Intelligent Materials and Structures

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Intelligent materials and structures (IMSs) are systems which have their own sensors, controls and actuators. In this contribution, an overview of the science and the technology of smart materials and intelligent structures is presented. This presentation includes some related definitions and classifications of IMSs. Classes of sensors and actuators are introduced and potential, as well as actual applications, of intelligent materials and structures are outlined. The subject of the active control of structures is briefly discussed and a new theoretical stability controlled model of active shells is presented.

INTRODUCTION

In the last decade, there has been an increasing need to design and construct material systems that can adapt their behavior, composition, outlook and shape to the needs imposed on them by changing environmental and design requirements. The functional requirements for space antenna and vehicles embedded in changing environmental conditions, the need to replace damaged organs with artificial organs made of biocompatible materials, the desire to control the behavior of structures during earthquake motion, the need for continuous monitoring of systems and many other industrial needs have all contributed to advancements in materials science and structural technology.

The outcome of relatively extensive research work in various directions, viewed in a unified perspective, has been the evolution of the science of smart materials and the engineering of intelligent structures. Intelligent materials and structures (IMSs) are characterized by the ability to sense and respond to external stimuli in an appropriate manner. In short, IMSs can be defined as material entities with attached or embedded sensors and actuators capable of actively responding to external stimuli to the end of achieving a desired behavior. Shape Memory Materials (SMM) and structural forms which can undergo controlled change of configuration and adaptation of their geometry to the requirements of their environment are examples of some of the developments in this area.

Along with technical advances in manufacturing of new materials and construction of new structures, the past years have been a period of re-examination of design principles. New views of materials have emerged and new expectations of structures have formed. Developments in three different fields have made fruitful contributions to activities in the area of smart materials; these disciplines are advancements in materials research, progress in adaptive control research and research on artificial intelligence, including computers.

Review of the research done on intelligent

1. EMPA, Dubendorf, Switzerland

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materials and structures is not an easy task, it requires a multidisciplinary approach by a team of experts in various areas, as well as general systems theorists. However, a personal attempt to summarize some aspects of new developments in this area, however schematic, may prove useful.

In this contribution, some of the research trends in the area of IMSs are put into perspective and some developments which have taken place in this area are briefly outlined. Furthermore, results of new investigation on the stability control of active shells and rods will be presented.

In this work, an overview of various topics related to IMSs will be discussed. Due to the growing bulk of literature and the multidisciplinary nature of the field, and also due to space limitation, this presentation will be schematic in nature. It will be limited to the discussion of the general features; detailed presentation of instruments, methodologies, mathematical models, products and systems will not be attempted.

INTELLIGENT MATERIALS

Various definitions for the so-called "smart materials" or "intelligent materials" have been presented in the literature; some of these definitions are as follows:

In some literature, intelligent materials have been defined as materials which manifest their own functions intelligently and respond appropriately to the environmental changes. Elucidation of function, intelligence and environments are, to some extent, clarified in Figure 1. In this figure, three levels of functionality are differentiated; these are primitive functions, intelligent functions and subjective functionality, i.e., the function as viewed by human beings [1].

In some other works, intelligent or smart materials have been defined as materials "containing distributed and/or integral actuators, sensors and microprocessors' capabilities". In other writings, intelligent materials have been defined as "materials which can feel the equivalent of pain [2]; in this sense, they act as the nervous system of a material.

Intelligent materials have also been defined from a systemic viewpoint, Accordingly, an intelligent material is one which has enough information content to define and determine its organization and behavior. In this sense, all biological materials are considered to be highly intelligent; in fact they are equipped with a built-in intelligence. Biological materials do not only respond to the environment intelligently, but are capable of higher functions such as growth, adaptation, self-diagnosis, self-repair and reproduction in a most optimal and efficient fashion.

Common to these and other definitions, proposed for intelligent (smart) materials, are the following features:

1. Presence of embedded/bonded/intrinsic sensors to recognize environmental conditions.
2. Existence of some information processing system and control mechanism for controling the response. At higher levels, a closed-loop feedback system would also exist.
3. Possession of embedded/bonded/intrinsic actuators to respond to the stimuli.

Smart materials may have one or several modes of behavior, their behavior may have one of the following manifestations:

- Change of color or surface luster according to the applied load.
- Change of appearance according to internal damage.
- Change of geometrical, mechanical/thermal/electrical properties with the environmental conditions.
- Change of chemical composition according to the surrounding conditions.

These features can, more or less, be found in all materials; however, a controlled change in the modes of existence according to a predetermined goal and design is an added feature which

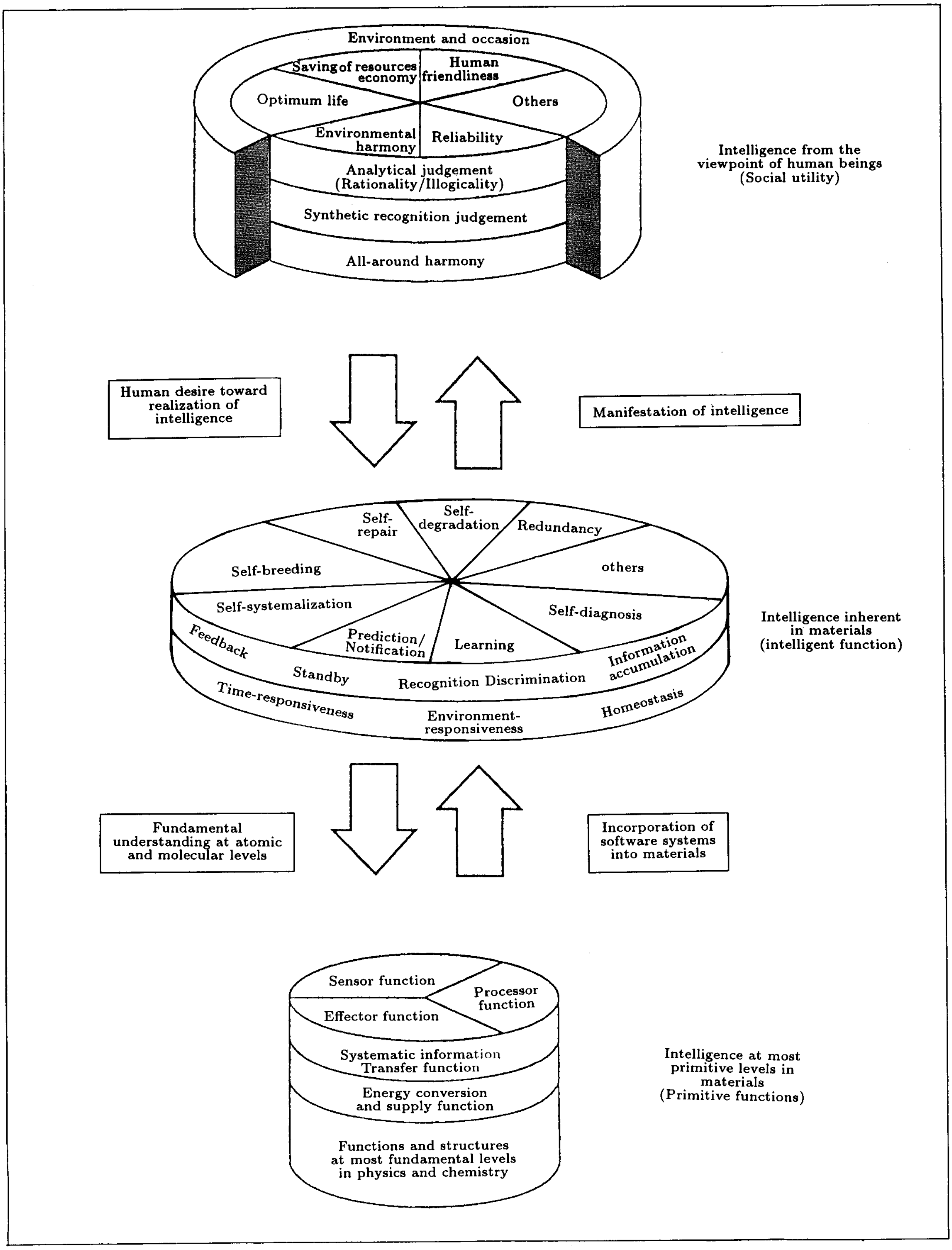

Figure 1. Schematic representation of intelligence in materials [1].

would characterize various degrees of intelligence. Transition from ground materials with basic structural/functional/material properties to intelligent materials is made when functions such as sensing, memory, processing, signal and effector actions are combined with the material properties. Once this transition is made, the new material will become capable of higher level activities [3]. An integral system composed of the sensor, the actuator, an information processing unit and an appropriate feedback comprises the brain of the intelligent material.

SENSORS

Intelligent materials and structures contain sensors as receptors of information. Sensors may be discrete or continuous, they may be bonded to the surface or embedded in the body and they may be extrinsic or intrinsic. Categories of sensors include:

Optical Sensors

Optical sensors, as their name implies, are materials which are sensitive to light. In addition, they are capable of converting the light energy to other energy forms; hence they have high potential as signal transmitting devices. Optical sensors may be in the form of long fibers or films.

Optical Fibers

Optical fiber sensors can be used extrinsically as light transmitters or intrinsically as means of detecting other quantities. Extrinsic applications of fiber optic sensors include:

- Measurement of force through induced birefringence.
- Measurement of pressure by piezoelectric effect.
- Measurement of bending by piezo-absorption.
- Measurement of density change through luminescence.
- Measurement of electric field through electro-optical effect.
- Measurement of temperature through thermal change in refractive index, absorptive properties, fluorescence or thermo-luminescence.
- Measurement of changes in the chemical composition through changes in absorption and refractive index.
- Applications in experimental fracture mechanics. For example detection of cracks; a crack width increase in the range of 5 to 30 μm has been measured by optical fibers.
- Weighing of moving vehicles.
- Smart cables containing embedded sensors.

