SMART STRUCTURES —
IMPRACTICAL OR INEVITABLE?

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What are smart structures

Wouldn’t it be nice if inanimate objects such as bridges, airplanes, and even houses could sense when they had been damaged and then repair themselves, just as living creatures do. These self-healing structures are closer than you think! Some elements of this procedure are already in place. The heart of the system is called a smart structure. Read on to glimpse the future!?

A smart structure or system incorporates sensors and actuators into the material of the system in such a way that enables the structure to sense its environment and then respond appropriately in a preprogrammed manner. Typical smart structures or smart material systems are composites, although that is not a requirement. Composite structures especially lend themselves to the inclusion of sensors and actuators because of the way composites are made (in laminar structures). Therefore, only composite smart structures will be discussed in this article.

A closely related type of structure is called an intelligent structure. Intelligent structures are smart structures that have the added capability of learning and adapting rather than simply responding in a preprogrammed manner. This learning and adapting is usually accomplished by the inclusion of an artificial neural network (ANN) into the smart structure. The nature of both smart structures and intelligent structures can be seen in Figure 1 where their relationship to general structures, sensors, actuators, and ANNs can be seen as overlap regions.

The role (application) of smart structures

One important application is in bridges and other civil engineering structures where the structure's components (walls, decking, etc.) could sense when the structure needs repair, such as from cracks or corrosion, and then report the location and the extent of the problem. The sensors could also activate motors that could dampen the structure during an earthquake to minimize shaking damage.

Alternately, a smart airplane or boat could sense cracks, leaks (either externally or internally as with fuel), or excessive forces. The responses could be to report the problem and its extent, initiate the application of a sealant (preloaded into the critical space), or activate motors that might actually change the shape or stiffness of the outer structure to minimize the effects of the forces and thus prevent damage and/or improve operational performance. A small scale model of a F/A-18 fighter has already been made and is under test in wind tunnels to verify these performance concepts.

Noisy products can be silenced by smart structures that sense the acoustic waves being generated by the appliance and then cancel those waves through active damping.

Most of these smart structure concepts are still in the research and development phase but some smart structures have found their way into actual commercial use. One of the most common of these is the damping of vibrations. In this application the sensors detect excessive vibrations through piezo-electric devices which then apply an opposing current to stimulate changes in the structure which counteract the vibrations. Alternately, the vibrating structure could be made with a passive damping layer – one that dissipates the energy of the vibrations.

Components and types of smart structures

Smart structures can be categorized by the type of device that is used to do the sensing or actuation. The most common of these devices are: piezo-electric, fiber optic, shape memory alloys, electro-rheological fluids, and other electro-oriented techniques.

Piezo-electric – These are either ceramic or polymeric film devices which are electro-mechanical transducers; that is, they change electrical signals into mechanical motion and vice versa. If an electrical signal is applied across a piezo-electric device, the device shape will change (usually length) because of the change in electrical voltage. Alternately, mechanical deformation of the device will result in a change in the voltage output. Hence, the device can both sense changes in the structure that it might be embedded in, and also give an electrical signal that can be amplified and used to change the characteristics of the structure in which it resides.

- Advantages: The ceramic devices can be used as both the sensor and the actuator and it has a rapid response time (although the films are just sensors).
- Disadvantages: The ceramic devices are brittle and they have a very small range of mechanical motion which limits their ability to sense or control large spatial deviations directly. Some potential applications cannot use electrical devices, thus prohibiting the use of piezo-electricals. Another problem is the need to have a large number of the devices spread throughout the structure to sense and regulate the structure.

Fiber optics – These are similar to the normal fiber optic cables which are used to transmit telecommunication signals. When embedded in composite structures, the output light signal of these devices changes in relation to conditions of their surrounding environment. For instance, if the structure moves, the fiber optic will change in diameter, thus changing some components (frequency, amplitude, phase, polarization, etc.) of the imposed optical signal. These changes in signal can be detected and related to the changes in the structure. Other examples of environmental changes which can be detected might be temperature, pressure, rotation, acceleration, acoustics, chemical composition, radiation, fluid flow, and liquid level.

