# Smart Structures and Materials

*V K Wadhawan*

**A structure is an assembly that serves an engineering function. It is reasonable to expect that all engineering design should be smart, and not dumb. But one can still make a distinction between smartly designed structures and smart structures. The latter term has acquired a specific technical meaning over the last few decades. A smart structure is that which has the ability to respond adaptively in a pre-designed useful and efficient manner to changes in environmental conditions, including any changes in its own condition; the response is adaptive in the sense that two or more stimuli or inputs may be received as anticipated and yet there is a single response function as per design. Smartness ensures that the structure gives optimum performance under a variety of environmental conditions. While structures with some degree of smartness have been designed from times immemorial, the current activity and excitement in this field derives its impetus from the level of sophistication achieved in materials science, information technology, measurement science, sensors, actuators, signal processing, nanotechnology, cybernetics, artificial intelligence, and biomimetics.**

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## Introduction

In conventionally engineered structures there is a tendency for over-designing, usually for meeting safety requirements. Ideally, one would like to have "passive design for purpose, and adaptive design for crises". By contrast, the usual conventional approach is to ensure that the passive structure is adequate for crises also, thus entailing higher costs due to over-designing. Some examples wherein, ideally, adaptive action should come into play only for crisis or special situations are buildings in earthquake zones, aircrafts during take-off and landing, and

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vehicles in crashes. A smart configuration would be that in which normal loads are taken care of in normal conditions, and suitable actuation systems are activated to tackle abnormal loads.

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Even for normal loads, corrosion and other aging effects can render the original passive design unsuitable (even unsafe) with the passage of time. If continuous monitoring can be built into the design through distributed embedded sensors, timely repairs can be taken up, thus saving costs and ensuring a higher degree of safety.

Two types of smartness in structures can be distinguished: *closed-loop* and *open-loop*. A closed-loop smart structure senses the changes to diagnose the nature of the problem, takes action to mitigate the problem, and also stores the data of the episode for future reference. Open-loop smartness means that the design is such that structural integrity is enhanced only when needed, and the structure relapses to its normal state when there is no need for enhanced integrity.

*Smart bridges* are a particularly attractive proposition. Bridges involve an enormous amount of investment on construction, maintenance, repair, upgrade, and finally replacement. Possible vehicular accidents, earthquakes, and terrorism are additional problems to contend with. Embedding optical fibres as distributed sensors at the construction stage itself is not a very costly proposition. On-line monitoring and processing of the vast amount of sensor data is again not a difficult thing to do by present-day standards. And the overall advantages in terms of lower maintenance costs, higher safety and security, and avoidance of inconvenience caused by closure for repair work can be enormous, not to mention the prevention of disasters like bridge collapses.

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*Adaptronic structures* is another term used for smart structures. In the years to come, we shall see an increasing trend to incorporate smartness into the design of even ordinary items of use. Rogers has given a particularly vivid description of the nature of structural designs of the future: *Adaptronic structures must, as their basic premise, be designed for a given purpose; and, by the transduction of energy, must be able to modify their behaviour to create an envelope of utility. As an example, a ladder that is overloaded could use electrical energy to stiffen or strengthen itself while alerting the user that the ladder is overloaded. The overload response should also be based upon the actual 'life experience' of the ladder to account for aging or a damaged rung; therefore, the ladder must determine its current state of health and use this information as the metric for when the ladder has been overloaded. At some point of time, the ladder will then announce its retirement, as it can no longer perform even minimal tasks.*

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## Biomimetics

Biological structures or systems are the smartest, and in terms of energy consumption the most economical. *Figure* 1 shows the basic essential configuration of a biological system. There are sensors (nerves), actuators (muscles), a control centre (the brain), and the host structure (the body, with or without bones). A source of energy is also needed.

