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SMART MATERIALS AND STRUCTURES

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The Role of Smart Materials and Structures in Robotics

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Abstract

There is an increasing awareness of the benefits to be derived from the development and exploitation of smart materials and structures in applications ranging from hydrospace to aerospace. With the ability to respond autonomously to changes in their environment, smart systems can offer a simplified approach to the control of various material and system characteristics such as light transmission, viscosity, strain, noise and vibration etc. depending on the smart materials used.

There are a number of materials that act as both sensors and actuators that can monitor and respond to their environment. However, with the ability to also modify their properties in response to an environmental change, they can be `very smart' and, in effect, learn. The characteristics of those materials and systems that are regarded as "smart" are discussed and illustrated with examples drawn from a number of ceramics and ceramic-based composites.

INTRODUCTION

Discussion of what have recently been termed "smart materials" automatically raises the question: what is meant by `smart'? While definitions do not exist for the word used in this context, it generally refers to materials which sense and respond to changes in their environment - changes which can be naturally or artificially imposed. Such materials are said to be `mission sensitive'. On this basis, many materials and systems are smart, it is only our thinking that is limited, e.g., photographic film and thermal paper are `smart': both respond (darken) on exposure to portions of the electromagnetic spectrum.

The first workshop on this subject was held over ten years ago by the US Army Research Office at Virginia Polytechnic Institute where the concept of smart materials/systems was given as:

> "*a system or material which has built-in or intrinsic sensor(s), actuator(s), and control mechanism(s) whereby it is capable of sensing a stimulus, responding to it in a predetermined manner and extent, in a short/appropriate time, and reverting to its original state as soon as the stimulus is removed*".

The term stimulus may include stress, strain, incident light, electric field, gas molecules, temperature, hydrostatic pressure etc. Whereas, the response could be any of a number of possibilities, such as motion or change in optical properties, conductivity, surface tension, dielectric, piezoelectric or pyroelectric properties, mechanical modulus or permeability.

Although Japanese and American scientists have rather different views of smart/intelligent materials, they are generally regarded to be a group of materials that have varying degrees of sensing and actuating functions that can be incorporated into systems having feedback loops to constantly vary or "tune" one or more material property such as size, shape, colour, structure or composition. Using sophisticated hardware (control devices e.g., actuators) and software these materials can be incorporated into what is described as a smart/intelligent system, that possesses a higher level of intelligence such as self-diagnosis, self-repair, learning ability, ability to discriminate shapes and forms, ability to judge etc. The basic components of a smart system may include embedded sensor(s), an information processing (software) system for data analysis, logic and decision making and system hardware (e.g., multiplexers, actuators etc) interfaced to a computer for control, actuation and feedback.

SMART MATERIALS

In this section, the basic properties of some selected intelligent/smart materials are discussed. The aim is to relate the above basic concepts to the material characteristics and illustrate their potential as smart materials/systems. Typically a smart system/structure consists of a host structural material having a network of embedded sensors/actuators interfaced to a micro-processor based data acquisition/manipulation and control unit. Some of the most promising smart materials known today include, piezoelectrics, electrostrictors, shape memory alloys, electro-rheological fluids, fibre optics, conducting polymers, composites, bio-materials etc. Of this growing group of materials, the discussion below focusses on ceramic materials and their contribution to smart systems.

Ceramic-based Actuator Materials

It has been tacitly assumed to this point that all actuator materials behave similarly, however, that is not the case. In broad terms, some actuators are developed using piezoelectric materials whereas others exploit electrostrictive materials based on relaxor ferroelectrics. In addition, within the piezoelectric materials there is considerable variation in how each material responds to an applied voltage which is a reflection of both their composition and microstructure. Some examples of this variation are shown in Fig. 1 in which PMN refers to lead magnesium niobate, BST refers to barium tin titanate, and PZST refers to lead zirconium tin titanate [$Pb_{0.99}Nb_{0.02}(Zr_xSn_{1-x})_{1-y}Ti_y)_{0.98}O_3$ where x=0.70, y=0.045 for (a) and x=0.60, y=0.055 for (b)] [1].

