Smart systems and smart materials

Science and technology has made amazing developments in the design of electronics and machinery by using standard materials, which did not have particularly special properties (i. e. steel, aluminum, gold etc). Imagine the range of possibilities, which exist for special type of materials that have properties scientists can manipulate. Some such materials has the ability to change shape or size or simply by adding a little bit of heat, or to change from a liquid to a solid almost instantly when it is near a magnet; these materials are called smart materials.

Smart materials are the materials that have one or more properties that can be dramatically altered. Most everyday materials have physical properties, which cannot be significantly altered; for example if an oil is heated it shall become little thinner, whereas a smart material with variable viscosity may turn from a fluid which flows easily to a solid. A variety of smart materials already exists, and is being researched extensively. These includes piezoelectric materials, magneto-rheostatic materials, electro-rheostatic materials, and shape memory alloys. Some everyday items are already incorporating smart materials (coffeepots, cars, the International Space Station, eyeglasses) and the number of applications for them is growing rapidly.

Each individual type of smart material has a different type of property which can be significantly altered, such as viscosity, volume, and conductivity. The property which can be altered influences what types of applications the smart material can be used for.

Smart systems and smart materials

Smart structures are the new emerging materials systems which combines contemporary materials science with information science. The smart system is composed of these:- sensing, processing, actuating, feedback, self-diagnosing and self-recovering subsystems. These system uses the functional properties of advanced materials to achieve high performances with the capabilities of recognition, discrimination, and adjustification in response to make change of its environment. Each component of this system must have functionality, and the entire system is integrated to perform a self-controlled smart action, similar to a living creature that can “ think”, make judgment and take actions. A smart system can be considered as a design philosophy that emphasizes predictivity, adaptivity and repetivity. A smart system/structure is defined as a non-biological physical structure having the following attributes:

(1) a definite purpose;

(ii) means and imperative to achieve that purpose; and

(iii) a biological pattern of functioning.

Smart materials are the subset of the smart systems, i. e. smart structures at the microscopic or mesoscopic scales. Smart systems are the non-biological structures which means that the system functions as a biological system rather than the pattern of functioning as a Turning machine.

These materials will generally include at least one structural element, some for means of sensing the environment and its own state, and some type of processing and adaptive control algorithm. Science and technology in the

21st century will have to rely heavily on the development of new materials that are expected to respond to the environmental changes and manifest their own functions according to the optimum conditions. The development of these materials will undoubtedly be an essential task in many fields of science and technology such as informatics science, micro-electronics, computer science, medical treatment, life science, energy, transportation, safety engineering and military technologies. Materials development in the future, therefore, should be directed toward creation of hyperfunctional materials which will surpass even biological organ in some aspects. The present materials research is to develop various pathways that will lead the modern technology towards the smart systems.

Types of Smart Materials

Piezoelectric materials:-

Piezoelectric materials have two unique properties that are interrelated. When a piezoelectric material is deformed, it gives off a small but a measurable electrical discharge. Alternately, when an electrical current is passed through a piezoelectric material it experiences the significant increase in size (approx. up to a 4% change in volume)

Piezoelectric materials are widely used as sensors in different type of environments. They are often used to measure fluid composition, fluid density, fluid viscosity, or the force of an impact. An example of a piezoelectric material in everyday life is an airbag sensor in our car. The material senses the force of an impact on the car and thus sends and electric charge deploying the airbag.

Example of Piezoelectric materials

Electro-rheostatic (ER) and magneto-rheostatic (MR) materials:-

Electro-rheostatic (ER) and magneto-rheostatic (MR) materials are fluids, which can experience dramatic change in their viscosity. These type of fluids can change from thick fluids (similar to motor oil) to nearly a solid substance within a span of a millisecond when exposed to a magnetic or an electric field. The effect can completely be reversed just as quickly when the field is removed. MR fluids experience viscosity changes when exposed to a magnetic field, while ER fluids experience similar type changes in an electric field. The composition of each type of smart fluid varies widely. The most common form of MR fluid consists of the tiny iron particles suspended in oil, while ER fluids can be as simple as milk chocolates or corn-starch and oil.

MR fluids are mostly being developed for use in the car shocks, damping washing machine vibration, prosthetic limbs, exercise equipment, and surface polishing of machine parts. ER are mainly being developed for use in the clutches and valves, as well as engine mounts designed to reduce noise and vibration in the vehicles.

Shape memory alloys:-

Shape memory alloys (SMA’s) are the metals, which exhibit two intresting unique properties, pseudo-elasticity, and shape memory effect. Arne Olander first observed these unusual properties in 1938 (Oksuta and Wayman 1998), but until the 1960’s were no any serious research advances made in the field of shape memory alloys. The most effective and widely used alloys includes- NiTi (Nickel – Titanium), CuZnAl, and CuAlNi.

The unusual properties mentioned in the above are being applied to a wide variety of applications in the number of different fields.

