-8, Urbana, Illinois, 1990.

15. M.V.Ghandi, and B.S.Thompson, in "Smart Materials, Structures, and Mathematical Issues," ed. by C.A.Rogers, Technomic Publishers, Lancaster, PA, 1989, 63-68.

16. R.E.Rosenweig,"Ferrohydrodynamics," Cambridge University Press, New York, 1985.

17. C.E.Bond,"Biology of Fishes," Saunders College Publishing Co., Philadelphia, 1979.

18. P.B.Moyle and J.J.Cech, Jr., "Fishes: An Introduction to Ichthyology," Prentice Hall, Englewood Cliffs, N.J. (1988).

19. R.J.Urick, "Principles of Underwater Sound," McGraw Hill, New York, 1975.

20. K.A.Klicker, J.V.Biggers, and R.E.Newnham, Composites of PZT and Epoxy for Hydrostatic Transducer Applications," *J.Amer.Cer.Soc.* **64**, 5-9 (1981)

21. T.R.Gururaja, W.A.Schulze, L.E.Cross, R.E.Newnham, B.A.Auld, and J.Wang, "Resonant Modes in Piezoelectric PZT Rod-Polymer Composite Materials," Proc. of IEEE Ultrasonic Symposium, 523-527 (1984).

22. Q.C.Xu, J.Belsick, S.Yoshikawa, T.T.Srinivasan, and R.E.Newnham, "Piezoelectric Composites with High Sensitivity and High Capacitance for Use at High Pressures," *IEEE Proceedings*, in press.

23. Q.C.Xu, R.E.Newnham, M.Blaskiewicz, T.T.Fang, T.T.Srinivasan, and S.Yoshikawa, "Nonlinear Multilayer Composite Transducers," Presented at the 7th International Symposium on Applications for Ferroelectrics, June 6-8, Urbana, Illinois, 1990.

24. E.I.Rivin,"Properties and Prospective Applications of Ultra Thin Layered Rubber-Metal Laminates for Limited Travel Bearings," *Tribology Int.* **16**, 17-25, (1983).

25. R.E. Newnham. "The Golden Age of Electroceramics," Adv. Ceram. Mat.3, 12-16 (1988).