It can be seen that the strain developed as a function of applied voltage varies considerably. In the case of piezoelectric BST, the response is nominally linear with voltage, showing moderate hysteresis. This situation is improved in electrostrictive PMN with gives a larger strain and a much lower hysteresis but now with a decidedly non-linear response. However, PMN has an exceptionally high dielectric constant (K>20,000) and is unsuitable for applications requiring very rapid response - in such cases, a more commonly used material would be Ba-doped PZT in which K is –3 000. Both these materials exhibit limited strains (between 0.07 and 0.1%), for even larger displacements, actuators are often based on PZT which can range to over 0.2% strain. However, the various doped piezoelectric PZT=s also exhibit considerable hysteresis which can range over 80% (expressed as the ratio of the displacement hysteresis at half voltage to the displacement at full voltage).

The existence of a sometimes considerable hysteresis in an actuator material may or may not be a concern depending on the application. For example, the hysteresis shown by the PZT-based materials may be of little consequence in pulse-drive motor actuators where a quick response is important. However, it would be a major concern in applications in which the fine manipulation of optical components to fractions of a wavelength is required. In such cases, PMN-based materials are being developed as they offer a small but adequate strain coupled with a low hysteresis to minimize Alash@ in the system. In some cases, the hysteresis can be extreme such as exhibited by PNZST during the antiferroelectric-to-ferroelectric phase transition which gives a longitudinal strain of over 0.3% which is greater than that expected of a piezoelectric. In those cases where a sufficiently large hysteresis occurs during voltage cycling [PNZST(b)] a digital displacement actuator can be built for applications requiring precise micropositioning with a constant distance change such as for optical diffraction gratings and photolithography. On the other hand, with a modified composition [the shape memory material PNZST(a)] which retains a considerable displacement at zero field it is possible to fabricate latching relays which can hold their Aon@ state without requiring a constant power supply.

At present, the authors are involved in a development program to produce electrostrictive and piezoelectric actuator materials for various applications. The materials are based on selected composites derived from the ternary system PMN-PT-PZT (PT - lead titanate) with various added dopants and processed under a variety of conditions to control the microstructure and grain and grain boundary compositions. Figure 2 shows the extremes of hysteresis that can be generated in this system by varying the PZT content. A similar effect is also observed in PMN with increasing temperature as the material switches from a piezoelectric to an electrostrictor to a paraelectric. Details on these materials and their other properties have been published elsewhere [1].

With the addition of PZT to PMN, the material changes from an electrostrictor to a piezoelectric. In general this is accompanied by an increase in strain developed at a given field. However, the penalty is that the hysteresis also increases which is undesirable for fine micro-positioning applications. This ability to transform from a piezoelectric to an electrostrictor imparts other attractive characteristics. Like piezoelectric ceramics, electrostrictive ceramics show a dimensional change when an electric field is applied. However, in piezoelectric materials induced strain is directly proportional to applied field, resulting in a positive or negative displacement, depending on polarity. Whereas, in electrostrictive materials, the induced strain is proportional to the square of the applied field, creating unidirectional displacement regardless of polarity. Since electrostrictive ceramics always give positive displacement, they are always in compression when doing work. This avoids the typical weakness of ceramics in tension, which can be experienced with the piezoelectric ceramic actuators.

Electrostrictive materials offer important advantages over piezoelectric ceramics in actuator applications: they do not contain domains and so return to their original dimensions immediately after the field is removed; they show microsecond recovery time upon withdrawal of the electric field, compared to millisecond for piezoceramics. The metastability of the poled state and availability of many alternative domain arrangements in piezoelectric materials can provide stress relief leading to dielectric aging and associated dimensional drift associated with domain rearrangement. This occurs particularly when the piezoceramic is driven hard by high electric fields, as required in many actuator applications. When the electric field is removed piezoceramics exhibit significant hysteresis, and require negative voltage to return to original size or shape. Electrostrictive ceramics on the other hand exhibit little remnant displacement, making them suitable for extremely accurate (micron-level) displacement control device applications.