The living system senses the changes in the environment, and the information from the distributed sensors is sent to the brain (or to the locally distributed control systems). The organism has a purpose or objective (for example, the need to survive and

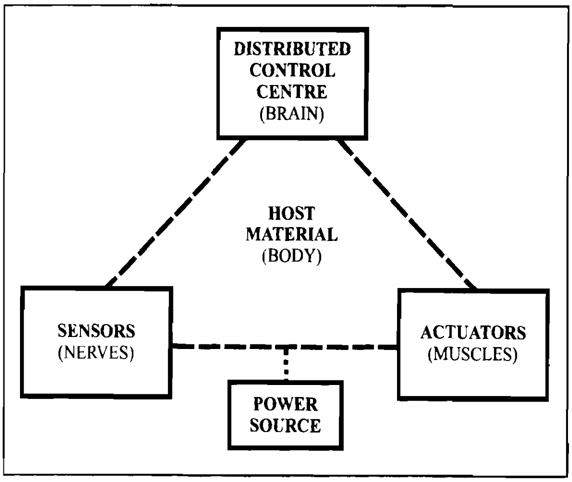

***Figure 1. The basic essential configuration of a biological or living system.***

sustain itself). In keeping with the objective the brain sends command signals to the muscles or actuators to take appropriate action. For example, if the sensors sense excessive heat in the environment, the actuators take the system away from the hot region. All along there is continuous interaction and feedback among the sensors, the actuators and the decision-making centre(s).

Smart structures are designed to mimic biological systems to a small or large extent. Biomimetics is already a flourishing science. In fact, smart structures can be alternatively defined as those which possess characteristics close to, and, if possible, exceeding, those found in biological structures.

Biological structures have several characteristics: sensing; actuation; adaptability; self-repair; self-replication or reproduction, etc.

Designers of smart structures strive to achieve as many of these features as possible, at minimal cost. 'Very smart structures' are those which have several of the features listed above; the degree of smartness can vary from case to case.

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The conventional approach to design and engineering is to imagine a worst-case situation and build-in enough redundancies and a large safety margin. The smart-structure approach, by contrast, learns from biological systems and introduces *distributed* and *on-line* sensors, actuators, and microprocessors. One tries to replace one-time design and fabrication by on-line or lifelong *adaptability*.

Adaptability requires several things. One of them involves the way materials from which a structure is built respond to external or internal forces. Let us take a look at this aspect of adaptability.

## Linear and Nonlinear Response of a Material

Suppose a force $X$ is applied on a material, and there is a response $Y$ (the force can be anything: mechanical, electrical, magnetic). Naturally, $Y$ will depend on $X$. Suppose it is possible to express this dependence accurately as $Y = A_1 X$, where $A_1$ is a constant. This is an example of *linear* response. There are many real-life situations in which this is not the case; i.e. the proportionality factor depends on the value of $X$: $Y = A_2(X)\ X$. In such a situation, if we were to plot $Y$ as a function of $X$, we would not get a straight line, but rather a curved line. This is *nonlinear* response. Nonlinear response implies that the relevant property of the material is not fixed; rather it is *field-tunable*, and can therefore be adapted to fulfil a pre-designed requirement.

There are several ways of achieving nonlinear response. One possible scenario is that in which we can have a large force field $X$, so that, although the material normally exhibits linear behaviour (at small $X$), it enters the nonlinear regime when $X$ is large. A second way is to work with a material that undergoes *ferroic phase transitions*, so that its response (in a certain range of operation) is inherently nonlinear (even for small $X$). A third way is to exploit the properties of what has come to be called 'soft matter'; many of the biological materials are soft matter, and they are complex nonlinear systems. Size-dependent properties of nanostructured materials also offer exciting possibilities.

## Smart Systems, Structures, and Materials

A temperature-controller module is an example of a smart *system*. Information about the temperature to be kept constant is fed into the system. Any deviation from this set temperature generates an 'error' signal, and a negative-feedback mechanism determines the corrective action for restoring the temperature to the set value. There is complicated electronic circuitry, and the system comprises a number of distinct and separate component-systems. The configuration is not that of an integrated or embedded structure. If the system were to be split into, say, two parts arbitrarily, it would stop functioning. Of course, such systems have been in use for a long time, although the use of the term 'smart systems' for them is of recent origin.