Optical fibers can be embedded in the structures or bonded to the surface of the structure. Embedded optical fibers are used for strain measurements in composite components, concrete structures, bridge decks and bearings [4] and soils, dams and aerospace installations [5]. A typical surface-bonded optical fiber has a core diameter of about 100 μm and a coating diameter of about 140 μm. A commercial coated optical fiber can withstand up to 5% strain without fracture. The signal attenuation introduced by a typical fracture of an optical fiber is about 30%-3 dB. Coating of the bonded optical fibers may be done by a number of materials. For CFRP and GFRP composite elements, polimide has appeared to have yielded satisfactory results. Thin coating seems to be more satisfactory than thick coating [6].

Thin Optical Films

Thin optically sensitive sheets composed of metallophthalocyanines have been made. In some works, these optical sheets have been called the "smart skins".

Considerations on Installation of the Optical Fibers Films

There are two possible ways of attachment of the optical fibers/sheets to the structure: one is embedding; the other one is surface bonding. Each of these two systems has its advantages and disadvantages. The advantages of surface bonding are; preservation of the properties of structure, possibility of repair, easiness of input-output handling and easy installation. Disadvantages of surface bonding are: possibility of damage due to exposure and lack of information about the internal events. The embedded sensors have advantages and disadvantages more or less opposite to those mentioned for the surface-bonded sensors.

While considering the possibility of using embedded fibers, the problems associated with the interaction between the structure and the fibers must be taken into account. One such type of problem is the local (length scales of several diameters of the fiber) interaction between the optical fiber and its surrounding medium. Local strain and stress concentrations may be caused by these interactions; in calibration of the fibers and in fatigue studies, these effects must be taken into consideration.

Piezoelectric Sensors

Piezoelectricity is an electromechanical phenomenon in which there exists a coupling between the elastic and the electric fields in the piezoelectric bodies. Forces/pressures generate electric/voltage in a piezoelectric material; this is called a direct piezoelectric effect. Conversely, an applied electric charge/field induces mechanical stress and strain; this is called the converse piezoelectric effect. In active piezoelectric structures, the direct effect is used for distributed sensors and the converse effect for distributed actuator/control [7]. Use of the Shape Memory Alloys (SMA) in the form of fibers and layers as embedded distributed actuators has also been considered [8].

Piezoelectric materials may have organic or inorganic sources. Inorganic piezoelectric materials can be crystals or ceramics. An example of piezoelectric ceramics is piezoelectric paints, these paints consist of lead zirconate titanate (PTZ), ceramic powder as a pigment and epoxy as a binder. One type of PZT paint has been produced by grinding piezoceramics to micron-sized particles and mixing them with a typical lacquer or enamel. This paint would be applied with a spray or a brush; it would be activated by applying a DC electric field across its electrodes. When stressed, it would exhibit direct piezoelectric effect and would act as a sensor [9]. A paint made up of PZT ceramic powder and epoxy resin brushed on an aluminium beam sample has been used as a vibration sensor [10].

Conductive Polymers

There are some polymeric materials which are capable of transmitting electrical fields and these materials can serve as sensors. One of the conductive polymeric materials is polyvinylidene fluoride (PVDF) or PVF_2 film as thin as 50-300 μm. This type of piezoelectric film can be easily bonded to the surface of structures; it can also be embedded in the structure. As embedded films, they can, for example, be used as sensors for monitoring laboratory scale adhesive joints [11]. If the PVDF film is curved, it produces sound; in this way, it can act as a sensor. For more on these polymers, see the next section.

Some of the properties of piezoelectric films made of PVF_2 are [12]:

- Young's modulus, 2000 MPa.
- Density, 1780 kg/m^3.
- Poisson's ratio, 0.3.

Some other conductive polymers are:

- Polypyrole.
- Polythiophene.
- Polyaniline.
- Polytyramine.
- Polymer gels.

A polymer gel consists of an elastic cross-linked network and a fluid that fills the interstitial space of the network. A polymeric gel can change its size and shape in response to environmental changes such as PH, salt concentration, temperature and electric field.

Shape Memory Alloys (SMA)

Remarkable development in the field of smart materials has taken place on the basis of the knowledge of the so-called shape memory effect

(SME). SME can be described as follows: "An object in the low-temperature martensitic condition, when plastically deformed and the external stresses removed, will regain its original (memory) shape when heated ... . The process, or phenomenon, is the result of a martensitic transformation taking place during heating" [2]. One may state that shape memory materials have a history and are, in contrast to, for example, viscoelastic/plastic materials, faithful to the source of their history. Examples of SMAs are nickel-titanium alloys-nitinol, NiTi, InTi, and other alloys such as CuAl, NiAl, AgZn, and AgCd (see also the next section).

Developments in the area of shape memory materials have included both actuator and sensor systems.

Piezoelectric Rubber

Piezoelectric rubber (e.g., chlorobren) was developed for sensor cables. They can be used as vehicle sensors for traffic lights and can be made continuous up to 20 m length [2].

Temperature Sensors

These sensors are prepared by contact with a metal ceramic superconductor. Bi-metals and optical fibers can also be used as temperature sensors.

Chemical Sensors

There are a variety of materials which, due to their chemical composition and interaction with the environment, are capable of transmitting signals, Examples of chemical sensors are:

- Molecular wires made of polythiophene chains.
- Photo electrochemical sensors made of organic molecules.

ACTUATORS

Materials and/or elements that allow a smart structure to adapt to its environment are called actuators or effectors. Actuator materials have the ability to change the shape, stiffness, position, natural frequency, damping, friction, flow rate and other mechanical characteristics in response to loading, temperature and other environmental conditions. Effector materials/elements include:

Shape Memory Alloys (SMA)

As pointed out before, nitinol is one of the well-known SMA materials; its name is derived from Ni (nickel), Ti (titanium) and NOL (Naval Ordinance Laboratory). The phenomenotogical performance of nitinol is that the material can be plastically deformed at its low temperature martensite phase. By heating it above the characteristic transition temperature, a solid-to-solid phase transformation takes place; consequently, it tends to its original configuration or shape. In this sense, one may say that the material has a "memory"; it can recall its history and can return to its original position when heated above its transition temperature. Figure 2 depicts the basic features of a SMA and its characteristic response to load and temperature.

Plastic strains of up to about 8% can be completely recovered by heating. In the process of returning to its "remembered" shape, the SMA can generate a very large force; this can be useful for actuation. A typical stress amounting to about 1000 N/mm^2 may be generated by the SMA. By changing the composition of the

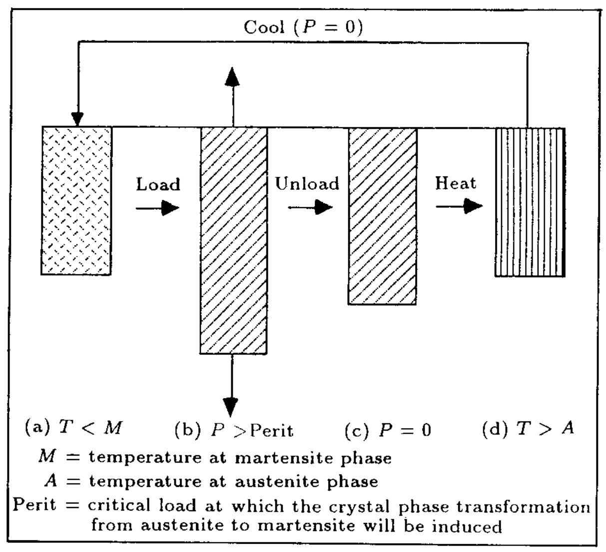

Figure 2. Schematic of phase transformation in SMAs.

material, the transition temperature can be altered. The Young's modulus of the high-temperature austenite of SMAs is about three to four times as large as that of low-temperature martensite. The transition temperature range for the Young's modulus of nitinol is about 10 to 30 degrees; its Young's modulus is a function of temperature.

Typical properties of nitinol (55% N) are [13]:

Martensite finish temperature	9.0° C
Martensite start temperature	18.4° C
Austenite start temperature	34.5° C
Austenite finish temperature	49.0° C
Stress influence coefficient	0.3+6 Pa/° C
Thermal conductivity	18.0 W/m° C
Martensite resistivity	0.90 E-6 Ωm
Austenite resistivity	0.73 E-6 Ωm
Emissivity	1.0
Density	6500 kg/m^3
Sensible specific heat	920 J/kg° C
Latent heat	72130 J/kg
Martensite Young's modulus	26.3 E+9 Pa
Austenite Young's modulus	67.0 E+9 Pa
Maximum recoverable strain	6.7%
Martensite thermoelastic tensor	0.289 E+6 Pa/° C
Austenite thermoelastic tensor	0.442 E+6 Pa/° C

The yield stress of martensite nitinol is approximately 984 N/mm^2 (12000 psi). The recovery stress is temperature dependent and it ranges from zero at 60° F to 563 N/mm^2 (80 Ksi) at 380° F [2]. SMAs have been used as force actuators, usually in the form of wire, rod, or spring. A spring made of nitinol can change its spring constant by a factor of four. Figure 3 shows the transformation phases of nitinol.

SMA materials can find a variety of applications. One area of application of these composite elements is vibration control of structures. By placing films or fibers of SMA materials in the structural elements and by proper application of electric fields, the mode shapes and vibration characteristics of the system can be controlled. One may refer to this as the active damping. Another potential application

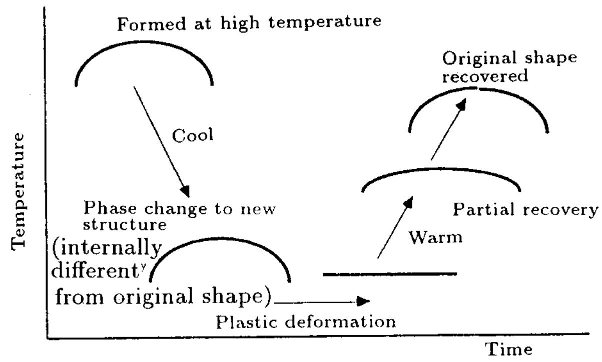

Figure 3. Phase transformation of the nitinol SMA.

is active stabilization and buckling control in which the unstable equilibrium configurations are stabilized through a closed control loop. Shape control of structures, i.e., alignment, position and configuration of various elements in a structure, is another area of application of SMA materials.