An additional advantage of electrostrictive PMN is that the micropolar regions that form due to compositional heterogeneity give rise to very high nonlinear polarization over a range of temperatures near the mean Curie point (-15E to –50EC depending on composition) without a stable remnant polar state. This nonlinear behaviour imparts tuneable characteristics to PMN-based electrostrictors, i.e., they are very smart materials [1]. Electromechanical strains comparable to PZT can be induced in PMN through the application of high dc fields (3-4 kV/mm) without experiencing the severe hysteresis shown by PZT. For example, PMN based ceramics can exhibit a d_{33} value of 1300 pC/N, about 3 times larger than PZT under a bias field of 3.7 kV/cm). Figure 3 shows the exceptionally low hysteresis that has been obtained in an experimental PMN actuator under development by the authors.

DEVICES

As discussed earlier, the essence of many actuator applications is the ability to offer very fine movement (of the order of fractions of a wavelength) in a reproducible manner and with minimal or no hysteresis. From a systems application point of view, other characteristics also become desirable such as the ability to offer such control using a low voltage signal (ideally at the 5V level of TTL logic), the movement/volt ideally should be constant over the anticipated temperature range of application, and the material/device should be stable with time and exhibit no ageing effects. At present, these requirements are only partially met: while it is possible to obtain very fine movement which is a fraction of a wavelength, hysteresis still occurs and the devices still have to be operated at high voltage gradients (sometimes > 1kV/mm) to achieve sufficient displacement.

For many of the earlier applications, the occurrance of hysteresis was inconsequential, however, with the increasing interest and subsequent developments in micromanipulation and micropositioning, the issue of hysteresis became of increasing importance as the demand for both fine and reproducible movement increased. The areas where such control is in demand include optical systems capable of reproducibly moving a mirror etc fractions of a wavelength, similar high levels of control are required for deformable mirrors (c.f. repairs to the Hubble telescope) and in high precision machining centres in which ceramic servo-actuators allow the machining of optical flats. A slightly lower degree of reproducibility is also required for microscope stages and in micro-positioning sensors such as VCR heads, swing CCD image sensors, etc. In these and similar applications there is an increasing demand for:

X reduced (or eliminated) hysteresis,
X increased displacement for a given applied voltage (ideally operating at 5V TTL levels),
X materials that exhibit little or no ageing effects,
X low cost materials,

X durable materials that perform for at least 10^{10} cycles.
X A wide working temperature range,
X Small size and weight
X High power and
X Compatible with silicon technology.

The requirements of reduced hysteresis, no ageing effects, durability, a wide working temperature range and high power are predominantly material dependent while low cost is primarily a function of the processing route and increased displacement per applied field is a function of both the material and the device geometry. Of these, the requirement to increase the strain as a function of applied field, has been partially achieved by some elegant design solutions such as the development of the bimorph, the Arainbow@ and the stack actuator, discussed later.

Compared with a monolithic block of material, each of these configurations generates a much greater motion for a given applied voltage. However, that increased movement can only occur at a lower stress level, e.g., while a bimorph can generate .two orders of magnitude greater strain than a monolith, it can only generate that motion at three orders of magnitude lower stress as shown in Fig. 4 (after Ref. [1]).

Direct Extensional Devices

Monolithic Geometry (High Stress, Low Strain)

The simplest actuator of all is a monolithic body driven by an applied voltage and responding either as an electrostrictive material (true of all materials) or as a piezo-electric material. The magnitude of the displacement for an electrostrictive material is generally very small and is proportional to the square of the applied field whereas the displacement of a piezoelectric material can be up to an order of magnitude larger and it is directly proportional to the applied field. In some cases, such as high permittivity ferroelectric materials just above the Curie point (e.g., those based on lead meta-niobate (PMN), the magnitude of the displacement is sufficiently high that the material can be used in displacement devices. As a consequence, considerable research and development has occurred in the past 10 years into various PMN-based ceramics for actuators.