Some experts regard a thermistor as an example of a smart *material.* Its resistivity is a pre-designed useful function of temperature. What is more, if it is cut into two or more parts arbitrarily, each part is still a thermistor which can act as a 'smart' material, adjusting its electrical resistance autonomously, in a predesigned manner, against variations in temperature. Thermistors may be called *passively* smart materials (PSMs). It is easy to find many examples of PSMs: varistors, photochromic glasses, optical limiters, and many others.

Smart *structures* have features intermediate between those of smart materials and smart systems. *Actively smart structures* not only have a sensor feature and an actuator feature, but, unlike passively smart materials, they also involve external biasing or feedback. There is thus externally aided, nonlinear self-tunability in their design with respect to one or more properties of the material(s) used.

One can make a distinction between smart structures and *intelligent* structures, reserving the latter term only for applications incorporating cognitive capabilities and adaptive learning in the design, generally entailing the use of fast, real-time, information processing with neural networks.

There is a viewpoint that, by and large, a *material* cannot be smart; only a *structure* or a *system* designed from a judicious choice of materials can possibly be smart. Culshaw [2] has introduced the so-called *information-reduction criterion* in this context. Culshaw takes the view that there is nothing smart about a material (or a structure) making a *fixed* linear or nonlinear response to a stimulus. What is required for smartness is that the response be according to some pre-designed functional dependence on the input parameter, *irrespective of other relevant inputs impinging on the material (or structure).*

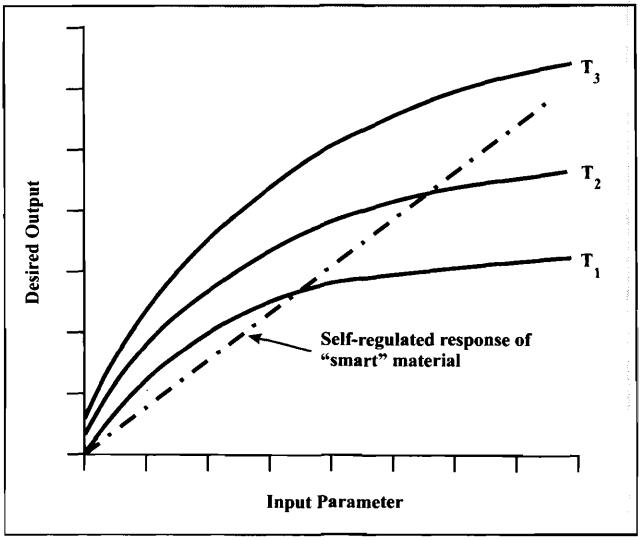

*Figure 2. A possible example of a smart material. Dependence on ambient temperature or pressure is the natural response of any material. If self-regulatory corrections exist such that the response is independent of all such parameters, and is only as per design, then we do have a smart material. [After Culshaw, 1996. [2] ]*

*Figure* 2 makes the point with an example. The response of the material is (naturally) temperature dependent. If, by any dispensation, the response can be made, say, linear (or some other desired function of the input parameter), and, in this example, *independent of temperature*, then we are indeed dealing with a smart material. There is a process of information reduction in this scenario. The material takes in the additional information about change of temperature, and yet reduces it to a single value of corrected output. There is a one-to-one relationship between the input parameter and the desired output which is independent of temperature.

It may appear that no single material by itself can be smart, according to this criterion. But we argue here that a material with a nonlinear response, *and with a bias field applied to it*, can act smart, at least in certain situations. For example, we can take a block of a relaxor-ferroelectric ceramic and electrode a pair of its opposite faces. The objective here is to make it operate as a capacitor, the capacitance $C$ of which is independent of temperature. The permittivity of relaxors is large, and also a decreasing or increasing function of temperature, depending on the chosen temperature span. These materials also produce a large and temperature-dependent electrostriction strain. We can apply a fixed voltage $V_{bias}$ to produce a certain reference strain (through electrostriction), giving a net separation $d$ between the electrodes. Temperature-induced changes of permittivity (and therefore of capacitance $C$) can be cancelled by temperature-induced changes in the electrode separation $d$, brought about by the dependence of electrostrictive strain on temperature. The bias voltage $V_{bias}$ can be chosen to achieve an exact cancellation of these two effects in the temperature-range of operations. The end result is that a signal voltage $V_s$ (the $x$-axis in *Figure* 2) produces a charge $q_s$ (the $y$-axis in *Figure* 2), through the equation $q_s = C\ V_s$, that is independent of temperature $T$ (over a certain range of temperatures).