The actuator action of SMAs is as follows: Plastically elongated shape memory fibers tend to return to their original shape when activated by increasing the temperature to a certain degree. Through this contraction tendency, they apply tensile forces, mainly along the fibers, to the structure. In the shape memory composites, the total strain is the sum of the initial plastic strain and the added strain. The actuator behavior of SMA resembles a "mechanical muscle".

Electro-rheological Fluids

Electro-rheological (ER) fluids are very fine dielectric particles (1 to 100 μm in diameter) suspended in an carrier medium. Being sensitive to electric fields, the flow characteristics of ER fluids change in an interval of milliseconds. In the presence of an electric field, the particles are oriented along the field and a progressive gelling, proportional to the electric field, occurs. This gel is stiff enough to carry shear forces. The particles in ER fluids are based on polymers, minerals and ceramics. Carrier fluids, which must be good isolators, are usually silicone oil, mineral oil or chlorinated paraffin.

ER fluids exhibit controllable rheological behavior in the presence of an applied electric field. These materials can be used as active (tuneable) dampers and vibration isolators; damping of the system can be controlled by applying different electric fields. Experiments have been carried out in which the viscosity of an ER fluid has been varied to increase the damping efficiency of a composite beam [14].

Piezoelectric Actuators

Piezoelectric materials exhibit coupled electromechanical properties. They can generate an electric charge in response to mechanical deformation/force or, conversely, provide a mechanical strain when an electric field is applied across them. One group of piezoelectric materials are piezoceramics. Examples are piezoceramics based on zirconate titanate (PZT). As actuators, they are used, for example, for controlling the vibration response of composite structures.

Magnetostrictive Materials

These materials respond mechanically to magnetic fields; inversely, a magnetic field is induced in them due to mechanical effects. An example of magnetostrictive materials is $Tb_xDy_{1-x}(Fe_yMn_{1-y})n$.

Shape Memory Alloy Hybrid Composites

Composite structural elements containing SMA fibers of films have also been constructed. These elements have the capability of changing their stiffness by addition of heat, i.e., application of a current through the fibers/films. In this way the stiffness of the element can be controlled.

Shape Memory Polymers (SMP)

As discussed before, these are materials with an "elastic memory". They have the capability of a large, reversible change in their elastic modulus across the glass transition temperature (T_g). Across T_g, the material can change from a glassy state to a rubbery state, allowing a large change in the elastic modulus. Figure 4 shows the basic response of SMPs.

One of the SMPs has polynorborene as its base and has a glass transition temperature range T_g of 35° C to 40° C. One area of application of this material is in fittings of polymer pipes and automotive parts. Another SMP has trans-isopolyprene as its base and has a T_g of 67° C. Yet another SMP is styrene-butadiene based with a T_g ranging from 60° C to 90° C. There are also other types of SMP materials.

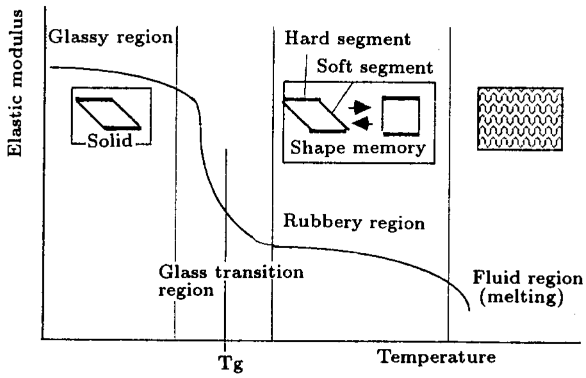

Figure 4. Variation of elastic modulus of SMP.

Potential uses and some of the realized applications of SMP materials as actuators are automotive parts, biomechanical area, electronic parts, clothing, sporting and packaging.

Conductive Polymeric Materials

Conductive polymeric materials capable of actuation include:

- Shape memory polymers (SMP).
- Molecular wires made of polythiophene chains.
- Polymer gels; used as electrically driven muscles. One type of gel is PAMPS (2- acrylamido 2methypropanesulfonic acid); another type is polyacrylonitrile (PAN) contractible gel, which is produced in fibers.
- PVDF films under AC voltage applied across their cross-section can be used as actuators. In actuation applications, they can be used as flat films or be hot-pressed or bonded to the surface of the curved elements. For example, they can be so attached to a shell such as on airplane fuselage. In corrugated form, they can also be attached to flat plates as actuators. Applications of PVDF

actuators are in acoustic and resonance control [15,16].

- Quinone polymer enhanced by other functional groups acting as a molecular switching device; switching is of the photochemical type.

INFORMATION PROCESSING IN IMSs

Information processing and decision making is an essential part of all IMSs. Varieties of information processing systems in IMSs are:

Holonic Systems

These are distributed information processing systems. They utilize a synthesizer and a memory composed of many unit oscillators (holons); each of the holons has excitatory/inhibitory interactions with its neighbors. A holonic system can perform pattern recognition by entrainment among the holons in the synthesizer and the memory [17].

Neural Networks

These include distributed information processing systems characterized by self organization. A neural network is composed of many identical inter-connected processing elements (neurons). Each neuron has incoming and outgoing connections. Its operation is local and it produces an output signal depending only on the input signal and the values in the memory [17].

Cellular Automata

They consist of distributed information processing systems containing a large number of simple identical processing elements with local interactions. Each cell determines its state from the previous values of neighboring cells. A cellular automaton can act as a transducer and produces an output information pattern in response to an input information pattern [17].

Analog Devices

These are mechanical material systems that solve specific problems through analogies. An analog device is a simulation machine. There are many analogies in mechanics on which an analog device can be built. Membrane torsion analogy is one example of such an analogy.

INTELLIGENT COMPOSITE MATERIALS

Intelligent composite materials are structural elements which have been made intelligent by placement of sensor and actuator fibers and/or films. In this way, a hybrid construction composed of otherwise passive structural parts and sensor/actuator components is formed.

The passive structural part itself may consist of a composite construction. Examples of composite construction are; glass fiber reinforced composites (GFRC), carbon fiber reinforced composites (CFRC) and steel reinforced concrete (SRC) elements. These elements can then be made intelligent by addition of sensors, actuators and control mechanisms.

Examples of intelligent hybrid (composite) construction are composites which contain SMA fibers or films as actuators, composites with PVDF films and composites which contain optical fibers as sensors. For instance, in the first example, by heating of the element, the SMA fibers are activated. As a result, the stiffness of the element can be changed and in this way some behavioral features of the hybrid composite element such as its vibration characteristics can be controlled. Vibration control of these element is, in fact, some sort of "energy tuning" in the sense that the resulting deflections are controlled and the corresponding stored energy is "tuned" in a desirable fashion. Buckling behavior of composite construction can also be controlled in a similar fashion.

INTELLIGENT STRUCTURES

Smart materials and smart structures have common basic definitions and characteristics. The salient feature of smart materials is, however, that the sensor, the actuator and the control elements are part of the microstructure itself. In smart structures, they may be externally attached to an otherwise passive structure. In some cases, they may be an integral part of the structure itself.

A structure has been defined as "a device which determines the relative position of numbers of points in space" [18]. This definition has been extended to include intelligent structures. Accordingly, they have been defined in terms of their intrinsic intelligent static and dynamic material and geometrical properties.

Terms like "intelligent", "smart", "adaptive" structures are normally used to describe structures which contain their own sensors, actuators and control mechanisms by means of which they can respond actively to their environmental stimuli. "Intelligent structures" may be constructed of "intelligent materials" in an integrated and continuous form or they may be made of relatively inactive materials/elements, but be equipped with sensors, actuators and control mechanisms in a discrete fashion.

A set theoretical classification is made of the so-called "active structures" [19]. Figure 5 shows such a classification. In this figure, sets of structural systems, their unions and intersections are defined. The categories mentioned in Figure 5 are: (S) the sensory structures; those which possess sensors which monitor the state of the system. These structures may have no controlling mechanism to alter their state, (P) potentially adaptive structures; these are structures which possess actuators to alter the state of the system, but they may have no sensors, (C) controllable structures which fall in the intersection of the sensor and the

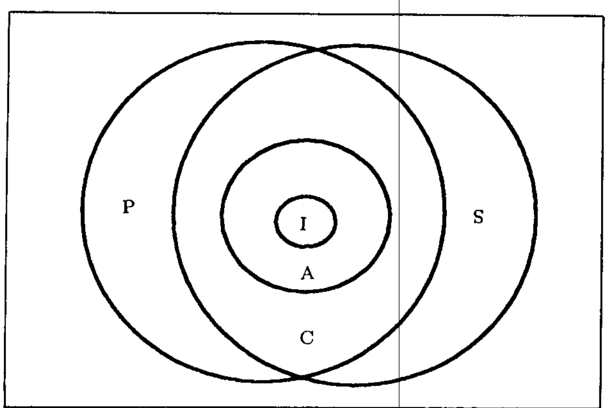

Figure 5. Classifications of structures [19].

