Part 1

Fundamentals

1

Introduction to Smart Systems

1.1 COMPONENTS OF A SMART SYSTEM

The area of smart material systems has evolved from the unending quest of mankind to mimic mechanical systems of natural origin. The indispensable common objective in all such initiatives has been to develop technologies to produce non-biological systems that would achieve optimum functionality widely observed in biological systems through emulation of their adaptive capabilities and integrated design.

Smart materials are usually attached or embedded into structural systems to enable these structures to *sense* disturbances, *process* the information and *evoke reaction* at the actuators, possibly to negate the effect of the original disturbance. Thus, smart materials *respond* to environmental stimuli and for that reason are also called *responsive materials*. Since these smart material systems should mimic naturally occurring systems, the general requirements expected in these nonliving systems that integrate the functions sensing, actuation, logic and control include:

- A high degree of reliability, efficiency and sustainability of whole systems
- High security of infrastructures, even in extreme ambience
- Full integration of all functions of the system
- Continuous health and integrity monitoring
- Damage detection and self recovery
- Intelligent operational management system.

As one would notice, the materials involved in implementing this technology are not necessarily novel, but the smart systems technology has been accelerating at a tremendous pace in recent years. This has indeed been inspired by several innovative concepts developed around the world. The prime movers for this technology have been the military and aerospace industries. Some of the 'proof-of-concept' programs have addressed structural health monitoring, vibration suppression, shape control and multifunctional structural aspects for spacecraft, launch vehicles, aircraft and rotorcraft. These demonstrations have focused on showing potential system-level performance improvements using smart technologies in realistic aerospace systems. Civil engineering structures, including bridges, runways and buildings, that incorporate this technology have also been demonstrated. Smart system design envisages the integration of the conventional fields of mechanical engineering, electrical engineering and computer science/information technology at the design stage of a product or a system.

The concept of 'self-healing materials' has received wide attention in recent years. For example, self-healing plastics may use materials that have the ability to heal cracks as and when these occur. Shape memory alloys (SMAs) in composites can stop propagating cracks by imposing compressive forces, resulting from stress-induced phase transformation. SMAs have also been used in spectacle frames to repair bends. Current research aims at developing adaptive, 'self-repairing materials' and structures that can arrest dynamic crack propagation, heal cracks, restore structural integrity and stiffness and reconfigure themselves to serve even more functions.

Before we head any further with this discussion, some clarifications regarding the terminology is called for. Several of these (e.g. smart, adaptive, intelligent and active) are sometimes used almost interchangeably to represent the type of materials and structures described above. Before we formally define a smart system, we would like to quote (Webster's) dictionary meanings of these terms [1]:

Smart Material Systems and MEMS: Design and Development Methodologies V. K. Varadan, K. J. Vinoy and S. Gopalakrishnan

- Active: producing or involving action or movement.
- Adaptive: showing or having a capacity for or tendency toward adaptation.
- Smart: making one smart; mentally alert; bright, knowledgeable.
- Intelligent: having or indicating a high or satisfactory degree of intelligence and mental capacity; revealing or reflecting good judgment or sound thought; skillful.
- Material: the elements, constituents or substances of which something is composed or can be made.
- Structure: the aggregate of elements of an entity in their relationships to each other.
- System: a group of devices or artificial objects or an organization forming a network especially for distributing something or serving a common purpose.

In the present context, a smart material is one whose electrical, mechanical or acoustic properties or their structure, composition or functions change in a specified manner in response to some stimulus from the environment. This response should be repetitive. However, the means by which the objectives are met could be many. Recall that dimensions of most materials change when heated; but then what distinguishes a smart material from the rest? This is one in which we *design* the material so that such changes occur in a specific manner. In addition, some other objective can also be accomplished based on it. Hence, the main objective in the area of smart materials is to identify materials which would respond to external stimuli that most materials are unresponsive to. Furthermore, one would want to maximize such response, at least one or two orders of magnitude better than the rest of the materials.

Being responsive to external stimuli is probably not sufficient to call a material smart. To define this more precisely, a structure or material system may be considered smart if it somehow evaluates the external stimuli and take some action based on them. This action may be to neutralize the effects of the external stimuli or to perform a function (completely different). This definition requires the system to have sensor(s), a feedback controller and actuator(s). The selection of sensors may be based on the type of stimuli expected, the controller may consist of information processing and storage units, while the actuator may depend on the type of function expected of the system. Materials or material systems that can be 'programmed' (possibly by tailoring their composition) to behave in a certain way in response to an external stimulus may be called smart. These systems should:

- monitor environmental and internal conditions
- process the sensed data according to an internal algorithm
- decide whether to act based on the conditions(s) monitored
- implement the required action (if warranted)
- repeat the steps continuously.

As with any other engineering problem, systems designed with the above objectives should also have a high degree of reliability, efficiency and sustainability [2]. It should be possible to integrate such a system to existing platforms by replacing 'dumb' counterparts with little or no modifications to the rest of the platform. Thus, the technology areas that require urgent attention have been in developing new sensing and actuation materials and devices, and control techniques. In addition, another area that holds immense potential is in self-detection, self-diagnostic, self-corrective and self-controlled functions of smart material systems [2].