Multi-layer Geometry (Moderate Stress, High Strain)

One way of generating an increased strain per applied field is to replace a single solid monolithic body with a stack of thin slices, Fig. 5 (after Ref.[1]). In this case the same voltage can be now applied across a multitude of much thinner wafers. In this way. the voltage gradient is increased up to two orders of magnitude and the strain is also increased significantly.

The fabrication of these so-called Astack actuators@ can be achieved by slicing wafers from a fired monolithic block and assembling the structure using a silver-containing epoxy-based adhesive which plays the dual role of acting as a conductive internal electrode and also cementing the wafers together. Alternatively, these assemblies can be fabricated using tape-cast green ceramic sheets onto which a compatible metallic ink is screen printed and layers are punched and stacked by automated equipment to form a multi-layer assembly which can be fired to a dense coherrent structure as is the current practice in industry for the fabrication of multi-layer capacitors. Of these two routes, the latter is much more complex and is a challenge: first tape has to be developed, then compatible inks have to be developed, the patterned layers have to be punched stacked and bonded without defects, and finally the whole assembly has to be fired slowly to burnout the organics without delamination or forming carbon which can reduce the components and ruin the dielectric properties.

The advantages of such a configuration over the straight monolithic material are that either a much reduced voltage is required to generate the same strain (thereby saving on the cost of the power supply) or that a greater strain can be developed for the same applied voltage. In both cases, the devices are fast acting, responding to the field in .10Φs: the monolithic giving fractions of a Φm displacement while the multi-layer may give between 10 and 20Φm displacement.

Because this geometry affords a greater displacement for a given applied field than is possible for a monolithic body of the same dimensions, it has been used in a number of devices with various driving materials. In those cases where hysteresis is not an important factor, PZT-based materials have been used, for example in dot-matrix printer heads, ink-jet printers, piezoelectric relays, oil-pressure servo valves etc. [1]. However, for applications where reduced hysteresis is required, the material of choice is generally the relaxor: PMN-PT, which can range from essentially a pure relaxor having a low strain and low hysteresis (PMN) to a soft piezoelectric (with increasing PT content up to about 35%) having a higher displacement but with increasing hysteresis, cf. Fig. 2.

Because the low PT-containing materials lack the complex domain structure of a piezoelectric material, these electrostrictive materials exhibit essentially no ageing with use, i.e., they are ideal for use in the control of fine motion, the reproducibility of which is stable with time. When used in multi-layer devices, electrostrictive PMN exhibits high precision and reproducibility in the field-induced strain, a low thermal drift and a moderately low loss. These characteristics are being developed for use in various multi-layer positioner elements for:

$ the stage translation of optical and electro-optical microscopes,
$ tip translation in scanning tunneling microscopes and atomic force microscopes,
$ semi-conductor mask alignment in VLSI chip manufacture,
$ microscope autofocusing,

- fibre optic alignment and splicing,
- laser diode and fibre assembly
- laser mirror translation and alignment
- angular mirrors,
- active deformable mirrors
- tunable optical fibres: Fabry, Perot Etalons,
- microelectronic probe positioners,
- micromachining tools controls
- X-ray lithographic position controls
- magnetic and optical disc head micropositioners [1].

In attempts to generate even greater displacements, other geometries have been developed such as the so-called unimorphs, bimorphs and rainbows: all of which bend under an applied field in a manner similar to the action of a bi-metallic strip used in temperature regulators. In that case, the metal strip bends in response to temperature change as the two metal elements are deliberately chosen to have markedly different coefficients of thermal expansion/contraction. A similar effect can be generated in laminates of a piezo-electric and another material (metal, ceramic or plastic) to create a unimorph. The effect can be enhanced when the second material used is another piezoelectric but poled in the opposite sense, Fig. 6.

Unimorphs and Bimorphs (Low Stress, High Strain)

The essence of these actuators is the generation of movement as the result of a differential expansion or contraction generated by an electrical field. In the case of a unimorph, bending of a laminated beam consisting of a piezoelectric strip bonded to an inert material such as Be-Cu alloy or acrylic sheet occurs when the field is applied because the ceramic expands but the inert element does not. Such devices offer displacments of well over 100 Φm but at moderate to low stress.