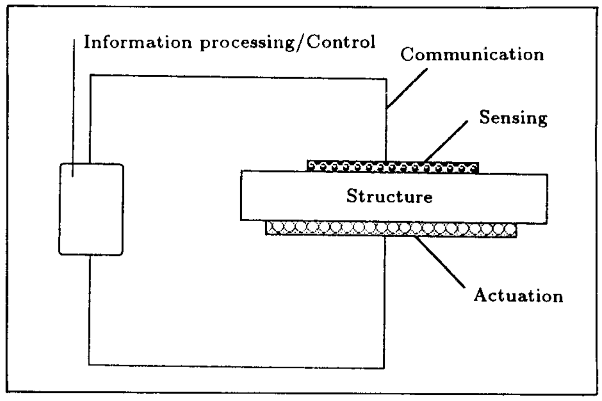

Figure 6. Composition of an adaptive structure.

actuator structures. These structures possess feedback mechanisms through which the behavior of the system is monitored and controlled: (A) active structures are controllable structures which possess sensory and actuator mechanisms which are integrally built in their architecture, (I) intelligent structures are those in which the integration of sensory and actuator mechanisms are highly accomplished.

The basic feature of smart structures at any level is adaptation. To make a structure and its behavior adaptive, certain mechanisms are needed. Figure 6 shows the basic ingredients of an adaptive structure. These include the structure itself, a sensing system, an information processing and control system and actuator system. These systems can be discrete in space or in time. They may be different from the structure or be continuous in space and in time and integrated with the structure.

Depending on the sensor-control-actuator systems and their interactions with the structure, different levels of intelligence can be achieved. On this basis, and in mind of further elaboration, we may describe the above mentioned structures as follows:

Adaptable Structures

Adaptive structures have been defined as those which possess actuators that can alter the states and/or characteristics of the system in a controlled manner. These structures may be geometry adaptive or material adaptive. The geometry adaptive structures can undergo large controlled geometric changes. Shape controlled space cranes and aircrafts which have been constructed are examples of geometry adaptive structures. Shape control of a structure may be realized by means of temperature field, electric field or the use of SMM [19].

Controlled Structures

Controlled structures possess both sensory and actuator mechanisms which are related through a feedback architecture. Due to presence of such feedback loops, these structures are distinguished from the adaptable structures and form a subset of the latter. These structures may be controlled in a number of ways; these are [19]:

1. Control of material properties (e.g., elastic moduli).
2. Control of the state of the system (e.g., position, velocity and acceleration of the material points and/or the overall structure).
3. Control of mechanical characteristics (e.g., stiffness, damping, natural frequency and buckling load).
4. Control of thermal state (e.g., temperature distribution).
5. Control of optical properties (e.g., hue and intensity).
6. Control of shape and dynamic response. This type of control takes place by the so-called active damping of wave propagation and vibration characteristics. Examples of such control are flutter control and control of structural response during earthquake.

Active Structures

Active structures are a subset of controlled structures in which the sensor and the actuator mechanisms are integrated with the structure itself to such a degree that "the distinction between the control functionality and structural functionality is blurred" [19]. Such structures possess discreetly or continuously placed sensors and actuators which are built into the architecture of the structure. Distributed strain actuators, which are bonded to the surface or are embedded within a composite structure, are means by which the integration of control and function has been achieved. Natural crystals, polymers, ceramic materials, magnetostrictive materials and SMMs, in the form of sheets or laminates bonded to the surface or embedded in the body of a composite structure, are examples of distributed actuators.

Intelligent Structures

Intelligent structures are a subset of active structures; they are differentiated from the other types of active structures by the presence of a highly distributed control system. An intelligent structure contains highly integrated sensory and control logic, placed in an hierarchical order. Such an integral and organized architecture provides the system with an extreme degree of material cognition and control.

A systemic hierarchical classification and ordering of structures described herein, is presented in Figure 7. A most efficient smart structure may be conceived to be the one which can adapt itself to all possible environmental requirements. It would then be able to function at any level, i.e., it would have a fractile nature. This idea, however, is something that should be explored in future research.

USES OF INTELLIGENT MATERIALS AND STRUCTURES

Varieties of applications have been envisaged for intelligent materials and structures. Some of these applications have been conceived of as potential uses and others have already come to realization. To summarize, the potential and the actual applications of intelligent materials and structures include:

1. Aerospace applications. This area of application embodies space antennae, mirrors, elements of spacecrafts and aircraft structures. A number of aerospace applications of IMSs are treated by [20-22].
2. Artificial intelligence and neuro-computers.

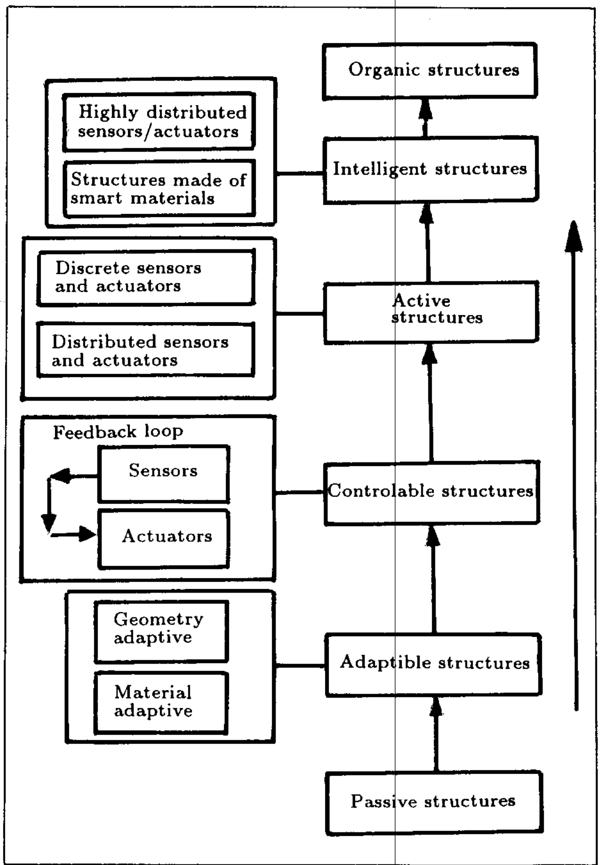

Figure 7. A systemic hierarchical classification and ordering of structures.

3. Biomedical engineering. Various applications of IMSs in bioengineering include: Biocompatible materials, biomaterials, biosensors and elements exhibiting self-adjusting function. These include biostructural elements such as artificial bones and intelligent implants [23] as well as biofunctional elements such as artificial skin and internal organ structures. In this connection, contractible polymeric materials have been considered to act as actuators [24]. These gels may be used in artificial muscles.

4. Robotics applications. Controllable mechanical assemblies has found its wide range of applications in robotics. Some of the related literature can be found in [25].

5. Objects of daily use, such as clothes.

6. Civil engineering. Civil engineering deals with design, analysis and construction of such structures as buildings and building elements, bridges, dams, cooling towers, silos, runways and roads. Monitoring of these installations is of prime importance and sensors are normally installed to monitor the behavior of such structures. Developments in sensor/actuator/control technology can be used to advantage in raising the quality and safety of these installations.

   The concept of creating intelligent structures has had one of its roots in the field of civil engineering. The need to control the response of tall buildings during an earthquake or in wind has given rise to extensive research, some of which has lead to systems such as active base isolations and active dampers. Some aspects of structural control are dealt with later. Recently, extensive research has been carried out in which optical fibers have been used as sensors for monitoring the behavior of various structures and elements [26].

7. Self-diagnosing and self-healing/self repairing objects. In this area, various actual and potential schemes may be conceived. For example, research has been carried out on materials which could contain types of hollow porous fibers filled with a chemical which would be released into the matrix at appropriate occasions. This has been intended for sensing, corrosion control, energy absorption, change in the properties, fracture investigations and repair of the cracks [27].

8. Self-adapting objects; objects which adapt their geometry and material-optical-thermal-chemical properties to the surrounding conditions.

9. Health monitoring application. Health monitoring involves such functions as recognition, discrimination, warning, self repair and damage control. One example of damage control application can be found in a class of material objects which, for

instance, respond to the stress field by detecting the induced cracks and moreover, by closing the crack tip. Another example is the class of materials which can recognize a damage that has occurred and can warn and/or suppress the advancement of the damage and even repair the damage.

10. Non-destructive evaluation and monitoring the status of a system.
11. Acoustic and vibration control.
12. Attitude and/or position control of the overall structures and vehicles; this is referred to as the rigid-body control.
13. Food processing and environmental contaminant detection.
14. Micro machines and biomotors.
15. Intelligent drug delivery systems; as for the means and specific applications, one may cite:
    - Polymeric membranes.
    - Polybasis gels [28].
    - Insulin delivery systems [29].
16. Aircrafts and space vehicles. Examples of these applications are: airplane wings that can reconfigure themselves to accommodate the flying conditions, submarines which can become invisible to sonar detection and helicopter blades which can maximize their lift forces [14].
17. Rehabilitation of existing installations. Most of the above-mentioned applications are primarily aimed at newly designed and constructed systems. One should add to these applications the concept of "making the existing installations and structures intelligent". There are many important structures which have been built and have operated for some years. It would be important to monitor the behavior of such structures and/or make them active, i.e., make them capable of actively responding to the environmental conditions. This idea can be materialized by installing sensors and actuators to the system. Structures such as dams, bridges, cooling towers, pipelines and containment structures are examples of systems which may be "made intelligent" by appropriate schemes.
18. Other potential applications. Among other applications of the IMSs one may cite:
    - Smart cables for hoisting objects and cable bridges.
    - Smart pipelines; for example development of no-leakage pipeline systems [30].

MODELLING, COMPUTATION AND DESIGN ASPECTS

Control of Structural Behavior

A Model for Active Structural Control

The quest for control of structural response has had different motivations. The need to reduce and confine damage caused by earthquake to buildings, dams, power plants and sensitive installations and also the requirement to limit the undesired vibrations of machinery and moving objects have been the main motives for seeking active structures, i.e., structures which respond actively to stimuli and exert their own control on their behavior.