Some examples of smart system components are given in Table 1.1. These materials are usually embedded in systems to impart smartness. As this list indicates, most materials involved in smart systems are not new, while the smart system technology in itself is new. Smart systems are the result of a design philosophy that emphasizes predictive, adaptive and repetitive system responses. The improvements in the technology and widespread availability of cost-effective digital signal processors (DSPs) and microcontroller chips have a major influence on the accelerated growth in the smart systems market.

Brief descriptions of the materials included in Table 1.1 are given in the following.

Piezoelectric materials These are ceramics or polymers which can produce a linear change of shape in response to an applied electric field. The application of the field causes the material to expand or contract almost instantly. These materials have already found several uses in actuators in various diverse fields of science and technology. The converse effect has also been observed, which has led to their use as sensors.

Electrostrictive materials These materials can also change their dimensions significantly on the application of an electric field; the effect is reciprocal as well. Although the changes thus obtained are not linear in

Table 1.1 Examples of materials used in smart systems.

Development stage	Material type	Examples
Widely commercialized	Shape memory alloys	NITINOL
	Polymers:	
	piezoelectric	PZT-5A, 5H
	electrostrictive	PMN-PT
Early commercialization or under development	Magnetostrictive materials	Terfenol-D
	Fiber-optic sensor systems	—
	Conductive polymers	—
	Chromogenic materials and systems:	
	thermochromic	—
	electrochromic	—
	Controllable fluids:	
	Electrorheological	—
	Magnetorheological	—
Early research and development	Biomimetic polymers and gels	—
	Fullerenes and carbon nanotubes	

either direction, these materials have also found widespread application in medical and engineering fields.

Magnetostrictive materials These are quite similar to electrostrictive materials, except for the fact that they respond to magnetic fields. The most widely used magnetostrictive material is TERFENOL-D, which is made from the rarest of the rare earth elements, i.e. terbium. This material is highly non-linear and has the capability to produce large strains, which in turn can produce large 'block forces'. These materials are also used in similar applications to those of electrostrictive materials.

Rheological materials While the materials described above are all solids, rheological materials are in the liquid phase. These can change state instantly through the application of an electric or magnetic charge. These fluids may find applications in brakes, shock absorbers and dampers for vehicle seats.

Thermoresponsive materials Shape memory alloys (SMAs) are another widely used type of smart materials, which change shape in response to changes in temperature. Once fabricated into a specified shape, these materials can retain/regain their shape at certain operating temperatures. They are therefore useful in thermostats and in parts of automotive and air vehicles.

Electrochromic materials Electrochromism is the ability of a material to change its optical properties (e.g. color) when a voltage is applied across it. These are used as antistatic layers, electrochrome layers in liquid crystal displays (LCDs) and cathodes in lithium batteries.

Fullerenes These are spherically caged molecules with carbon atoms at the corner of a polyhedral structure consisting of pentagons and hexagons. These are usually embedded in polymeric matrices for use in smart systems.

Biomimetic materials Most physical materials available contrast sharply with those in the natural world where animals and plants have the clear ability to adapt to their environment in real time. Some of the interesting features of the natural world include the ability of plants to adapt their shape in real time (for example, to allow leaf surfaces to follow the direction of sunlight) and limping (essentially a real-time change in the load path through the structure to avoid overload of a damaged region). The materials and structures involved in natural systems have the capability to sense their environment, process this data and respond instantly. It is widely accepted that living systems have much to teach us on the design of future man-made materials. The field of biomimetic materials explores the possibility of engineering material properties based on biological materials and structures.

Smart gels These are gels that can shrink or swell by several orders of magnitude (even by a factor of 1000). Some of these can also be programed to absorb or release fluids in response to a chemical or physical stimulus. These gels are used in areas such as food, drug delivery and chemical processing.

In addition to having sensing and/or actuation properties, smart materials should also have further favorable characteristics [2]:

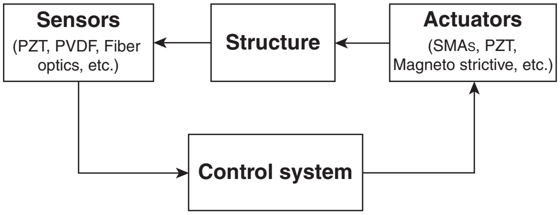

Figure 1.1 Building blocks of a typical smart system.

- Technical properties (e.g. mechanical, behavioral, thermal, electrical).
- Technological properties (e.g. manufacturing, forming, welding abilities, thermal processing).
- Economic aspects (e.g. raw material and production costs, availability).
- Environmental characteristics (e.g. toxicity, pollution, possibility of reuse or recycling).

Similar to a smart material, a smart structure would also require sensors, actuators and a controller, as shown in the schematic given in Figure 1.1. However, unlike smart material systems, the number of possible environmental stimuli monitored in this context is very limited and may include vibrations, cracks, etc. One distinctive feature of smart structures is that actuators and sensors can be embedded at discrete locations inside the structure. One such example where this can be done is the *laminated composite structure*. Furthermore, in many applications the behavior of the entire structure itself is coupled with the surrounding medium. These factors necessitate a coupled modeling approach to analyze smart structures. The functions and descriptions of the various components of a smart structure are summarized in Table 1.2.