The configuration of a bimorph is similar: two unimorphs are bonded together but in such a way that the poling directions of each piezoelectric complement each other. In this manner, when the field is applied, one unimorph will expand whereas the other will contract thereby augmenting the bending motion. Such devices are used extensively as high strain (several hundred Φm displacement) moderate stress actuators in valves and fans for electronic equipment where space is restricted.

Rainbows (Cerambows)

These devices were first developed in 1993 by G.H. Haertling. The material is a composite of metallic lead, reduced PZT and oxidized PZT in a single body that is developed by preferentially reducing one side of a fired fully oxidized PZT disc down to metallic lead by placing it on a carbon block at 950EC for one hour in air. The CO/CO_2 atmosphere generated at the carbon PZT interface is sufficient to reduce some of the material down to free lead.

The initial acronym ARainbow@ (Reduced and Internally Biased Oxide Wafers) reflected the inventor=s belief that an internal bias mechanism operated to create the domed wafers that result from this process. However, by 1995, it had been recognised that the Abias@ was strictly mechanical: in effect, the development of a layer of metallic lead (α . 300.10^{-6}) at high temperature bonded to a ceramic (α . 8.10^{-6}) and the differential shrinkage that occurred on cooling was the reason for the dome-shape of the wafers. Most recently, the author reported that the reduction process was not necessary - bonding any material with a sufficiently different expansion coefficient was sufficient to produce an actuator [1]. For example, brass shim stock soldered to a silvered disc on a hot plate (must be done fast [<5s] to avoid the solder scavenging the Ag electrode) produces an actuator. Other materials such a shrinkfit plastic or superglue (cyanoacrylate) should work as should lucite (poly methyl methacrylate: α . 80.10^{-6}). The inventor recently assigned the worldwide rights for the production of these devices (now renamed Acerambows@) to Aura Ceramics Inc., New Hope, MN, USA [1].

By their nature, these cerambows offer considerable displacement, e.g., up to 300Φm at 750v in a unipolar configuration and into the range of 700 to 800 Φm for the same field but in a dipolar device in which two actuators are put back-to-back in a clamshell configuration, Fig. 8. However, the stress level is modest at . 0.6MPa (85psi).

Composite Device (Moonie Stack Actuator: Displacement 20-100Φm)

The essence of this configuration is to convert the relatively small strain of a monolithic piece into a greater strain by the exploitation of Ahalf-moon@ shaped cavities developed inside the metal end caps, Fig. 9. Known as AMoonies@ by the developers (R.E. Newnham et al., Penn. State University), they offer a major increase in sensitivity when used as sonar transducers [1].

The end caps, in effect, act as mechanical amplifiers transforming the motion of the radially-driven ceramic which is glued to the end caps at the ceramic periphery to a thickness mode motion of the device. When stacked, they can offer displacments up to 100Φm and they exhibit strain and stress characteristics which are intermediate between those of a conventional stack actuator and a bimorph. The vertical displacement generated by this configuration depends on many factors including the thickness of the metal, the ratio of the air cavity diameter to overall diameter, the depth of the cavities, the material used for the end caps and the ceramic itself. In operation, when a voltage is applied to the ceramic, it expands in the z-direction (d_{33}) and contracts in the x- and y-direction (d_{31}

and d_{32}). These combined motions result in the ceramic compressing (and buckling) the end caps in the x-y plane to generate a significant vertical motion to which an additional and lower magnitude direct component of motion is added arising from the expanion of the ceramic in the z-direction. Typically, the strain in the z direction measured at the centre of the end caps is at least an order of magnitude greater than that generated by the ceramic itself.

In order to obtain higher strain, these devices can be stacked, or a multilayer configuration can be used in place of a monolithic ceramic driver - or both. Typically a doubly stacked moonie fabricated using a PZT-5A ceramic will afford a displacement of .40 Φm at room temperature under a field of 1kV/mm [1], whereas a series of stacked multi-layer driven moonies can give displacements >100Φm.