Essential to design of active structures and evolution of intelligent material systems are the sensor and the actuation/control mechanisms. Figure 8 shows a systemic representation of the control-structure interaction [31]; in this diagram, the feedback interaction between the sensor, the actuator, the structure and the control is highlighted.

Referring to Figure 8, one may conclude that an active structural control may involve four major processes: gathering the sensory data, computation of the state of the system based on the sensory information, determination of the control forces based on a control strategy and driving the actuators [32].

Mathematical Model of Structure-Control Interaction

According to Figure 8, a controlled structure must contain some feedback mechanism through which the response of the structure can

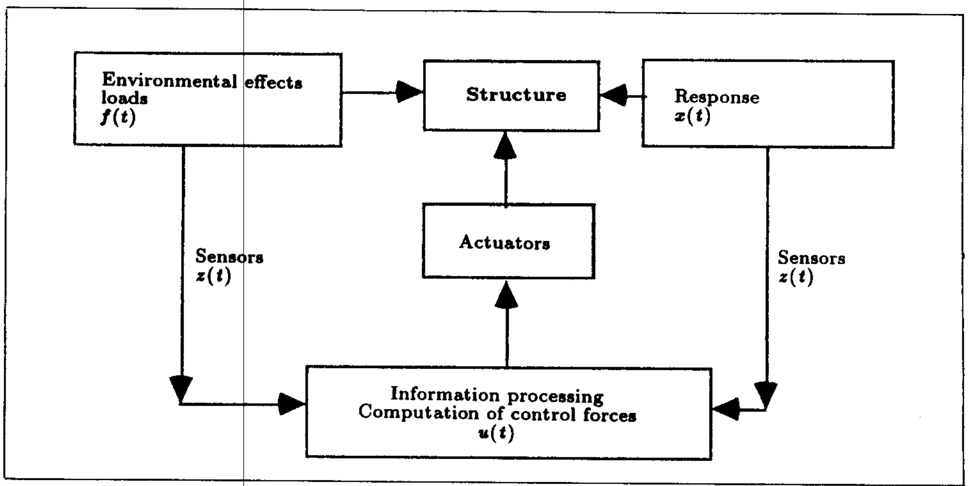

Figure 8. Elements of an intelligent structure.

be monitored and processed and desired control force be applied. Hence, a sound mathematical model of this system must include the parameters related to this combined structure-control system. A number of mathematical models representing such structure-control interaction have been proposed. A mathematical model which contains the common feature of various formulations can be outlined as follows [32].

Governing equations for the structure:

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{D}\dot{\boldsymbol{q}} + \boldsymbol{K}\boldsymbol{q} = \boldsymbol{f} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{G}\boldsymbol{w} \ . \qquad (1)$$

Relation for the sensor output:

$$\boldsymbol{z} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{v} \ . \qquad (2)$$

Sensitivity relation for the estimator:

$$\dot{\tilde{\boldsymbol{x}}} = \boldsymbol{A}\tilde{\boldsymbol{x}} + \boldsymbol{E}\boldsymbol{f} + \tilde{\boldsymbol{B}}\boldsymbol{u} + \boldsymbol{L}(\boldsymbol{z} - \boldsymbol{H}\tilde{\boldsymbol{x}}) \ . \qquad (3)$$

The control force:

$$\boldsymbol{u} = -\boldsymbol{F}\tilde{\boldsymbol{x}} \ . \qquad (4)$$

In these relations, the state variables and their estimates are defined as:

$$\boldsymbol{x} = \begin{Bmatrix} \boldsymbol{q} \\ \dot{\boldsymbol{q}} \end{Bmatrix}, \qquad \tilde{\boldsymbol{x}} = \begin{Bmatrix} \tilde{\boldsymbol{q}} \\ \dot{\tilde{\boldsymbol{q}}} \end{Bmatrix} \ . \qquad (5)$$

The matrices $\boldsymbol{H}$, $\boldsymbol{L}$, and $\boldsymbol{F}$ have the following decompositions:

$$\boldsymbol{H} = [\boldsymbol{H}_d \ \boldsymbol{H}_v], \ \boldsymbol{L} = \begin{bmatrix} \boldsymbol{L}_1 \\ \boldsymbol{L}_2 \end{bmatrix}, \ \boldsymbol{F} = [\boldsymbol{F}_1 \ \boldsymbol{F}_2] \ . \qquad (6)$$

These equations can be written in the following compact form:

$$\begin{Bmatrix} \dot{\boldsymbol{x}} \\ \dot{\tilde{\boldsymbol{x}}} \end{Bmatrix} = \begin{bmatrix} A & & -\bar{B}F \\ LH & , & A - \bar{B}F - LH \end{bmatrix} \begin{Bmatrix} \boldsymbol{x} \\ \tilde{\boldsymbol{x}} \end{Bmatrix} + \begin{Bmatrix} \boldsymbol{E} \\ \boldsymbol{E} \end{Bmatrix} \boldsymbol{f} + \begin{Bmatrix} \boldsymbol{G} \\ 0 \end{Bmatrix} \boldsymbol{w} \ , \qquad (7)$$

where $\boldsymbol{M}(n \times n)$ is the mass matrix, $\boldsymbol{D}(n \times n)$ is the damping matrix, $\boldsymbol{K}(n \times n)$ is the stiffness matrix, $\boldsymbol{f}(n \times l)$ is the applied load, $\boldsymbol{B}(n \times m)$ is the actuator location matrix, $\boldsymbol{G}(n \times r)$ is the disturbance location matrix, $\boldsymbol{q}(n \times l)$ is the generalized displacement vector, $\boldsymbol{w}(n \times l)$ is a disturbance vector, $\boldsymbol{z}$ is the measured sensor output, $\boldsymbol{H}_d$ is the matrix of displacement sensor locations and $\boldsymbol{H}_v$ is the matrix of velocity sensor locations. Vector $\boldsymbol{v}$ is the measurement noise. The superscript $\sim$ denotes the estimated states. The actuator output (the control) $\boldsymbol{u}$ is a function of the state estimator variable, $\tilde{\boldsymbol{x}}$ and $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$ are control gains. The observer is governed by the matrix $\boldsymbol{L}$; this is the filter gain matrix. Numerical schemes have been used to solve these systems of equations and to achieve a desired structure-control interaction [31,32].

These equations of control-structure interaction embody a set of $4n$ coupled nonsymmetric relations. The real-time processing of such a system presents many difficulties, so an efficient computation strategy should be adopted to solve these equations. In reference [32], a partitioning method has been proposed to solve these equations. Simplified versions of these equations have been used in literature to study the problems of shear frames, trusses and structures with limited degrees of freedom.

Hierarchically Organized Sensors/Controls of Structures

An intelligent building, embedded in nondeterministic environment, should be able to anticipate and to process the stochastic disturbances and to respond to these stimuli in a controlled purposeful fashion. A hierarchical order for control of an intelligent building system may be conceived and in this ordering, different levels of control imposed. For instance, a three-level hierarchical control has been proposed [33]. These consist of the local controller having high precision and low intelligence, the coordinator level, and the supervisor level having high intelligence and low precision.

The three levels of control proposed by [33] have the following functions. The function of the supervisor is an overall operating deterministic scheduling and optimization of the system for its steady state normal operations. The function of the coordinator level is to compensate for unexpected nondeterministic events. Its function is thus based on stochastic/fuzzy diagnosis and reasoning and provides a fast response to unexpected events. At the local control level, the monitoring diagnoses and optimization of the higher levels are precisely implemented and, when necessary, local changes imposed.

Pertinent to processing of the input information and imposition of proper control is the existence of a sensor/corrector system. The sensory/actuator system of the human body presents a very good example of such a system. It contains a complicated and yet efficient communication network for relaying and processing of the signals.

Inspired by biological systems, a neural model is proposed, as shown in Figure 9 [34]. This neural system receives input, processes this input and sends out output. This model of the neural communication and processing system consists of several layers (levels) of interconnected neurones (processors). The output from one processor passes to all the processors in the next layer. This is a model of the feed-forward multilayered networks. In this model, there is no learning process involved; the learning process would involve back-propagation of the signals and the errors.

The sensory system in an intelligent structure may be hierarchically organized in the form of a neural network similar to the one shown in Figure 9. In parallel, a model of neural computation must also be developed. This neural system can be further developed to be self-learning. The self-learning mechanism may be built-in by providing a processor that compares the command with the realized action. The differences can then be fed to the controller to correct the action.

Neural computation is now undergoing some new developments. Further work is needed, however, to achieve a computational model which includes the holographic and hierarchical features of the interwoven neural networks.

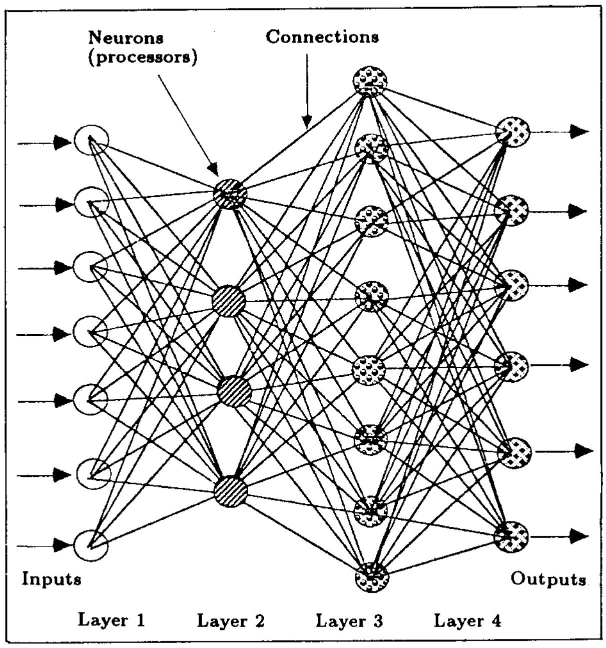

Figure 9. A neural communications model.