Note that when these fiber optics are used for transmitting signals in normal communications, the system operator desires to minimizes the very effects which allow fiber optics to be used as sensors. That is, they want to minimize changes in the signal, which might be caused by environmental effects on the fiber. Thus, using the fibers as sensors is inherently counter to their use as signal transmitters. This duality obviously complicates the interpretation of the data obtained using these devices.

- Advantages: The fiber optic devices have the ability to sense many different effects. They are highly compatible with composites (because both are fibers). These devices can sense both general and local changes and are largely immune to electro-magnetic interference.
- Disadvantages: Glass is brittle and is easily damaged with relatively small movements, although some polymeric optical fibers may eliminate this problem. One difficulty is getting the signal out of the device with the proper interpretation unless the general nature of the environment is well characterized. These devices are really only sensors.

Shape memory alloys – These are materials that have a memory because of a transition that occurs within them between two separate phases or other internal structures. For instance, a metal might switch back and forth between crystal structures, such as between a martensitic phase when cooled and an austenitic phase when heated. This allows the metal to remember the shape it had when it was cool (or hot) even when it is subjected to the other conditions. Therefore, when a material is changed from one phase to the other by changing the temperature, the material wants to change shape, but if constrained, will exert tremendous forces on its constraints. These forces can be used to sense and change the configuration of the assembly in which the shape memory material is placed. These materials are, therefore, used as actuators in smart structure applications. Most of the shape memory alloys are titanium-based although other materials can also possess these properties.

- Advantages: Shape memory alloys can exert very high forces and generate high strains. The material is ductile, thus resisting impact damage.
- Disadvantages: These materials have limited ability to sense changes. They are sensitive only to temperature changes therefore it is difficult to obtain rapid response since temperatures change slowly. These materials are susceptible to fatigue and relatively low in efficiency.

Other techniques – Several other methods have been investigated as components of smart structures. Some of these include: electro-rheological fluids (fluids which change their viscosity as a result of an applied electrical field, used primarily for damping); electro-strictive materials (materials that constrict when an electric field is applied); magneto-strictive (constrict when a magnetic field is applied); and various types of more traditional actuators and sensors in combination.

Barriers or impediments to implementation

Many of the same barriers that inhibit the rapid adoption of composite structures, also slow the introduction of smart structures. These barriers include: lack of design data (especially the effects of inclusion of sensors and other smart structure components); high initial cost (smart structures have the cost of the components added to an already high cost of composites, plus the additional cost of installing the components during the manufacturing of the smart structure); enhanced problems of durability of the composite structure because of the presence of the smart structure component; adequate methods for quality control and inspection; and repair difficulties. In all of these, the problems of smart structures are added to the already significant problems of composite material adoption. This fact is especially true in fields where composites are new, such as the infrastructure (i.e., civil engineering structures).

Some of these challenges can be solved as the promise of smart structures becomes realized. For example, although the initial costs will be high, the costs over the life of the structure might be considerably lower when maintenance costs, inspection costs, and structural failure costs are included.

The smart structure devices (components) themselves present additional challenges. For instance, some components are notorious for being fragile (especially the ceramic-based devices) which raises the question of long term durability of the entire system. This further points out the increase in system complexity which includes not only fibers and matrix but now, sensors, actuators, connectors, processors, communication links, power, and feedback. Perhaps this complexity is not surprising if we consider another self-sensing and repairing mechanism – the human body. Surely just the sensing components of the body (nervous system) are many times more complex than even the most complex of smart structures. This analogy is illustrated in Figure 2.

In addition to the complexity of the system, some problems have arisen with just the methods of manufacturing the smart structures. How should the devices be installed? If the device is a fiber optic line, it can be filament wound along with the reinforcing fibers. However, if the structure is made of chopped strand, that option is not open. Piezo-electrics are usually installed manually and that raises the question of manufacturing uniformity from structure to structure. Even some seemingly simple manufacturing steps are vastly more difficult because of the presence of the smart structure components. For instance, trimming must be done with great care because of the presence of leads that connect the devices to the external portions of the system, if any. Current technology requires the use of external components.