The recent development of these various device configurations has succeeded in generating useful displacements in many cases that can be exploited in many commercial devices. However, several undesirable features remain:

X the need in many cases for a high field power supply to drive the device,
X the relatively low strain generated and
Xthe continued display of significant hysteresis.

In large part, these are all material dependent characteristics that can be partially addressed. It has been shown that multi-layer devices can significantly reduce the voltage required to drive a device, high strain configurations such as cerambows and bimorphs have been developed and high strain electrostrictive material such as PMN has been developed. However, for fine control such as in optical applications and micro-machining it is necessary to have both adequate strain and (ideally) no hysteresis.

In general, fine motion can be obtained using various materials that exhibit properties such as magnetostriction, electrostriction, and piezo-electricity. These characteristics all have drawbacks to exploitation in devices, e.g., magnetostrictors require high magnetic fields which in turn demands super-conducting materials operating at low temperatures thereby requiring ancilliary refrigeration. In addition, while magetostrictors can offer considerable strain (greater than typical piezo- and electro-strictors), they also suffer from excessive hysteresis. Both the piezoelectrics and electrostrictors require high driving voltages that also dictate additional and undesirable complication. However, overall, the emphasis on materials for the control of motion in the past has been on piezoelectric and increasingly on selected (high displacement) electrostrictive materials.

Applications

The combination of sensing and actuating functions in the same material are attractive in a number of applications. For example, it is possible to sense a change in the environment and to nullify or minimize that change. This has been shown by Newnham et al. [1] in their demonstration of a controlled compliance or vibration damping system based on PZT piezoelectric stack actuators and sensors arranged as shown in Fig. 10. in which a thin rubber sheet separates the two stacks. The driver actuator is triggered using an ac voltage. The pressure waves so generated (monitored through the upper sensor) impinge upon the lower sensor. This signal is amplified using a low noise amplifier and fed back through a phase shifter to the lower actuator to control the compliance. When the phase of the feedback voltage is adjusted to cause the responder to contract rather than expand in length the 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 signal is a measure of the effectiveness of the feedback system. Alternatively the system can be made to mimic a very stiff solid.

This concept has already been exploited in the automotive industry by both Toyota and Cadillac in their active suspension systems, Fig. 11. First introduced by Toyota in 1991 as their piezoTEMS (Toyota Electronic Modulated suspension), these systems have been developed to improve the driveability and stability of the automobile and enhance passenger comfort [1]. The system uses a closed loop of piezoelectric ceramic sensors and actuators to continually monitor the suspension vibration arising from road roughness. The sensor produces a voltage which is amplified, altered in phase, and applied to the 88-element piezoelectric actuator. The actuator produces .50µm displacement which is hydraulically amplified to 2mm and which is sufficient to adjust the damping force in the shock absorber system from firm to soft within .20 milliseconds.

One of the variations in developing a micro-positioning system is based on the construction of a so-called piezoelectric bimorph in which two thin wafers of ceramic of opposite polarity are bonded together and driven with a dc signal in such a way that as one side expands, the other contracts resulting in the beam bending, Fig. 12A. When this configuration is modified as in Fig. 12B, then the bending can be more complex as shown. This geometry is now used in video tape equipment for the precise positioning of the recording head. Because the head position during read-back of the tape is dictated by a feedback loop that monitors the signal from the tape, the head can be micro-positioned to ensure that a maximum signal:noise ratio is achieved. A variation of this assembly has been available for some time in which an ac signal forces the beam to `wag' thereby acting as an effective compact cooling fan for instrumentation.

In the United States, NASA space missions have been the major motivator of the design and development of intelligent/smart systems. The space based systems requiring large (20-100 metres) precision structures such as reflectors , antennas, interferometers, etc., pose serious vibration problems due to the absence of gravity in space. For stable operations these structures require accuracy in micron to submicron dimensions. The Jet Propulsion Laboratory at the California Institute of Technology, has developed [1] precision composite truss structures that can be actively damped using piezoelectric sensor/actuator systems attached or embedded in structural members. Severe vibrations in a horizontal truss have been shown to disappear within three oscillations by activating the smart systems.