Categories of Active Structural Control

Some of the current research activities in the field of structural control have been summarized as follows [35]:

- Active Bracing System (ABS); active control using structural braces and prestressed tendons connected to controlling servomechanisms.
- Active Mass Damper and Active Mass Driver (AMD); previously, passive tuned mass was in existence. Those included mass dampers were tuned to the first (fundamental) frequency of the structure (effective for tall buildings). For other structures, in which the vibration energy is distributed over a frequency range, an active damping system would be more appropriate.
- Variable stiffness systems.
- Pulse control.
- Active parameter control to optimize the use of control energy.
- Aerodynamic appendage; for control of building vibrations against wind.

Active Structural Control Against Earthquake Motion

The technology of vibration isolation of machinery and buildings is, to a large extent, developed. As sensing devices there are thin films of micromachined silicon films. For actuation, there are devices such as hydromechanical vibration absorbers, cables, shape memory alloys and hybrid composites and, for communication, neural networks have been envisaged and in some cases actualized. Specifically, the following approaches have been proposed for control of the structural response due to earthquakes and wind effects:

- Use of additional masses and dampers at critical points of the structure. These are called the mass-dampers. The number, magnitude and location of the mass-dampers should be so designed as to achieve a certain response under assumed excitation. Mass-damping systems may be passive or active depending on their being unchangeable or capable of changing according to the varying stimuli.
- Base isolation by means of a sliding isolation system or hybrid friction controllable sliding bearings. In this scheme, the friction force would be controlled with a hydraulic mechanism. This would confine the sliding displacement in an acceptable range while reducing the response acceleration [36].
- The hybrid earthquake protective control system. This system consists of a base isolation mechanism connected to passive and/or active mass-dampers.
- Using structural members and/or active bracing system to alter the stiffness and, thus, the dynamic characteristics of the structure, these being the damping and the natural frequencies associated with the dominant earthquake frequency. Use of active members in trusses and cables to exert control forces has been a proposal in this direction [37].

Active Shells and Plates

Shells have varieties of applications in civil engineering, pressure vessel and pipe technology, roofing, containment structures and aircraft structures. Flat plates are shells with zero curvature. Laminated flat plates and strips are used in various structures, such as precision and devices, and micro-sensor/actuators. Due to the wide range of applications, interest in designing plate and shells which would actively respond to the external stimuli has considerably increased in recent years.

To control the response of plate and shell structures, discrete and/or distributed sensor/actuator mechanisms may be used. Shells having thin piezoelectric lamina bonded to their surface or embedded inside their thickness belong to the class of continually sensed/actuated active structures.

So far, research effort in this direction has been mainly oriented towards designing piezoelectric members for distributed active vibration control of the shell continua, including curved shells, flat plates and beams. In these designs, the active member contained piezoelectric layers as sensor/actuators. The stability control of one-dimensional members has been the subject of investigation. However, the stability control of shells with distributed sensors/actuators remains to be further explored.

In this section, a simplified stability theory of active shells is proposed. This theory is an extension of the stability theory of passive shells treated by [38]. In this theory, the term "generalized shells" refers to shells with arbitrary geometry which depict the effect of local rotation and consequently the possibility of the so called membrane instability, in addition to other modes of elastic instability.

Figure 10 shows an infinitesimal element of a shell faced with two active layers. These are distributed sensor/actuator mechanisms. In this element, three coordinate systems are defined: the local XYZ system is oriented along the principal directions of the curvature; the $X_1Y_1Z_1$ and $X_2Y_2Z_2$ systems are local coordinate systems at the other adjacent corners. The rate of change of orientations of these two systems, relative to XYZ are described by the two vectors Ω_2 and Ω_2.

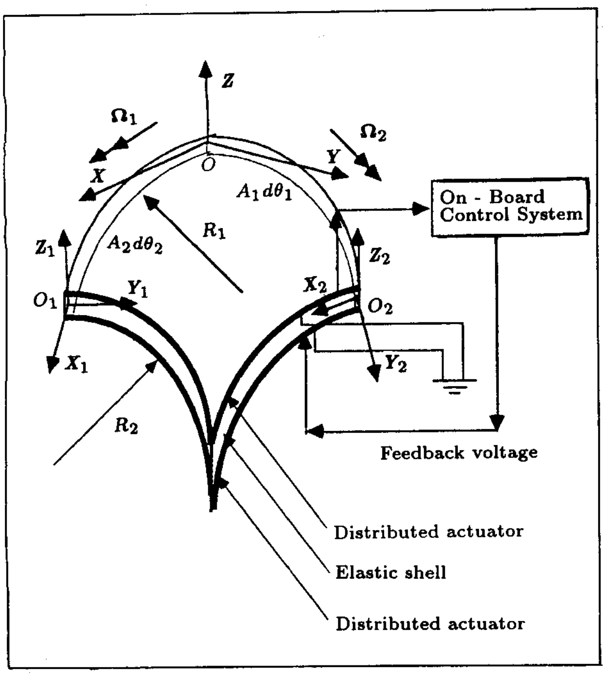

Figure 10. An element of an active generalized shell.

The perturbed vectorial stability equations of "generalized shells" can be written as (for details, see [38]):

Perturbed Equilibrium Equations

$$\boldsymbol{n}_{\alpha,\alpha} + \Omega_{o\alpha} \times \boldsymbol{n}_\alpha + \omega_{o\alpha} \times \boldsymbol{N}_{o\alpha} + \boldsymbol{f} = \boldsymbol{0} \qquad \alpha = 1,2 \tag{8}$$

$$\boldsymbol{m}_{\alpha,\alpha} + \Omega_{o\alpha} \times \boldsymbol{m}_\alpha + \omega_{o\alpha} \times \boldsymbol{M}_{o\alpha} + \boldsymbol{t}_\alpha \times \boldsymbol{n}_\alpha + \boldsymbol{g} = \boldsymbol{0} \quad \alpha = 1,2 \tag{9}$$

In these equations, $\boldsymbol{n}_\alpha$ and $\boldsymbol{m}_\alpha$ are vectors of perturbed internal force resultants. $\Omega_{o\alpha}$ is the rate of change of orientation of $X_1Y_1Z_1$ and $X_2Y_2Z_2$ systems relative to XYZ in the critical state and $\omega_{o\alpha}$ is the perturbation in this rate of change of orientation. $\boldsymbol{t}_\alpha$ ($\alpha = 1,2$) are the tangent vectors associated with the XYZ axes. $\boldsymbol{f}$ and $\boldsymbol{g}$ are perturbations in the applied external forces. The subscript comma (,) denotes partial differentiation with respect to the curvilinear coordinates θ_α ($\alpha = 0\ 1,2$); the corresponding Lame parameters are denoted by $\boldsymbol{A}_\alpha$ ($\alpha = 0\ 1,2$). $\boldsymbol{N}_{o\alpha}$ and $\boldsymbol{M}_{o\alpha}$ are resultants of the internal forces and the internal moments in the critical stage.

Kinematic Relations

The relations between the strain vectors ε_α ($\alpha = 1,2$) and the change of curvature vectors ω_α ($\alpha = 1.2$) with the displacement and rotation vectors $\boldsymbol{u}$ and Φ are [38] the strain displacement-rotation relationship:

$$\varepsilon_\alpha = [(\boldsymbol{u}_{.a} + \Omega_{o\alpha} \times \boldsymbol{u} + \boldsymbol{t}_\alpha \times \Phi]/A_\alpha \quad (\alpha = 1,2)\ , \tag{10}$$

and the change in curvature-rotation relationship:

$$\kappa_\alpha = (\Phi_{.a} + \Omega_{o\alpha} \times \Phi)/A_\alpha \quad (\alpha = 1,2)\ . \tag{11}$$

Constitutive Relations

The coupled electromechanical constitutive relations can be expressed as follows:

$$\boldsymbol{n}_\alpha = \boldsymbol{c}_\alpha\ \varepsilon_\alpha - \boldsymbol{e}^{T_\alpha} \boldsymbol{E}_\alpha\ , \tag{12}$$

$$\boldsymbol{m}_\alpha = \boldsymbol{I}_\alpha\ \kappa_\alpha - \boldsymbol{g}^{T_\alpha} \boldsymbol{S}_\alpha\ , \tag{13}$$

$$\boldsymbol{D}_\alpha = \boldsymbol{e}_\alpha\ \varepsilon_\alpha + \boldsymbol{h}\ \boldsymbol{e}_\alpha\ \kappa_\alpha + \boldsymbol{r}_\alpha\ \boldsymbol{E}_\alpha\ , \tag{14}$$

$$\boldsymbol{R}_\alpha = \boldsymbol{f}_\alpha\ \kappa_\alpha + \boldsymbol{p}_\alpha\ \boldsymbol{S}_\alpha\ . \tag{15}$$

The inverse relations would be:

$$\varepsilon_\alpha = \boldsymbol{s}_\alpha\ \boldsymbol{n}_\alpha + \boldsymbol{d}_\alpha \boldsymbol{E}_\alpha\ , \tag{16}$$

$$\kappa_\alpha = \boldsymbol{Q}_\alpha\ \boldsymbol{m}_\alpha + \boldsymbol{H}_\alpha \boldsymbol{S}_\alpha\ , \tag{17}$$

$$\boldsymbol{D}_\alpha = \boldsymbol{d}_\alpha\ \boldsymbol{n}_\alpha + \boldsymbol{r}_\alpha\ \varepsilon_\alpha\ , \tag{18}$$

$$\boldsymbol{S}_\alpha = \boldsymbol{a}_\alpha\ \boldsymbol{R}_\alpha + \boldsymbol{k}_\alpha\ \kappa_\alpha\ . \tag{19}$$

These vectorial constitutive relations relate the internal forces and moments ($\boldsymbol{n}_\alpha$ and $\boldsymbol{m}_\alpha$) and electric displacement and spin vectors ($\boldsymbol{D}_\alpha$ and $\boldsymbol{R}_\alpha$), on one hand, with the mechanical strains and curvature change (ε_α and κ_α) and electric field intensity and electric field moment intensity ($\boldsymbol{E}_\alpha$ and $\boldsymbol{S}_\alpha$), on the other hand. Transformation of these sets of quantities to each other takes place by means of tensors of elastic properties ($\boldsymbol{c}_\alpha, \boldsymbol{I}_\alpha$) and tensors of the electrical properties ($\boldsymbol{e}_\alpha, \boldsymbol{d}_\alpha$) where:

$\boldsymbol{c}$	=	elastic stiffness matrix,
$\boldsymbol{s} = \boldsymbol{c}^{-1}$	=	elastic compliance matrix,
$\boldsymbol{r}$	=	permissibility matrix,
$\boldsymbol{e}$	=	piezoelectric stress matrix,
$\boldsymbol{d}$	=	piezoelectric strain matrix.