Shape memory alloys use

) pH sensitive polymers:-

pH sensitive or pH responsive polymers are the materials which responds to the changes in the pH of the surrounding medium by varying or changing their dimensions. Such materials either swell or collapse depending on the pH of their own environment. These behaviour are exhibited due to the presence of certain type of functional groups in the polymer chains.

There are only two kinds of ph sensitive materials:- one that have acidic group (-COOH, -SO3H) and swells in basic pH, and others that have basic groups (-NH2) and swells in acidic pH. Polyacrylic acid is an example of a former and Chitosan is an example of a latter. The mechanism of response is just same for both, just the stimuli varies. Their response is triggered due to the presence of ionisable functional groups (eg -COOH, -NH2) which get ionized and acquires a charge +/- in a certain pH. The polymer chains are now having similarly charged groups which causes repulsion and thus the material expands in dimensions. The opposite of this happens when pH changes and the functional groups loses their charge hence the repulsion is therefore gone and the material collapses back. These materials are being widely used for controlled drug delivery systems and biomimetics

Halochromic material:-

Halochromic materials are the materials which changes colour when pH changes occurs. The term ‘ chromic’ is defined as the materials that can change their colour reversibly in the presence of a factor. In this case, the factor is pH. The pH indicators have this type of property.

Halochromic substances are suited for use in environments where pH changes occur very frequently, or the places where changes in pH are most. Halochromic substances can detect alterations in the acidity of substances, eg- detection of corrosion in metals. These substances can be used as indicators to determine the pH of the solutions of unknown pH. The colour obtained is compared with the colour obtained when the indicator is mixed with solutions of known pH. The pH of the unknown solution can then be estimated. Obvious disadvantages of this type method include its dependency on the colour sensitivity of the human eye, and those of unknown solutions that are already colour can be used.

example of halochromoic

The colour changes of halochromic substances occur when a chemical binds to existing hydrogen and hydroxide ions in solution. Such bonds result in changes in the conjugate systems of the molecules, or the range of electron to flow. This alters the amount of light absorbed, which in turns results in a visible change of colour. Halochromic substances does not display a full range of colour for a full range of pH because, after certain acidities, the conjugate system does not changes. The various shades resulted from different type of concentrations of halochromic molecules with the different conjugate systems.

(6)Dielectric elastomers (DEs):- Dielectric elastomers are the smart material systems which produces large strains (even up to 300%) and belong to the group of electro active polymers (EAP). Based on their simple principle of working dielectric elastomers actuators (DEA) transform electric energy directly into the mechanical work. DE are lightweight, and have a high elastic energy density and are investigated since the late 1990's. Many of its potential applications exist as prototypes. Every year in spring a SPIE conference takes place in San Diego where the newest research results concerning DEA are exchanged between.

Self-healing materials:-

These materials are the class of smart materials that are having the structurally incorporated ability to repair damage caused by mechanical usage over time. The inspiration comes from the biological systems, which have the ability to heal after being wounded. Initiation of cracks and other types of damage on a microscopic level have been shown to change the thermal, electrical, and acoustical properties, and eventually lead to the whole scale failure of these materials. Usually, cracks are mended by hand, which is difficult because cracks are often hard to detect. A material (polymers, ceramics, etc.) that can intrinsically correct the damage caused by normal usage could lower production costs of the number of different industrial processes through longer part lifetime, reduction of inefficiency over time caused by degradation, as well as prevent costs incurred by material failure. For a material to be called as self-healing, it is necessary that the healing process shall occur without human intervention. Examples shown below include healing polymers that are not “ self-healing” polymers.

Example of self healing

Temperature-responsive polymer:-

Temperature-responsive polymer is a polymer which undergoes a physical change when an external thermal stimulus is presented. Their ability to undergo such changes under easily controlled conditions makes this class of polymers fall into the category of smart materials. These physical changes can be exploited for many analytical techniques, especially for separation chemistry. After numerous investigations of poly(N-isopropylacrylamide) (poly-NIPAAm), there was a sparked interest in the applications of this and many other stimuli-responsive polymers. There have been extensive research in the applications of intelligent polymers for use as stationary phases, extraction compounds, surface modifiers, drug delivery, and gene delivery.

Temperature responsive polymer

Applications of smart materials

There are many possibilities for smart materials and structures in this world. Engineering structures can be operated at the very limited of their performance envelopes and to their structural limits without fear of the exceeding either. These structures can also give maintenance engineers a full report on the performance history, as well as the location of the defects, whilst having the ability to counteract the unwanted or potentially dangerous conditions such as excess vibration, and effect self repair.

Smart Materials in Aerospace:-

Some materials and structures are termed ‘ sensual’ devices. These are structures which can sense their environment and generate data for use in health and usage monitoring systems (HUMS). Today the most well established application of HUMS are in the field of aerospace, in the areas such as aircraft checking.

An aircraft constructed from a ‘ sensual structure’ could self-monitor its performance to a level beyond that of current data recording, and provide ground crews with the enhanced health and usage monitoring. This would minimise the overheads associated with HUMS and allow such aircraft to fly for more hours before any human intervention is required.