Some of these relaxor-ferroelectrics exhibit the so-called 'two-way shape-memory effect'. What this means is that they have a 'memory' of their shape at various temperatures. This effect can also be exploited to achieve the above objective, with the added advantage that there is no need to apply the voltage $V_{bias}$. This becomes possible because the shape-memory effect implies that, for a specific direction, the block of material will contract on heating and expand on cooling, thus adjusting the separation $d$ autonomously. There is thus an additional parameter available for self-adjustment.

Use of composites, instead of single-phase materials, can further extend the feasibility range of such ideas.

## Sensors

As shown in *Figure* 1, sensing action is an essential requirement for a smart structure. In biological systems, the sensor output can be of various types, but in man-made structures the most convenient sensor output is an electrical signal. Thus a sensor is usually a transducer involving a specific transduction principle for transforming a particular form of energy input into an electrical signal.

Of particular interest in the present context is an *integrated sensor*. It is a microsensor integrated with signal-processing circuits on a single package. Such a packaged sensor not only transduces the measurand into electrical signals, but may also have other signal-processing and decision-making capabilities, thus giving the feature of smart or intelligent sensing. Integrated sensors have several advantages: better signal-to-noise ratio; improved characteristics; and signal conditioning and formatting.

Optical fibres are the most popular choice as and for sensors in smart structures. One makes a distinction between *intrinsic* and *extrinsic* optical-fibre systems. In the former the fibre itself is the element undergoing modulation of light by the measurand. In the latter, the fibre acts only as a waveguide for the light going towards and away from the sensor.

In an intrinsic optical-fibre system the optical waves being guided by an optical fibre can be influenced (*modulated*) in a variety of ways by the environmental parameter to be sensed. Intensity, phase, frequency, polarisation, and colour of the optical beam are the main quantities analysed for the modulation caused by the measurand.

Optical fibres can be employed for *distributed* measurements, followed by a quick mapping of the measured field. Because of their thinness, they do not degrade the integrity of the composite in which they are embedded.

## Actuators

Like sensors, actuators are also an essential component of most of the conceivable smart structures. An actuator creates controllable mechanical motion from other forms of energy.

*Microactuators* offer special advantages, but they should be, by and large, compatible with the materials and processing technologies of silicon microelectronics. They should be capable of being powered and controlled electrically, thus allowing full utilisation of integration with on-chip electronics. There are two types of microactuators: 'mechanisms' which provide displacement through rigid-body motion; and 'deformable microstructures' which provide displacement by mechanical deformation or straining.

Ferroic materials are involved in the fabrication of a variety of actuators, although several other types of materials are also used. Particularly popular are the shape-memory alloys like NiTi. Other options include piezoelectric and electrostrictive materials, as also electro-rheological fluids.

## Artificial Intelligence and Neural Networks

If smart structures are to graduate to intelligent structures, there has to be a provision for learning and decision-making.

If smart structures are to graduate to intelligent structures, there has to be a provision for learning and decision-making. This requires the use of computers for putting together at least the crude equivalent of the animal brain.

The human brain consists of $\sim 10^{11}$ neurons of various types. Each neuron typically connects, via an *axon* that eventually branches out into strands and substrands, to many thousand neurons. The *firing* of a neuron is mostly an all-or-nothing business; this discrete character being retained as the pulse travels down an axon. However, on arrival at a destination neuron, the pulse is handled by a *synaptic interface* characterised by an analogue parameter (typically an *excitation or inhibition weight*) the value of which may be, to some extent, history-dependent.

Serial processing of large amounts of information is generally not very efficient. Parallel processing can help a lot, although serial processing has its own advantages. The smartest model of how to handle information efficiently is that provided by the human brain. Artificial neural networks (NNs) are based on models of the brain and its behaviour. They are a set of 'neurons' working concurrently. They can learn system-dynamics without requiring *a priori* information regarding the system structure.