1.1.1 'Smartness'

As described above, a smart system is one that can assess a situation, determine if any responses are required and then perform these responses. In this context, 'smartness' may be characterized by self-adaptability, self-sensing, memory and decision making. Both active and passive systems have been used in this context. Usually, active sensors and actuators have been favored in designing smart structures. This is based on the requirement to generate the power required to perform responses. In recent years, the concept of *passive smartness* has come to the fore. Some characteristics of passive smartness are that it is pervasive and continuous in the structure, and there is no need for external intervention, and in addition, there is no requirement for a power source. This has a particular relevance to large-scale civil engineering infrastructures. Passive smartness can be derived from

Table 1.2 Purposes of the various components of a smart structure (adapted from Akhras [2].

Unit	Equivalent in biological systems	Purpose	Description
Sensor	Tactile sensing	Data acquisition	Collect the required raw data needed for appropriate sensing and monitoring
Data bus 1	Sensory nerves	Data transmission	Forward the raw data to the local and/or central command and control units
Control system	Brain	Command and control unit	Manage and control the whole system by analyzing the data, reaching the appropriate conclusion and determining the actions required
Data bus 2	Motor nerves	Data instructions	Transmit the decisions and the associated instructions to the members of the structure
Actuator	Muscles	Action devices	Take the action by triggering the controlling devices/units

the unique intrinsic properties of the material used to build the structure. One common example is an SMA embedded in aerospace composites. Such structures are designed to prevent crack propagation.

We will now try to define smartness by borrowing some definitions from the observations of the Research Theory and Development – Smart Adaptive Systems (RTD – SAS) Technology Committee and the EUropean Network on Intelligent TEchnologies (EUNITE) for Smart Adaptive Systems in the context of artificial intelligence, that 'smart' implies that intelligent techniques must be involved in the adaptation of a system for it to be considered a 'smart adaptive system' [3]. According to this, the accepted formal definition of 'adaptive' has three-levels of meanings, as follows:

(1) Adaptation to a changing environment
(2) Adaptation to a similar setting without explicitly being 'ported' to it
(3) Adaptation to a new/unknown application.

In the first case, the system must adapt itself to a drifting (over time, space, etc.) environment, applying its intelligence to recognize the changes and react accordingly. This is probably the easiest concept of adaptation for which examples abound, e.g. control of non-stationary systems (drifting temperature).

In the second case, the emphasis is more on the change of the environment itself rather than on a drift of some features of the environment. Examples include systems that must be ported from one situation to another without explicitly changing any of their main parameters. Another example could be aerospace structures built to prevent crack formations and civil engineering structures that can withstand earthquakes.

The third level is the most futuristic one, but several of its research objectives have been addressed. For example, in the 'machine-learning' field, starting from very little information on the problem, it is now possible to build a system through incremental learning. Although this may be the ultimate aim of most smart systems, such a level of smartness has not been observed in any man-made system.

1.1.2 Sensors, actuators, transducers

As discussed previously, smart systems should respond to internal (intrinsic) and environmental (extrinsic) stimuli. To do this, they should have sensors and actuators embedded in them. Let's first look at the dictionary meaning of these terms (Merriam Webster's Dictionary online [1]:

- *Transducer* A device that is actuated by power from one system and supplies power, usually in another form, to a second system.
- *Sensor* A device that responds to a physical stimulus (as heat, light, sound, pressure, magnetism or a particular motion) and transmits a resulting impulse (as for measurement or operating a control).
- *Actuator* One that actuates, e.g. a mechanical device for moving or controlling something.

Some of these devices commonly encountered in the context of smart systems are listed in Table 1.3.

1.1.3 Micro electromechanical systems (MEMS)

The emphasis here is to reduce the overall size of the system. Miniaturization can result in faster devices with improved thermal management. Energy and materials requirements during fabrication can be reduced significantly, thereby resulting in cost/performance advantages. Arrays of devices are possible within a small space. This has the potential for improved 'redundancy'. Another important advantage of miniaturization is the possibility of integration with electronics, thereby simplifying systems and reducing the power requirements. Microfabrication employed for realizing such devices has improved reproducibility. The devices thus produced will have

Table 1.3 Some examples of sensors and actuators used in smart systems.

Device	Physical quantity	Example	Technology
Sensor	Acceleration	Accelerometer	PZT MEMS
	Angular rate	Gyroscope	Fiber optic
	Position	LVDT	Electromagnetic
Transducer	Crack detection	Ultrasonic transducer	PZT
Actuator	Movement	Thermal	Shape memory alloy

increased selectivity and sensitivity, a wider dynamic range and improved accuracy and reliability.

Smart micro electromechanical systems (MEMS) refer to collections of microsensors and actuators which can sense their environments and have the ability to react to changes in such environments with the use of a microcircuit control. They include, in addition to conventional microelectronics packaging, integrating antenna structures for command signals into micro electromechanical structures for desired sensing and actuating functions. These systems may also need micro-power supply, micro-relay and micro-signal processing units. Microcomponents make the systems faster, more reliable, cheaper and capable of incorporating more complex functions.