The superscript (T) designates the transpose of the related matrix representation of these tensors; subscript α takes the values 1 and 2 corresponding to the two directions along the directions of principal curvature.

Assuming a piezoelectric material with hexagonal symmetry, the matrix representation of the material properties, expressed by the tensors $\boldsymbol{J}$, $\boldsymbol{d}$ and $\boldsymbol{c}$, are:

$$[I] = \begin{bmatrix} I_{11} & I_{12} & 0 \\ I_{21} & I_{22} & 0 \\ 0 & 0 & I_{33} \end{bmatrix},$$

$$[d] = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix},$$

$$[c] = \begin{bmatrix} c_{11} & c_{12} & 0 \\ c_{21} & c_{22} & 0 \\ 0 & 0 & c_{33} \end{bmatrix},$$

$$[e] = \begin{bmatrix} d_{31} & 0 & 0 \\ 0 & d_{32} & 0 \\ 0 & 0 & d_{36} \end{bmatrix}. \tag{20}$$

The properties related to the tensors $\boldsymbol{I}$, $\boldsymbol{D}$, and $\boldsymbol{C}$ can be similarly expressed. The electric field contributed by mechanical strain and electric displacement can be written as [7]:

$$E_\alpha = e_\alpha/c_{11} - \varepsilon_{\alpha 3} d_{15}/c_{11} \quad \alpha = 1, 2\ , \tag{21}$$

$$E_3 = e_3/c_{11} - (\varepsilon_{11} d_{31} + \varepsilon_{22} d_{31} + \varepsilon_{33} d_{33})/c_{33}\ , \tag{22}$$

where the symbols with subscripts represent the components of their related matrices.

Charge Equation of Electrostatic

$$[d_{31}\varepsilon_{11} + d_{31}\varepsilon_{22} + d_{33}E_3))\ A_1\ A_2 \\ (1 + z/R_1)(1 + z/R_2)]_{,z} = 0 \tag{23}$$

These field equations must be accompanied by appropriate mechanical and electric boundary conditions.

These governing stability relations of active shells embody, as their special cases, the stability equations of piezoelectric plates, rings, beams and shells with particular geometry such as cylindrical and spherical shells. Two Lame parameters (A_1 and A_2) and two radii of curvature (R_1 and R_2) are needed to specify a particular shell geometry.

The piezoelectric layers shown in Figure 10 are assumed to be thin and flexible; they are assumed to be polarized in the thickness

(z) direction. The thickness direction is the isotropic direction of the material.

Equations 8 to 23, together with appropriate boundary conditions, provide a set of stability equations for actively stability controllable shells, plates and rods. Details of this theory remain to be further clarified and specific applications to be presented; such an undertaking, however, would be beyond the present presentation.

INTELLIGENT STRUCTURES AND SYSTEMS OUTLOOK

Intensification of research and professional activities in fields such as "smart materials", "intelligent structure" and so on, mark the end of the era of atomistic/elementalistic view of the material systems. An era which had ancient roots, but had come to its culmination during the eighteenth to twentieth centuries. Now, for further developments in materials science and structural engineering, researchers are looking to nature more intensively as the main paradigm. It is with this new spirit that the following passage from the book Kinetic Architecture by Zuk and Clark has found renewed attention and has been quoted in some new literature:

"Life itself is in motion, from the single cell to the most complex organism, man ... It is these attributes of motion, mobility, of change, of adaptation that place living things on a higher plateau of evolution than static forms. Indeed, survival of these living species depends on their kinetic abilities: to nourish themselves, to heal themselves, to produce themselves, to adapt to changing needs and environments, and, in the case of man, to be materially and spiritually productive" [39].

The new vision of materials is organismic; its motives being to learn from nature and living systems and to apply this knowledge in such a way as "to enable man-made artifacts to have adaptive features of autopoiesis as we see throughout nature" [40]. This changing tendency has had its stages of development, which are best reflected in the literature on adaptive structures. As outlined in the previous sections, the concept of using different discrete sensors, actuators and controllers has been developed to integrate all these devices together with the structure itself. The guideline for such development was the notion that in nature the material, the structure and the function are integrated.

Specific lessons have been learned from living organisms for developing some intelligent structures, the so-called induced strain actuators, i.e., the bonded or embedded actuators which react to the applied force by contraction are but simple imitations of the muscles during contraction. It is believed that the SMA are actually artificial prototypes of the muscular filaments. The new tendencies of creating shape adaptive and material adaptive structures is another case of looking at nature for inspiration. Designing a shape adaptive truss which should behave like a plant is one of the many examples in this direction [18]. It is from a newly emerging organismic view that sensory devices such as optical fibers are conceived to be artificial nerves. The term "smart skins" is also akin to this conception.

New developments in materials and structures have altered the status of mechanical systems in the hierarchical architecture of the world systems. The traditional view in structural engineering has been to conceive of materials as networks of molecules and structures as shape-preserving material objects suitable for passively transferring the applied loading. From this viewpoint, structures were placed in the lowest level of the hierarchical level of the world systems. The salient features of intelligent structures, namely, active interrelations, feedback controls, hierarchical order, self-organization dynamic equilibrium and morphogenesis, instead of homeostasis, gives them a true systemic character which has been rather weak in the passive structures. This new status of materials and structures places them higher in the hierarchy of world systems [41]. Perseverance of form indicates the lowest stage and the dominance of function at the expense of form marks the higher order of this system's hierarchical architecture. The emerging views of materials and structures has many common features with the general system's outlook.

CONCLUDING REMARKS

Research and development in the field of intelligent materials and structures has a multidisciplinary character. Various specialities, instruments and methodologies are required to carry out fruitful research in this area and to develop an effective intelligent material/structure system. A comprehensive knowledge of this field should be gained by detailed information in the following areas:

- Sensor systems.
- Actuator systems.
- Signal and information processing.
- Control technology.
- Materials research.
- Mechanics and engineering of structures.

The piece-wise knowledge is, however, not sufficient to develop an intelligent materials technology. At some stage, these pieces must be put together and a synthesis of various pieces of information must be made. This synthesis requires a systems approach. In a systemic framework, different activities can be planned, carried out and integrally superimposed. The current literature shows strong inclinations towards this systemic outlook.

Two important parts of the intelligent material/structures technology are definitely the construction and the utilization aspects. New designs must be feasible and effective. Energy expenditures and efficiency play roles in design decisions. Some of the designs which may seem promising in the laboratory may not be as much realizable in practice. Complicated layout may not necessarily imply a more effective design.

Finally, the terms "smart", "intelligent" and so on, used quite freely by many researchers in these fields, touch upon very profound aspects of life which are definitely not present in man-made systems. They are also not value-free. The novelties in the areas of materials and structures certainly come very short in describing those aspects. The new materials and structures would be quite unable to represent those qualities. In this case, as in many other areas of human activity, a strong homeocentric viewpoint has been adapted. "Smart" and "intelligent" materials and structures have been defined in human eyes and in the framework of human desires. These points certainly deserve profound meditation. Nevertheless, the emerging organismic vision of materials and structures can revive the expectation that the broken ties with nature may again be established and the premises of nature once more respected.

REFERENCES

1. Takagi, T. "A concept of intelligent materials", *J. of Intelligent Materials Systems and Structures*, **1** (2) (1990).

2. Rogers, C.A. "An introduction to intelligent material systems and structures", in *Intelligent Structures*, K.P. Chong, S.C. Liu and J.C. Li, Eds., Elsevier Applied Science, London, pp 3–41 (1990).

3. Takagi, T. "A concept of intelligent materials and the current activities of intelligent materials in Japan", in *First European Conf. on Smart Structures and Materials*, B. Culshaw, P.T. Gardiner and A. McDonach, Eds., Inst. of Physics Publishing and EOS/SPIE EUROPTO Series, SPIE, **1777**, pp 13–18 (1992).

4. Wolf, R. and Meisseler, H.J. "Monitoring of prestressed concrete structures with optical fibre sensors", in *Proc. of the First Int. Conf. on Intelligent Materials, ICIM '92*, T. Takagi, K. Takahashi, M. Aizawa and S. Miyata, Eds., Technomic Publishing Co., Inc., Lancaster, UK, pp 23–29 (1993).

5. Caussignac, J.M., Chabert, A., Morel, G., Rogez, P. and Seantier, J. "Bearings of a bridge fitted with load measuring devices

based on an optical fibre technology", in *Proc. of the First Int. Conf. on Intelligent Materials, ICIM '92*, T. Takagi, K. Takahashi, M. Aizawa and S. Miyata, Eds., Technomic Publishing Co., Inc., Lancaster, UK, pp 207–210 (1993).

6. Culshaw, B. and Michie, C. "Fibre optic strain and temperature measurement in composite materials-a review of the OSTIC programme", in *Recent Advances in Adaptive and Sensory Materials and Their Applications*, Technomic Publishing Co., Inc., Lancaster, UK, pp 791–808 (1992).