NNs are circuits consisting of a large number of *processing elements* (PEs), and designed in such a way as to significantly exploit aspects of *collective behaviour*, rather than rely on the precise behaviour of each PE. NNs are a distinct conceptual approach to computation, depending in an essential way on statistical-physics concepts. A typical application for NNs is to help in making *decisions* based on a large number of input data having comparable *a priori* importance: for instance, reconstructing the characters on a license plate (a few bits of information) from the millions of pixels of a noisy and somewhat blurred and distorted camera image.

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NNs have three basic elements:

- PEs;
- a method to *train* the NN to solve problems; and
- a method to *recall information* from the NN.

A NN consists of PEs connected together. Each unit is associated with a numeric value, called the *connection weight*. PEs are divided into disjoint sets called *layers*. Each PE forms a weighted sum of the inputs impinging on it, using a *sum function*. This sum is then transferred by a *transfer function* to a value that is fed to an *output function*.

*Learning* is a process of adjusting the connection weights in order to make the NN develop correct *associations* between objects concerning some application. There is a single *learning rule* for an entire layer.

It is an interesting paradox that, although the human brain is largely a parallel computing system (and a massively parallel system at that), our final thinking process is predominantly serial or sequential (Try doing even five different things at the same time!).

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## Machine Consciousness

Consciousness is not easy to define or understand. Some researchers take the view that if we can model it, howsoever crudely, the very act of modelling it would lead to at least some incremental understanding. The so-called *global workspace theory*

### Box 1. The Born and the Made

There are three players in the game of life and evolution: human beings, nature, and machines. Machines are becoming biological, and the biological is becoming engineered. When the union of the born and the made is complete, our fabrications will learn, adapt, heal themselves, evolve. The distinction between the born and the made smart structures will become more and more blurred.

Man-made smart structures are on an evolutionary path, in the following sequence:

- *Actively* smart structures (sensor + feedback + enhanced actuator action).
- *Very* smart structures (sensor + feedback + enhanced actuator action + one or more other biomimetic features).
- *Intelligent* structures (actively smart structures endowed with a *learning feature*, so that the degree of smartness increases with 'experience').
- *Wise* structures (moral and ethical decisions).
- Consciousness in smart structures.
- Collective consciousness. The internet is already playing the role of some kind of a collective consciousness for the planet earth, and much more is still to come.
- Man-machine integration. 'Immortality' through repeated repair or replacement of worn out or unserviceable parts (both animate and inanimate).

of consciousness represents it as a phenomenon that emerges when a number of sensory inputs, such as images or sounds, activate competing processes in the brain, such as memory or basic emotions like fear or pleasure. These momentarily activated processes and mechanisms then compete with one another to determine the most relevant action.

'Action plans' are believed to be the basis of conscious thought. Many constituent parts play a role in determining the action plans.

One of the designs for a conscious machine starts by assuming that there is *a neural 'depiction' in the brain* that exactly matches every scrap of our inner sensations. In order to form consciousness, these depictions have to have at least five major qualities:

- a sense of place;
- awareness of the past, and imagination;
- the ability to focus on what one wants to be conscious about;

### Box 2. Existing Smart Structures and Materials

Four materials are star-performers, so far as their applications in existing smart structures and systems are concerned: PZT, Nitinol, PMN, and Terfenol-D.

PZT (lead zirconate titanate) is a piezoelectric material, having the largest longitudinal piezoelectric coefficient among all known single-phase materials. Its most familiar application is in gas lighters, used for lighting up the gas stove in your kitchen. A piezoelectric material can function as both a sensor and an actuator. Application of electric field produces change of dimensions (motion-generating strain) in it. Conversely, an applied stress (as in the case of the kitchen gas lighter) results in the appearance of a dipole moment and the concomitant surface charge.

PMN (lead magnesium niobate) is a relaxor ferroelectric, exhibiting a very large electrostriction effect: there occurs a large shape-changing strain proportional to the square of the applied electric field. PMN and its variants find uses in smart structures as nearly-hysteresis-free microactuators.