At the beginning of the 1990s, micro electromechanical systems (MEMS) emerged with advancements made in the development of integrated circuit (IC) fabrication processes, by which sensors, actuators and control functions are co-fabricated in silicon. Since then, remarkable progress has been achieved in MEMS under strong capital promotions from both government and industries. In addition to the commercialization of some less-integrated MEMS devices, such as micro-accelerometers, inkjet printer heads, micro-mirrors for projection, etc., the concepts and feasibility of more complex MEMS devices have been proposed and demonstrated for applications in such varied fields as microfluidics, aerospace, biomedical, chemical analysis, wireless communications, data storage, display, optics, etc. [4,5]. Some branches of MEMS, appearing as micro-optoelectromechanical systems (MOEMS), micro-total analysis systems (μTAS), etc., have attracted a great deal of research interests since their potential applications market. By the end of the 1990s, most of the MEMS devices with various sensing or actuating mechanisms were fabricated by using silicon bulk micromachining, surface micromachining and LIGA[1] processes [6,7]. Three-dimensional microfabrication processes incorporating more materials have been recently presented for MEMS when some specific application requirements (e.g. biomedical devices) and microactuators with higher output powers were called for [4,8,9].

Micromachining has become the fundamental technology for fabrication of MEMS devices and, in particular, miniaturized sensors and actuators. Silicon micromachining is the most mature of the micromachining technologies and allows for the fabrication of MEMS that have dimensions in the sub-millimeter range. It refers to fashioning microscopic mechanical parts out of a silicon substrate or on a silicon substrate, making the structures three-dimensional and bringing new principles to the designers. By employing materials such as crystalline silicon, polycrystalline silicon and silicon nitride, etc., a variety of mechanical microstructures, including beams, diaphragms, grooves, orifices, springs, gears, suspensions and a great diversity of other complex mechanical structures, has been conceived.

Silicon micromachining has been the key factor for the fast progress of MEMS in the last decade of the 20th Century. This refers to the fashioning of microscopic mechanical parts out of silicon substrates and, more recently, other materials. It is used to fabricate such features as clamped beams, membranes, cantilevers, grooves, orifices, springs, gears, suspensions, etc. These can be assembled to create a variety of sensors. Bulk micromachining is the most commonly used method but it is being replaced by surface micromachining which offers the attractive possibility of integrating the machined device with microelectronics which can be patterned and assembled on the same wafer. Thus, power supply circuitry and signal processing using ASICs (Application Specific Integrated Circuits) can be incorporated. It is the efficiency of creating several such complete packages using existing technology that makes this an attractive approach.

Micro devices can also be fabricated by using stereo lithography of polymeric multifunctional structures. Stereo lithography is a ‘poor man’s’ LIGA for fabricating high-aspect-ratio MEMS devices in UV-curable semiconducting polymers. With proper doping, a semiconducting polymer structure can be synthesized. By using stereo lithography, it is now possible to make three-dimensional microstructures of high aspect ratio. Ikuta and Hirowatari [10] demonstrated that a three-dimensional microstructure of polymers and metal is feasible by using a process named the *IH Process*, also known as Integrated Harden Polymer Stereo Lithography. Using a UV light source, an *XYZ*-stage, a shutter, lens and microcomputer, they have shown that micro devices, such as spring, verious valve and electrostatic microactuators, can be fabricated. In the case of difficulty with the polymeric materials, some of these devices can be micromachined in silicon and the system architecture can be obtained by photoforming or hybrid processing [11–13]. Photoforming or photofabrication employs an optical method, such as stereo lithography, a photo mask layering process and the IH process which involves

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[1] LIGA – German acronyn for Lithographie, Galvanoformung, Abformung (lithography, galvanoforming, molding).

solidification of the photochemical resin by light exposure. Takagi and Nakajima [14] proposed new concepts of ‘combined architecture’ and ‘glue mechanism’ by using the photoforming process to fabricate complicated structures by combining components, each of them made by its best fabrication process. Batch processing of such hybrid silicon and polymer devices thus seems feasible.

The combined architecture may also result in sheets of smart skins with integrated sensors and actuators at the μm to mm scale. For some applications (say airfoil surfaces), the smart skin substrate has to be flexible to conform to the airfoil shape and at the same time it has to be compatible with the IC processing for sensor and smart electronics integration. It has been proposed by Carraway [15] that polyimide is an excellent material for use as the skin because of its flexibility and IC processing compatibility. The control loop between the sensors and actuators employs multifunctional materials which provide electrical functionality at selected locations using conductive polymers and electrodes that are connected to on-site antennas communicating with a central antenna. A related and difficult problem, and one which has been largely unaddressed is the method for telemetry of the data. In some applications, stresses and strains to which the structure is subjected to may pose a problem for conventional cabling. In others, environmental effects may affect system performance. Advances in conformal antenna technology coupled with MEMS sensors/actuators appear to be an efficient solution. The integration of micromachining and microelectronics on one chip results in so-called smart sensors. In the latter, small sensor signals are amplified, conditioned and transformed into a standard output format. They may include a micro controller, digital signal processor, application specific integrated circuit (ASIC), self test, self-calibration and bus interface circuits simplifying their use and making them more accurate and reliable.

Many basic MEMS devices have a diaphragm, microbridge or cantilever structure. Special processing steps, commonly known as micromachining, are needed to fabricate these. For a given application, it may be necessary to have integrated MEMS employing one or more of the basic structures. These three structures provide some feasible designs for microsensors and actuators that eventually perform the desired task in most smart structures. However, the main issues with respect to implementing these structures are the choice of materials and the micromachining technologies to fabricate such devices.