Successful monitoring and modification of physical parameters hinges on the existence and knowledge of a unique relationship between the physical parameters of interest and the properties which can be modified. In other words, what does the data mean and how do you use it?

In general, researchers have been able to make test smart structures, put them into service, and correctly interpret the data from the sensors and to use that data for structure modification. All of this has been accomplished in real time, at least for some systems. These experiments seem to imply that the promise of smart structures is, in fact, achievable. However, large-scale commercial implementation still seems to be in the future.

Summary

Structures which can be made smart while maintaining the majority of their conventional properties offer tremendous advantages over the same structures which are not smart. Since a smart structure can respond to changes in the environment, the same structure can be used in a greater number of applications and/or over broader operating ranges. In addition, structures can be made smart to increase performance while simultaneously saving weight by eliminating over design. Through in-situ health monitoring of the structure, safety can be increased tremendously and cost can be cut by extending service life and eliminating the need for frequent in-service structural inspections. Thus the potential for greater safety promises enormous benefits, especially to industries where safety is a critical issue. For example: commercial airlines, automotive and construction industries could significantly reduce liability with more accurate failure predictions.

Therefore, are smart structures impractical? Today, yes. But enough near commercial progress has been achieved to give confidence in their eventual implementation. Therefore, are smart structures inevitable? Probably, yes.