Currently, the authors are involved in the development of a smart parabolic reflector for application in space structures. The system is shown conceptually in Figure13 and comprises a series of autonomous pie-shaped reflector elements arranged in a circle: each element contains both sensors and PZT-based patch actuators so that the degree of curvature of the segment can be monitored and altered. Driven by a central computer system, this structure is able to monitor the location of each element in free space, compare that information with the ideal shape held in a look-up table in memory, decide which element should be moved and in which direction (in order to minimize the differences between the actual element positions and the ideal shape held in the look-up table) and to affect the needed changes via the patch actuators.

Another important application of the smart material/system that is being developed in the U.S. is for the health monitoring (i.e., damage detection/control/life time prediction etc) of dynamic structures such as military or civilian aircraft, submarines, space based vehicles etc. Such a system may incorporate sensors, actuators, artificial intelligence (neural network), and advanced analytical techniques to provide real-time and continual health assessment. Figure 14 indictaes some systems envisaged or under development at present - some of the health monitoring systems can be built in during the manufacturing process. When the aircraft leaves the factory, it will have detailed engineering data stored in its computer memory. As a preflight check-up the integrality of the aeroplane can be judged against the engineering data stored in the memory. Thus the pilot as well as the maintenance staff can be provided with the visual display of the health of all systems prior to take-off. Any in-flight changes will be displayed with recommended action. The life history of the aircraft will be continually and automatically updated for accurate structural integrity assessments. This will lead to improved safety, reduced and simpler maintenance, and reduced life-cycle costs[1]. Researchers at the Virginia Polytechnic Institute and State University have recently shown that piezoelectric ceramics can be used for active fatigue or damage control [1]. The technique, mimicking the self-repairing function of biological beings, can greatly increase the lifespan and reliability of structures in the future. The basic concept in active damage control is to redirect the energy flow in the structure, resulting in less high-energy concentration, or high stress-concentration in the structure. The energy flow direction can also be altered by inputting energy from outside. The total energy of the system may increase, but the energy that is deteriorating the structure can be decreased. In a simple experiment, a composite beam was bonded to an aluminum bracket and subjected to a fatigue loading from a motor. Two PZT actuators mounted on the roof of the beam operated at the same frequency as the fatigue loading, but the induced stress from the actuators in the bonding area was 180 degrees out-of-phase with the fatigue loading. By reducing the fatigue stress amplitude, the lifetime of the bonded joint was increased significantly from 52,000 cycles to 500,000 cycles. At the same time, the vibration amplitude of the beam was also greatly reduced.

Other applications of electrostrictive actuators include micron-level manipulation of deformable mirror-surface contours to correct optical aberration at rates up to 1000 times a second. These actuators are also used for space-communication-system optical mirrors or lasers, micro-machining and tool controls, linear and rotational micromotors, automatic pattern recognition, vibrational control and management, micropositioning devices, high precision interferometric dilatometers, etc. The first electromechanical characterization system set up by the authors 10 years ago exploited a Michelson inferometer which incorporated a piezoelectric stack actuator in a feed loop to nullify the extraneous measurment signals arising from building vibration, passing traffic etc. - today such smart systems are becoming increasingly ubiquitous.

SUMMARY

Some of the recent developments in smart materials, devices and their applications have been surveyed. It has been shown that the field is very active active as these autonomous systems are increasingly incorporated into modern structures such as the automobile, aircraft, space structures, etc. The appearance of smart suspensions in automobiles suggests that this technology will enjoy widespread application as the benefits of vibration control become not only an engineering issue but a feature demanded by the consumer.

Irrespective of the specific application, there is an inherent appeal in the applications of these materials and systems - particularly, when they can offer potentially low-cost, high sensitivity and rapid response. The future is undoubtedly very bright for these materials.

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