To address the first issue, we note that in all of the three structures proposed the sensing and actuation occur as a result of exciting a piezoelectric layer by the application of an electric field. This excitation brings about sensing and actuation in the form of expansion in the diaphragm, or in the free-standing beam in the microbridge structure, or in the cantilever beam. In the former two cases, the expansion translates into upward curvature in the diaphragm or in the free-standing beam, hence resulting in a net vertical displacement from the unexcited equilibrium configuration. In the cantilever case, however, upon the application of an electric field the actuation occurs by a vertical upward movement of the cantilever tip. Evidently, in all three designs the material system structure of the active part (diaphragm, free-standing beam or cantilever beam) in the microactuator must comprise at least one piezoelectric layer as well as conducting electrodes for the application of an electric field across this layer. Piezoelectric force is used for actuation for many of the applications mentioned above. Micromachining is employed to fabricate the membranes, cantilever beams and resonant structures.

1.1.4 Control algorithms

As mentioned earlier, a smart system consists of a sensor, an actuator and a control system. The desired operations on a smart system are performed by an actuator by taking the instructions given by the control systems. These instructions are given to the actuator using a suitable control law that is driven by a set of control algorithms. The main objective of the control system is to inject a control force onto the system to perform the desired operation. These control forces can be injected into the system by using the coupling characteristics of smart materials. That is, for example, if we use a PZT actuator, in the absence of any mechanical disturbance, the passing of a voltage on the actuator causes the smart system to expand (or contract). These strains can be converted into forces to perform the desired operations such as vibration reductions in structural systems, shape control of aerofoil cross-sections in an aircraft, etc. The control algorithms necessarily direct the type of operations that a system has to perform to get the desired results.

The control law that drives a smart system could be ‘open-loop’ or ‘closed-loop’. In an open-loop system, the system is injected with a known parameter (for example, a known voltage in the case of a PZT actuator or a known value of AC current in the case of a magnetostrictive actuator) to generate the control forces for meeting the target application. Such a control system is not suitable in the real-world, wherein the uncertainties are so much that it is not always possible to quantify the value of the parameter that is required to meet the control objective. As opposed to the open-loop control, closed-loop control to a great extent can work better in a non-deterministic framework. The closed-loop control can be of two categories, namely the 'feed forward' and 'feed back', wherein the later is more easily realizable and hence extensively used in real-world application.

A closed-loop control system can be designed in many ways. The most common design essentially takes the sensed response and feeds it back to the actuator to obtain the desired control objective. The responses that are fed back to the actuator in structural applications could be displacements, velocities or accelerations. Such a controller design is called a Proportional, Proportional-Integral (PI) or Proportional-Integral-Differential (PID) controller.

1.1.5 Modeling approaches

The development of mathematical model for analysis depends on the following:

- The size of the smart system – Macro or micro system.
- The type of applications, such as vibration control, structural health monitoring etc.
- The constitutive behavior of the smart material, namely linear or non-linear.
- The frequency content of the input loading, that is, low-frequency or high-frequency loading.
- Small-deformation and large-deformation problems.

The most common method of modeling the macro structure is by the well-established Finite Element Method (FEM). This method can also handle effectively the material and geometrical non-linearities. However, FEM is limited to problems wherein the frequency content of input excitation is band-limited. However for problems involving, say, the structural health monitoring of smart laminated composite structures, one has to inject a pulse having a very high frequency content (of the order of kHz and higher) to detect the presence of small damages. This problem essentially transforms from a dynamics to a wave-propagation problem. For such problems, FEM is unsuitable from a computational viewpoint due to the limitation that the element size should be of the order of the wavelengths. In such situations, one can use wave-based Spectral Element Modeling (SEM). The main disadvantage with SEM, however, is that it is not as versatile as FEM in modeling arbitrary geometries. Hence, one has to judiciously choose the type of modeling to suit the problem on hand.

Modeling of a microsystem can also be handled by FEM. Many researchers have designed many new MEMS by using FEM. Modeling through techniques such as FEM are based on a continuum analysis. However, one has to clearly understand that beyond a certain size of the system, the continuum analysis assumption breaks down. In most MEMS devices that are reported in the literature, the sizes are such that the continuum assumption does hold and hence one can still use FEM to model these devices.

1.1.6 Effects of scaling

For the modeling of nano-scale devices, one has to bring in the effect of scale. Nano-scale devices are of the order of 10–100 nanometers in size. In most cases, at these sizes the continuum assumptions break down. A classic example is the analysis of single-wall or multi-wall carbon nanotubes. Analysis of such systems can be performed either by molecular dynamic modeling or quasi-continuum modeling, although there are a few reports that state that the results of continuum modeling are reasonable.

The effects of scale become more profound when these nanotubes are embedded in, say, composites. It is well known that these nanotubes have enormous stiffness and hence can resist the deformation significantly. This cannot be effectively captured if one resorts to single-scale modeling. Therefore, one should adopt a multi-scale modeling approach. That is, in a small region of the nanotubes, one has to adopt a nano-scale modeling approach, such as a molecular dynamics model, and 'lump' the effects of this onto a macro-model of the composites. Multi-scale modeling is an open area of research worldwide and many researchers are working towards breaking the size barrier and to come up with an effective way of incorporating the effects of scale on the modeling technique.