7. Tzou, H.S. "Active piezoelectric shell continua", in *Intelligent Structural Systems*, H.S. Tzou and G.L. Anderson, Eds., Kluwer Academic Publishers, Dordrecht, pp 9–74 (1992).

8. Jia, J., and Rogers, C.A. "Formulation of laminated shells theory incorporating embedded distributed actuators", in *Adaptive Structures*, B.K. Wada, Ed., The Amer. Soc. of Mech. Eng., New York, pp 25–34 (1989).

9. Rogers, C.A. and Stein, S.C. "Recent advances in structural control using intelligent material systems", in *Proc. of the First Int. Conf. on Intelligent Materials, ICIM '92*, T. Takagi, K. Takahashi, M. Aizawa and S. Miyata, Eds., Technomic Publishing Co., Inc., Lancaster, UK, pp 87–93 (1993).

10. Egusa, S. and Iwasawa, N. "Preparation of Piezoelectric paints as vibration sensors coated on the surface of structural materials", in *Proc. of the First Int. Conf. on Intelligent Materials, ICIM '92*, T. Takagi, K. Takahashi, M. Aizawa and S. Miyata, Eds., Technomic Publishing Co., Inc., Lancaster, UK, pp 101-104 (1993).

11. Anderson, G.L., Mommaaerts, J., Tang, S.L., Luke, J.C. and Dillard, Jr., D.A. "Monitoring adhesive joints using piezoelectric polymer film", in *Recent Advances in Adaptive and Sensory Materials and Their Applications*, Technomic Publishing Co., Inc., Lancaster, UK, pp 266–273 (1992).

12. Lee, C.-K. "Piezoelectric laminates: theory and experiments for distributed sensors and actuators", in *Intelligent Structural Systems*, H.S. Tzou and G.L. Anderson, Eds., Kluwer Academic Publishers, Dordrecht, pp 75–167 (1992).

13. Malafeew, E., Vick, B., Liange C. and Rogers, C.A. "Distributed electro-thermomechanical analysis of shape memory alloy actuators", in *Recent Advances in Adaptive and Sensory Materials and Their Applications*, Technomic Publishing Co., Inc., Lancaster, UK, pp 94–119 (1992).

14. Crowson, A. "Smart materials and structures: an army perspective", in *Recent Advances in Adaptive and Sensory Materials and Their Applications*, Technomic Publishing Co., Inc., Lancaster, UK, pp 811–821 (1992).

15. Liang, C. and Rogers, C.A. "A fully-coupled acoustic analysis of curved PVDF acoustic actuators for active sound attenuation", in *Recent Advances in Adaptive and Sensory Materials and Their Applications*, Technomic Publishing Co., Inc., Lancaster, UK, pp 765–779 (1992).

16. Oh, K., Nayfeh, A.H. and Pai, P.F. "Control of the resonant response of a cantilever plate using films as the sensor/actuator system: an experimental study", in *Recent Advances in Adaptive and Sensory Materials and Their Applications*, Technomic Publishing Co., Inc., Lancaster, UK, pp 625–632 (1992).

17. Amemiya, Y. "Information processing by intelligent materials-information processing–processing architectures for material processors", in *Proc. of the First Int. Conf. on Intelligent Materials, ICIM '92*, T. Takagi, K. Takahashi, M. Aizawa and S.

Miyata, Eds., Technomic Publishing Co., Inc., Lancaster, UK, pp 231–236.

18. Miura, K. "Studies of intelligent adaptive structures", in *Adaptive Structures*, B.K. Wada, Ed., The Amer. Soc. of Mech. Eng., New York, pp 89–94 (1989).

19. Wada, B.K., Fanson, J.L. and Crawley, E.F. "Adaptive structures", in *Adaptive Structures*, B.K. Wada, Ed., The Amer. Soc. of Mech. Eng., New York, pp 1–8 (1989).

20. Miura, K. and Natori, M.C. "Aerospace research status on adaptive structures in Japan", in *Second Joint Japan/US Conf. on Adaptive Structures*, Y. Matsuzaki, and B.K. Wada, Eds., Technomic Publishing Co., Inc., Lancaster, UK, pp 3–14 (1992).

21. Anderson, W.W. "The NASA-LaRC controls-structure interaction (CSI) technology program", in *Second Joint Japan/US Conf. on Adaptive Structures*, Y. Matsuzaki and B.K. Wada, Eds., Technomic Publishing Co., Inc., Lancaster, UK, pp 15–31 (1992).

22. Breitbach, E.J. "Research status on adaptive structures in Europe", in *Second Joint Japan/US Conf. on Adaptive Structures*, Y. Matsuzaki, and B.K. Wada, Eds., Technomic Publishing Co., Inc., Lancaster, UK, pp 32–48 (1992).

23. Mahmud, F. and Hastings, G. "A new intelligent implant for simulating bone fracture healing: design criteria", in *Proc. of the First Int. Conf. on Intelligent Materials, ICIM '92*, T. Takagi, K. Takahashi, M. Aizawa and S. Miyata, Eds., Technomic Publishing Co., Inc., Lancaster, UK, pp 505–514 (1993).

24. Solari, M., Morasso, P. and Casalino, G. "Contractible polymeric materials in the design of a linear actuator", in *Proc. of the First Int. Conf. on Intelligent Materials, ICIM '92*, T. Takagi, K. Takahashi, M. Aizawa and S. Miyata, Eds., Technomic Publishing Co., Inc., Lancaster, UK, pp 287–295 (1993).

25. Matsuzaki, Y. and Wada, B.K. Eds., *Second Joint Japan/US Conf. on Adaptive Structures*, Technomic Publishing Co., Inc., Lancaster, UK (1992).

26. Measures, R.M. "Smart structure technology and its potential for civil engineering", in *Applications of Fibre Optic Sensors in Engineering Mechanics*, F. Ansari, Ed., ASME Publication, New York, pp 17–38 (1993).

27. Dry, C. "Passive smart materials for sensing and actuation", in *Recent Advances in Adaptive and Sensory Materials and Their Applications*, Technomic Publishing Co., Inc., Lancaster, UK, pp 207–222 (1992).

28. Yoshida, R. and Sakai, K. " 'On-off' switching mechanism of pulsatile drug release using thermo-responsive poly (N-isopropyl acrylamide-co-alkyl methacrylate) gels", in *Proceedings of the First Int. Conf. on Intelligent Materials, ICIM '92*, T. Takagi, K. Takahashi, M. Aizawa and S. Miyata, Eds., Technomic Publishing Co., Inc., Lancaster, UK, pp 393–396 (1993).

29. Shiino, D., Kataoka, K., Koyama, Y. and Yokoyama, M. "A self-regulated insulin delivery system using boronic acid gel", in *Proc. of the First Int. Conf. on Intelligent Materials, ICIM '92*, T. Takagi, K. Takahashi, M. Aizawa and S. Miyata, Eds., Technomic Publishing Co., Inc., Lancaster, UK, pp 301–304 (1993).

30. Tani, J. and Ohtomo, K. "Sealing effect of a magnetic fluid at a crack", in *Proc. of the First Int. Conf. on Intelligent Materials, ICIM '92*, T. Takagi, K. Takahashi, M. Aizawa and S. Miyata, Eds., Technomic Publishing Co., Inc., Lancaster, UK, pp 139–142 (1993).

31. Wen, Y.K. and Ang, H.S. "Reliability and cost-effectiveness of structures with

active control", in *Intelligent Structures-2, Monitoring and Control*, Y.K. Wen, Ed., Elsevier Applied Science, London, UK, pp 63–76 (1992).

32. Park, K.C., Alvin, K. and Belvin, W.K. "Parallel computations and control of adaptive structures", in *Intelligent Structures*, K.P. Chong, S.C. Liu and J.C. Li, Eds., Elsevier Applied Science, London, pp 439–458 (1990).

33. Shoureshi, R., Rahmani, K. and Van Doren, V. "Intelligent building control systems", in *Intelligent Structures*, K.P. Chong, S.C. Liu and J.C. Li, Eds., Elsevier Applied Science, London, pp 196–215 (1990).

34. Rehak, D.R. and Garet Jr., J.G. "Neural computing for intelligent structural systems", in *Intelligent Structures-2, Monitoring and Control*, Y.K. Wen, Ed., Elsevier Applied Science, London, pp 147–161 (1992).

35. Housner, G.W., Masri, S.F. and Soong, T.T. "Recent developments in active structural control research in USA", in *First European Conf. on Smart Structures and Materials*, B. Culshaw, P.T. Gardiner and A. McDonach, Eds., Inst. of Physics Publishing and EOS/SPIE EUROPTO Series, SPIE, **1777**, pp 201–206 (1992).

36. Kawamura, S., Shinozuka, M., Fujii, S. and Feng, Q. "Hybrid isolation system using friction controllable sliding bearings", in *Intelligent Structures-2, Monitoring and Control*, Y.K. Wen, Ed., Elsevier Applied Science, London, pp 264–278 (1992).

37. Kobori, T. and Kamagata, S. "Dynamic intelligent buildings-active seismic response control", in *Intelligent Structures-2 Monitoring and Control*, Y.K. Wen, Ed., Elsevier Applied Science, London, pp 279–292 (1992).

38. Farshad, M. and Tabarrok, B. "A simplified stability theory of general shells", *Int. J. Solids and Structures*, **25** (3), pp 235–248 (1989).

39. Zuk, W. and Clark, R.H. *Kinetic Architecture*, 1st Ed., Von Nostrand Reinhold, New York, p 14.

40. Rogers, C.A. "Intelligent material systems - the dawn of a new materials age", *J. of Intelligent Material Systems and Structures*, **4** (1), pp 4–12 (1993).

41. Farshad, M. and Tabarrok, B. "Systems perspectives in applied mechanics", *Int. J. General Systems*, **14**, pp 45–58 (1987).