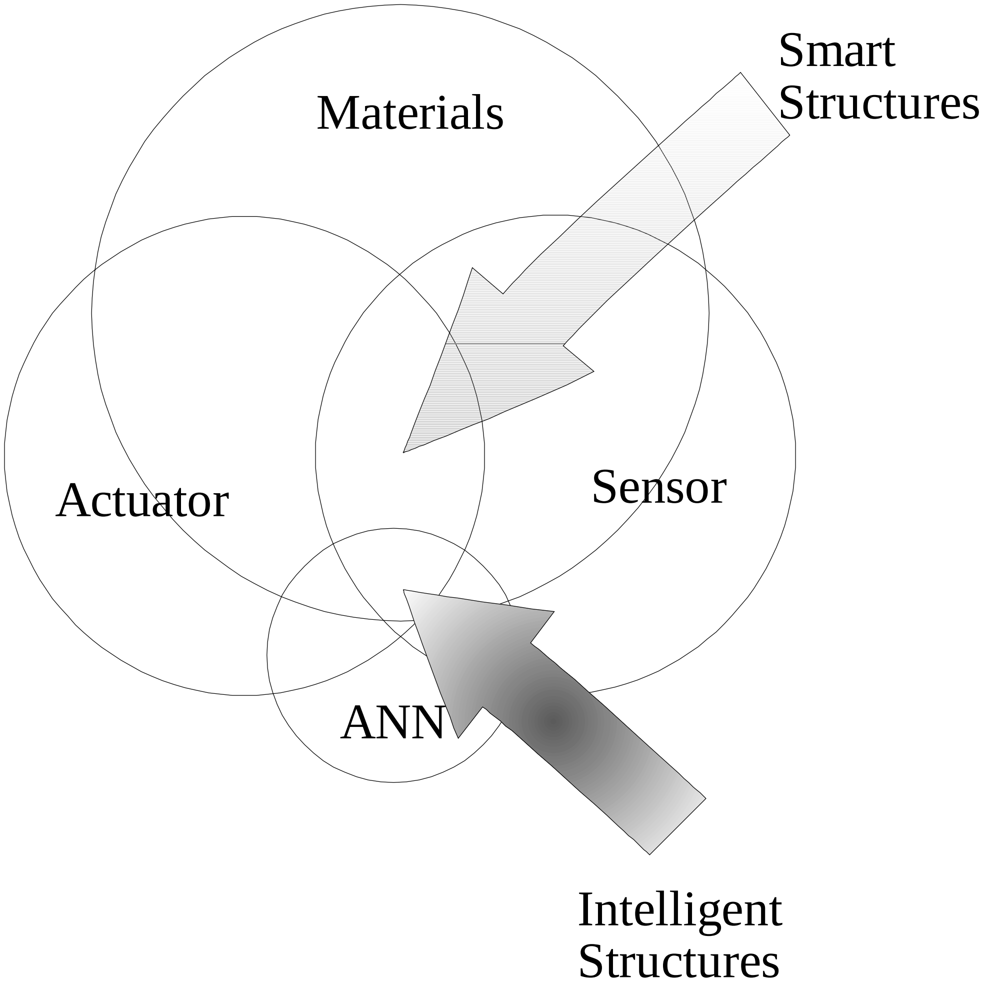


Figure 1 Diagram showing relationship of smart structures and intelligent structures