1.1.7 Optimization schemes

Optimization schemes forms an essential part in the modeling of a smart system. These schemes are necessary whenever constraints arise in designing a smart system. Most of the smart sensors/actuators are very expensive and these have to be located judiciously on the system, keeping cost in mind and at the same time maximizeing the efficiency of the system by meeting the required control objective.

For all optimization problems, an objective function is required. For example, for the placement of sensors and actuators in a structure, the main objective is to increase the sensitivity of the sensors. This sensitivity can be increased if it can effectively measure higher strains (and hence the stresses). Thus, the objective function for this problem will be to locate regions of higher strains and minimum stress gradients.

There are two major optimization schemes that are reported in the literature. One is the gradient-based optimization, where the assumption is made that the optimal solution to the problem lies in a space wherein the gradient of a variable (such as displacement, strains, stress, etc.) is minimum. This is the most common approach. The second approach is based on a genetic algorithm, wherein all probable solutions are assumed and eliminated by using the concept of Darwin's Theory of Evolution, namely 'survival of the fittest'.

1.2 EVOLUTION OF SMART MATERIALS AND STRUCTURES

The field of smart materials and structures is interdisciplinary between science and technology and combines the knowledge of physics, mathematics, chemistry, computer sciences, with material, electrical and mechanical engineering. It implements human creativity and innovative ideas to serve human society for such tasks as making a safer car, a more comfortable airplane, a self-repair water pipe, etc. Smart structures can help us to control the environment better and to increase the energy efficiency of devices.

Smart structures are usually systems containing multifunctional components that can perform sensing, control and actuation. Key materials used to construct these structures are called smart materials. The 'smartness' of these is gauged by their responsiveness (large change in amplitude) and agility (speed of response). Materials used in these applications may include single-phase or functional composite materials, and smart structures.

Single-phase materials used in this context have one or more large anomalies associated with phase-transition phenomena. Functional composites are generally designed to use nonfunctional materials to enhance functional materials or to combine several functional materials to make a multifunctional composite. Examples include donor-doped $BaTiO_3$ ceramics that are typically used for sensing temperature.

A magnetic probe is a multifunctional composite in which a magnetostrictive material is integrated with a piezoelectric material to produce a large magnetoelectric effect. The magnetostrictive material will produce shape deformation under a magnetic field, and this shape deformation produces a stress on the piezoelectric material which generates electric charge.

As mentioned earlier, smart structures involve sensors, actuators and a control system. Apart from the use of better functional materials as sensors and actuators, an important part of a 'smarter' structure is to develop an optimized control algorithm that could guide the actuators to perform required functions after sensing changes.

Active damping is one of the most studied areas using smart structures. A number of active damping schemes with guaranteed stability have been developed by using collocated actuators and sensors (i.e. physically located at the same place and energetically conjugated, such as force and displacement). These schemes are categorized on the basis of feedback type in the control procedure, i.e. velocity, displacement or acceleration.

Although several natural materials (such as piezoelectric, electrostrictive and magnetostrictive materials) are classified as smart materials, these usually have limited amplitude responses and must be operated in a limited temperature range. Chemical and mechanical methods may be used to tailor their properties for a particular smart structure design.

The ***shape memory effect*** in materials was first observed in the 1930s by Arne Olander while working with an alloy of gold and cadmium. This Au–Cd alloy was plastically deformed when cold but returned to its original configuration when heated. The shape memory properties of nickel–titanium alloys were discovered in the early 1960s. Although pure nickel–titanium has very low ductility in the martensitic phase, the properties can be modified significantly by the addition of a small amount of a third element. These groups of alloys are known as Nitinol^{TM} (Nickel–Titanium-Naval-Ordnance-Laboratories). Ni–Ti SMAs are less expensive, easier to work with and less hazardous than previous SMAs.

Commercial products based on SMAs began to appear in the 1970s. Initial applications for these materials were in static devices such as pipe fittings. Later SMA devices have also been used in sensors and actuators. In order to perform well in these devices, the SMA must experience a cycle of heating, cooling and deformation within a short time span.

Ferroelectric SMAs offer the possibility of introducing strain magnetically. This effect was discovered in the 1990s on SMAs with high magnetocrystalline anisotropy and high magnetic moment (e.g. Ni_2MnGa). These materials produce strain of up to 6 % at room temperature.

The ***piezoelectric effect*** was initially observed by Pierre and Jacques Curie in 1880. They discovered a connection between the macroscopic piezoelectric phenomena and the crystallographic structure in crystals of sugar and Rochelle salt. The reverse effect of materials producing strain when subjected to an electric field was first mathematically deduced from fundamental thermodynamic principles by Lippmann in 1881. Several naturally occurring materials were shown to display these effects. Nickel sonar transducers using this effect came to be used in the World War I.

This application triggered intense research and development into a variety of piezoelectric (ceramic) formulations and shapes. Since then, several sonar transducers, circuits, systems and materials have been reported. The second generation of piezoelectric applications was developed during World War II. It was discovered that certain ceramic materials, known as 'ferroelectrics', showed dielectric constants up to 100 times larger than common-cut crystals and exhibited similar improvements in piezoelectric properties. Soon, the barium titanate and lead zirconate titanate families of piezoceramics were developed. Some of these began to be used in structural health monitoring and vibration damping. Polymeric materials, such as poly (vinylidene fluoride) (PVDF), have also been shown to exhibit similar characteristics. Intense research is still going on to produce useful and reasonably priced actuators, which are low in power consumption and high in reliability and environmental ruggedness.