Nitinol is an alloy based on Ni and Ti. It exhibits the shape-memory effect (SME). Above a certain temperature it exists in a phase called 'austenite', and makes a transition to 'martensite' on cooling through that temperature. It can be deformed severely when in the martensitic phase, and yet it recovers its shape on heating to the austenitic phase. In other words, it behaves as if it has a memory of the shape it had while in the austenitic phase. This effect finds two types of uses in smart structures. Either the shape-recovery tendency is used for achieving large-throw actuation; or, if the material is prevented from recovering its shape, a strong internal stress is generated which changes the effective stiffness of the medium, thus finding uses in vibration-control applications. A large number of applications exist for shape-memory alloys (SMAs) like Nitinol. An example of an actively smart structure in this context is the folding-box type protective shroud. On being heated by solar energy in outer space, the SMA actuator converts itself from a stowed to a fully deployed (unfolded) shape, thus providing protection to the satellite from being hit by the debris of earlier or abandoned satellite parts.

Terfenol-D ($Tb_{1-x}Dy_xFe_2$) is a magnetostrictive alloy; therefore magnetic field can be used for producing actuator strain in it. A variety of high-energy-density actuators have been made using Terfenol-D. They are rugged and reliable, finding uses in high-power sonar and in vibration control.

The muscle of humans and other animals is a marvel of an actuator, and one would like to duplicate its performance in artificial smart structures. Substantial success has been achieved recently in the development of *artificial muscle*, based on dielectric elastic polymers ('elastomers') like silicones and acrylics. They are *electroactive*: Application of electric field makes them contract in the direction of the field and expand perpendicular to it by as much as 400%. Electroactive polymers are a very attractive proposition as actuators because one does not have to use motors, drive shafts or gears for generating motion. Consequently there is great scope for miniaturisation and cost-cutting.

*Continued...*

Smart sensors which are small and cheap enough to be produced in large numbers and distributed over the area to be monitored have been developed. Simple computers are linked by radio transceivers and sensors to form small autonomous nodes called motes. Running on a specially designed operating system, each mote links up with its neighbours. Although each unit by itself has only limited capabilities, a system comprising hundreds or thousands of them can spontaneously emerge as a *perceptive network*. Motes are already being manufactured, and have been used for helping biologists in studying seabird nests and redwood groves. Their near-future applications include monitoring of vibrations in manufacturing equipment, strain on bridges, and people in retirement homes. Defence applications are an obvious next step, as also the mapping and prediction of global weather patterns.

- the ability to predict and plan; and
- decision making and emotions.

The present status of modelling these qualities on the computer is that *emotions are the toughest to model*! No wonder.

## Concluding Remarks

In the days to come, we are going to see the merging of four megatechnologies:

- advanced materials,
- nanotechnology,
- information technology,
- biotechnology.

Nanoscience and nanotechnology are particularly relevant in the context of smart structures. The desired goal is to be able to manipulate atoms and molecules individually and, either place them, or induce them to go, exactly where needed, so as to produce a highly integrated structure for a given purpose. There are already major advances in the implementation of concepts like MEMS, NEMS, and motes.

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MEMS are micro-electromechanical systems comprising of computers linked to tiny mechanical and other devices like sensors, valves, gears, and actuators, embedded in semiconductor chips based on silicon. Polymers are also being increasingly used in the design and fabrication of MEMS.

NEMS go further down in scale from micrometers to nanometers. Large molecules are also being investigated for functioning as nanomachines.

Advances in digital electronics, laser-driven wireless communication, and MEMS have led to the idea of MOTES. Motes are wireless computers so small that they can be integrated into just about anything to create wireless networks. In the days to come, through processes like self-assembly of atoms and molecules, as well as by direct micro-manipulation of atoms, sensors the size of dust particles could be produced in very large numbers. They will collect data about the ambient conditions and transmit information to the network of motes, which, in turn, will initiate corrective or preventive action as programmed.

Our machines (smart structures included) will evolve, gradually undermining the distinction between technology and nature, and between the living and the non-living. The hardware and the software will produce its own hardware and software, as needed and desired (by whom ?!).

What will be the role of human beings in such a world ?

## Suggested Reading

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