Smart Structures Analogy

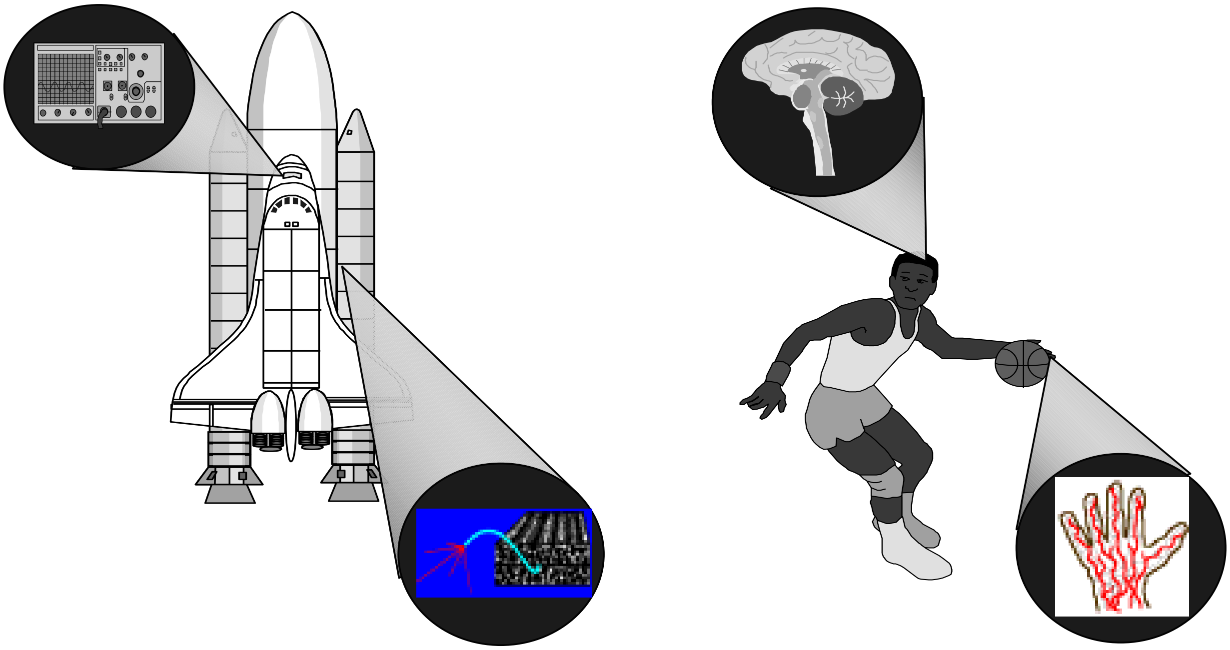
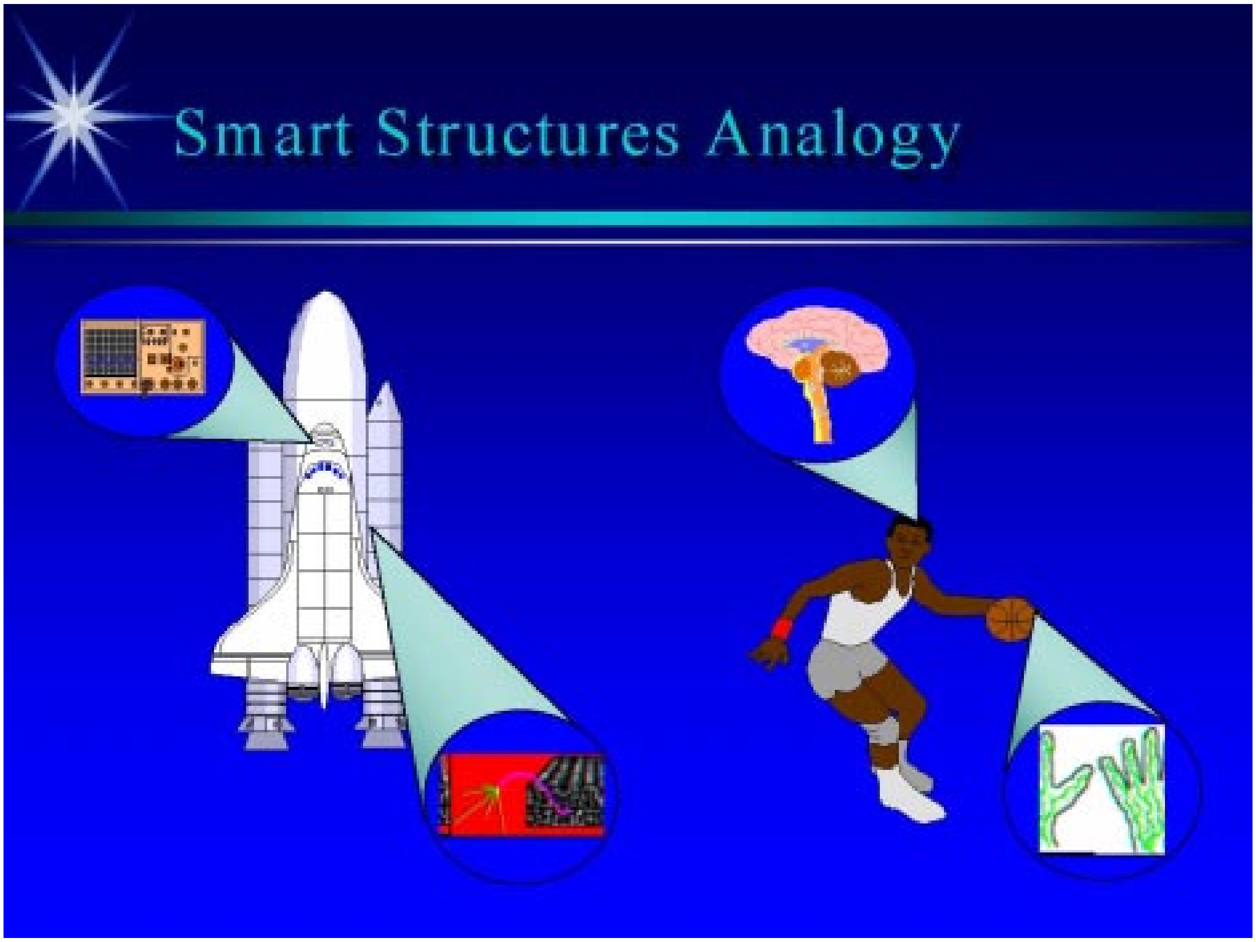


Figure 2. The human analogy of a smart structure is depicted. The human brain corresponds to the processing unit (computer) that receives and interprets the signals sent to it by the smart structure devices. These smart structure devices correspond to the nerves in the human body. Similarly the control surfaces in the rocket ship correspond to the muscles and skin of the human body. Both the smart structures in the rocket ship and in the human body are highly complex systems which require extensive inter-connectedness to operate properly.



Smart Structures Analogy