The ***electrostrictive effect*** is similar to piezoelectricity and converts the electrical pulse into a mechanical output; yet electrostriction is caused by electric polarization and has a quadratic dependence. The main difference between electrostrictive and piezoelectric materials is that the former doesn't show spontaneous polarization and hence no hysteresis, even at very high frequencies. Electrostriction occurs in all materials, but the induced strain is usually too small to be utilized practically. Electrostrictive ceramics, based on a class of materials known as 'relaxor ferroelectrics', show strains comparable to those of piezoelectric materials (strain $\sim 0.1\,\%$) and have already found application in many commercial systems. New materials such as carbon nanotubes have also been shown to have significant electrostrictive properties.

The ***magnetostrictive effect*** was first reported in iron in the 1840s by James P. Joule. The inverse effect was discovered later by Villari. Other materials, such as cobalt and nickel, also showed small strains. Some of the first sonars were built on this principle. Large-scale commercialization of this effect began with the discovery of 'giant' magnetostriction in rare-earth alloys during the 1960s. These showed 0.2–0.7 % strain, which is two orders of magnitude higher than nickel. An alloy of these materials, 'Terfenol-D' (named after its constituents, terbium, iron and dysprosium, and place of invention, the Naval Ordnance Laboratory (NOL) exhibits relatively large strains (0.16–0.24 %) at room temperature and at relatively small applied fields. Terfenol-D has now become the leading magnetostrictive material for engineering use. The development of polymer matrix Terfenol-D particulate composites has further overcome some of the limitations of 'pure' Terfenol-D.

'Field-responsive' fluids were also known to exist since the 19th Century. The effective viscosity of some pure insulating liquids was found to increase when an electric field is applied. This phenomenon, originally termed the 'electro-viscous effect', later came to be called the ***electro-rheological (ER) effect***. These materials usually consist of suspensions of solid semiconducting materials (e.g. gelatin) in low-viscosity insulating oils (e.g. silicone oil).

In some ER compositions, both Coulomb and viscous damping can be achieved so that a vibration damper can be fabricated. The limitations of most ER fluids include the relative low yield stress and its temperature-dependence, the sensitivity of ER fluids to impurities (which may alter the polarization mechanisms) and the need for high-voltage power supplies (which are relatively expensive).

The ***magnetorheological (MR) effect*** was discovered by J. Rabinow in the late 1940s. However, due to some difficulties in using MR fluids in actual applications, these have not yet become popular. One of the difficulties was the low 'quality' of the early MR fluids which caused the inability of the particles to remain suspended in the carrier liquid. Recently, MR fluids have found new potential in engineering applications (e.g. vibration control), due to their higher yield stress and the lower voltage requirement (compared to ER fluids). These have also been commercially exploited for an active suspension system for automobiles and controllable fluid brakes for fitness equipment.

1.3 APPLICATION AREAS FOR SMART SYSTEMS

Developments in the areas of smart materials and structural systems have centered around the natural human instinct of ‘mimicking nature’. Although the technology is yet far from this goal, several systems with consumer, aerospace and military applications have been produced in recent years. As one can imagine, new possibilities emerge as time goes by. Hence, readers are cautioned that the items described below should not be construed as representing an exhaustive list.

Reduction of vibrations in sporting goods. To increase the users’ comfort, several new smart sporting goods (e.g. tennis rackets, golf clubs, baseball bats, skis, etc.) are available on the market.

Noise control in vehicles. Composites of piezoelectric ceramic fibers are used reduce noise in vehicles, shaking in helicopter rotor blades or vibrations in air conditioner fans and automobile dashboards.

Aerospace applications. Demonstrated aerospace applications of smart structures include the spatial high accuracy position encoding and control system (SHAPECONS) and Frangibolt (used to deploy solar arrays, antennas and satellites from a launch vehicle) in the Clementine mission.

In addition, *several military applications* have been envisaged for smart materials and structures. In the battlefield, soldiers may wear clothing made of special tactile material that can detect signals from the human body to determine bullet wounds. This information can then be used to analyze the nature of the wound, decide on the urgency to react and possibly take some action to stabilize the situation.

There are several potential locations for the use of smart materials and structures in aircraft. Ground, marine or space smart vehicles will be a feature of future military operations. These manned or unmanned carriage systems, equipped with sensors, actuators and sophisticated controls, can improve surveillance and target identification and improve battlefield awareness. These smart vehicles could even be constructed using stealth technologies for their own protection. The B-2 stealth bomber or the F-117 stealth fighter are good examples of this technology. Smart systems are also needed for the quick and reliable identification of space or underwater stealth targets. Smart systems may also be used to improve the performance of otherwise ‘dumb’ systems. Examples of applications in many diverse areas are presented in Table 1.4.

In the future, it may even be possible to develop structures that are smart enough to communicate directly with the human brain using MEMS-based devices. Smart noses, tongues, etc. have already been developed by various groups. Newer sensors may even extend human sensing capabilities, such as by enabling us to detoct more scents, hear beyond our normal frequency range, and see what we cannot normally see (using IR). There is also significant scope for developing newer capabilities in the domain of smart structures. It can be expected that we will see further smarter materials and structures being developed in the near future.