Smart Materials in Civil Engineering

They can be used in the monitoring of civil engineering structures to assess durability. Monitoring of the current and long term behaviour of a bridge would lead to enhanced safety during its life since it would provide early warning of structural problems at a stage where minor repairs would enhance durability, and when used in conjunction with structural rehabilitation can be used to safety monitor the structure beyond its original design life. This will influence the life costs of such structures by reducing upfront construction costs and by extending safe life of the structures. ‘ Sensual’ materials and structures also have a wide range of potential domestic applications, as in food packaging for monitoring safe storage and cooking.

The above example addresses only ‘ sensual’ structures. However, the smart materials and structures offer the possibility of structures, which not only sense but also adapt with their environment. Such

types of adaptive materials and structures benefit from the sensual aspects highlighted earlier, but in addition have the capability to move, vibrate, and exhibit a multitude of other real time responses.

Potential applications of such adaptive materials and structures range from the ability to control the aeroelastic form of an aircraft wing, thus minimising drag and improving operational efficiency, to vibration control of lightweight structures such as satellites, and power pick-up pantographs on trains.

Ken Materials

‘ Mechatronic’ smart structures have demonstrated the capability of its technology, but raise the important issue of the complexity of the resulting system. This smart type of structures contains a multitude of different materials, and in the case of sensual structures it will generate large amounts of data. This increase in complexity has been described as the ‘ spaghetti syndrome’, and has led to the proposal for an alternative type of smart structure based on the concept of ken materials (the Chinese characters which means wisdom, structure, monitoring, integration and benignity is being pronounced ‘ ken’ in the Japanese language). Such structures will move functional integration into the constituent engineering materials by themselves.

Some of the practical examples of ken materials exist at present, although a structural composite based on this concept had been developed in Japan. This is a carbon and glass fibre reinforced concrete which able to monitor concrete structures by using only the structural reinforcing fibres, thus reducing the complexity of the system.

(4) Structural Uses

(a) Active control of structures

The concepts of the adaptive behaviour have been an underlying theme of active control of structures which are subjected to an earthquake and other environmental types of loads. The structure adapts its dynamic characteristics to meet the performance objectives at any instant.

Sun and Sun (vi) used a thermo mechanical approach to develop a constitutive relation for bending of a composite beam with a continuous SMA fibers embedded eccentric to neutral axis. The authors finally concluded that SMA’s can be successfully used for the active structural vibration control. Thompson(iii) also conducted an analytical investigation on the use of SMA wires to dampen the dynamic response of the cantilever beam constrained by SMA wires.

(b) Passive control of structures

Two families of the passive seismic control devices which are exploiting the peculiar properties of SMA kernel components has been implemented and tested within our MANSIDE project (Memory Alloys for New Seismic Isolation and Energy Dissipation Devices). They are the Special braces for the framed structures and isolation devices for the buildings and bridges.

(c) Smart Material Tag

These smart materials tag can be used for composite structures. These tags can be monitored externally throughout the life of those structures to relate the condition of internal material. Such measurements as stress, moisture, voids, cracks and discontinuities might be interpreted via a remote sensors.

(d) Retrofitting

SMAs can use as self-stressing fibres and therefore they can be applied for retrofitting. Self-stressing fibres are the ones in which the reinforcement is placed into the composite–non-stressed state. A prestressing force is therefore introduced into the system without the use of large mechanical actuators, by providing SMAs. These materials thus do not need specialized electric equipments nor do they create safety problems in the field. Treatment can be applied at any time after hardening of matrix instead of during its curing and hardening. So the Long or short term prestressing is introduced by triggering the change in SMAs shape using temperature or electricity.

The Future

The development of true smart materials at the small atomic scale is still progressing a little, although the enabling technologies are under the development. These require the novel aspects of nanotechnology (technologies which are associated with materials and processes at the nanometre scale, 10-9m) and the newly developing science of shape chemistry.

Worldwide, a considerable effort is being made to develop these smart materials and structures. The technological benefits of such types of systems have begun to be identified and, demonstrators are therefore under construction for a wide range of applications from space to aerospace, to civil engineering and to domestic products. In many of above, these applications, the cost benefit analyses of such systems are yet to be fully demonstrated. The Office of Science and Technology’s Foresight Programme has recognised these types of systems as a strategic technology for the future, having considerable potential for creation of wealth through the development of various unknown products, and performance enhancing the existing products in a broad range of the industrial sectors.

The concept of engineering materials and structures which respond to their own environment, including their human owners, is somewhat an alien concept. So it is therefore not only important that the technological and financial implications of these materials and structures are addressed, but also issues associated with public understanding and acceptance. Techno-democracy could only come about only through education and exposure of the general public to these technologies. However, such a general acceptance of smart materials and structures may in fact be more difficult than some of the technological hurdles which are associated with their development. A new “ smart materials” process — Multiple Memory Material Technology — developed by University of Waterloo engineering researchers promises to revolutionize the manufacture of diverse products such as medical devices, microelectromechanical systems (MEMS), printers, hard drives, automotive components, valves and actuators.