1.4 ORGANIZATION OF THE BOOK

This book is divided into fifteen chapters, describing fundamentals, design principles, modeling techniques, fabrication methods and applications of smart material systems and MEMS. The first two chapters of the book deal with the fundamental concepts of smart systems and their constituent components. Preliminary concepts of these materials will be introduced, along with important characteristics expected of them, in Chapter 2.

In the second part of the book, the design principles for sensors and actuators are discussed in detail. Here, we first begin with the design philosophy behind some commonly available sensors, such as accelerometers, gyroscopes, pressure sensors and chemical and biosensors. The design issues of bulk sensors made from piezoelectric, magnetostrictive and ferroelectric materials are also given in Chapter 3. This is followed (Chapter 4) by the basic design principles of several actuators. Chapter 5 is devoted to examples describing the design principles of sensors and actuators, wherein the principles behind developing components with SMAs, piezoelectric, electrostrictive and magnetostrictive materials are given.

Chapters 6–9 dwell on a detailed account of modeling of smart systems. First, the theory of elasticity and composites are introduced, which serve as prerequisites for the advanced techniques that follow. Next, the complete theory and application of finite element (FE) modeling is given, including an introduction to variational methods, various element formulations and equation solutions for both discretized statics and dynamics equations of motion in Chapter 7. Following this, the basic concepts of wave propagation and spectral finite element modeling is introduced, which are used to study wave propagation in isotropic and composite structures. This is followed, in Chapter 8, by the modeling of smart sensors and actuators, where the approach is demonstrated by using a number of examples. The last chapter

Table 1.4 Applications of smart systems in various areas.

Application	System	Use
Machine tools	Piezoceramic transducers	To control 'chatter' and thereby improve precisioln and increase productivity
Photolithography	Vibration control during the process using piezoceramic transducers	In the manufacture of smaller microelectronic circuits
Process control	Shape memory alloys	For shape control, e.g. in aerodynamic surfaces
Health Monitoring	Fiber-optic sensors	To monitor the 'health' of fiber-reinforced ceramics and metal–matrix composites and in structural composites
Consumer electronics	Piezoceramic and MEMS accelerometers and rotation-rate sensors; quartz, piezoceramic and fiber-optic gyros; piezoceramic transducers	For shake-stabilization of hand-held video cameras
Helicopters and aircraft	Piezoceramic stack actuators; PZT and MEMS accelerometers; magnetostrictive mounts	Vibration and twist control of helicopter rotor blades and adaptive control of aircraft control surfaces
	Piezoceramic pick-ups and error sensors; PZT audio resonators and analog voice coils; digital signal processor chips	Active noise control
Submarines	Piezoceramic actuators	Acoustic signature suppression of submarine hulls
Automotive	Electrochromics (sol–gel, sputtered and vacuum-evaporated oxides; solution-phase reversible organic redox systems); suspended particles; dispersed liquid crystals; reversible electrodeposition	Chromogenic mirrors and windows
	Piezo yaw-axis rotation sensors (antiskid, antilock braking); ceramic ultrasonic 'radar' (collision avoidance, parking assist); MEMS accelerometers (air bag controls); electronic stability controls (four-wheel independent auto braking)	
	Piezopolymer IR sensors; rain monitors; occupant identification; HVAC sensors; air pollution sensors (CO and NO_x)	Smart comfort control systems
In Buildings	IR, vision and fiber-optic sensors and communications systems	For improved safety, security and energy control systems; smart windows to reduce heating, ventilation and air conditioning costs

Table 1.4 (*Continued*)

Application	System	Use
Biomechanical and biomedical systems	Shape memory alloys and polymer gels	To develop artificial muscles; active control of *in vivo* drug-delivery devices (insulin pumps)
	Piezoceramic and other ultrasonic sensors and actuators	Catheter guide wires; surgical tools; imaging devices
Computer industry	Piezoceramic and MEMS accelerometers and rotation rate sensors; quartz, piezoceramic and fiber-optic gyros	For smart read/write head micropositioners in next-generation data storage devices
	bimorph-type piezo-positioner and asperity-detector arms	For high-density disk drives
	Piezo-accelerometers to provide error-anticipating signals	To correct for head-motion-related read/write errors

in this part (Chapter 9) deals with control techniques required for smart actuation.

Next, we present a complete 'bird's eye view' of the various fabrication techniques used for both bulk and microsensors and actuators. Building on the fundamental concepts from the earlier chapters, details of the bulk and surface micromachining concepts for the silicon-based processing of MEMS sensors and actuators are presented in Chapter 10. The techniques used to fabricate polymer-based systems, such as microstereolithography and micromolding, are also included in Chapter 11, opening up new opportunities, especially with regard to 3-dimensional microstructures. Due to their delicate nature, these microstructures are required to be packaged and integrated with the electronics. Chapter 12 is devoted entirely to these aspects. In addition, several examples of sensors and actuators fabricated by the above routes are included in Chapter 13.

The last two chapters of this book deal with some practical applications where smart technologies including microsystems are used to solve some real-world problems. Implementation issues in structural, vibration and noise-control applications are described in Chapters 14 and 15.

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