SMART MATERIALS

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Contents

1. Introduction

Materials enable virtually every sphere of human activity. Indeed the history of humankind is often presented as progress in the use of materials in stone, iron, and bronze. We use materials not only to make artifacts but also to help us record ideas and concepts and indeed to manipulate these concepts to facilitate their use and development. We live in an information age, which is wholly dependent on materials technologies. The relentless, but now threatened progress of Moore's Law must be matched by a quieter but critical similar progress in magnetic storage technologies. The 8 Mb 2½ L "Winchester Drive" of 1990 is now the 8 Gb drive in a cigarette packet. We also feel the need to transmit vast quantities of information around the planet and again silica in optical fibers and very mature materials processing are critical. Indeed it is a curious coincidence that two unrelated properties of silicon dioxide are so important. Its temperature coefficient of linear expansion is 1/5 the (still small) value for silicon so that the essential protective oxide layer is held under a compressive strain of more than 0.1%. If these thermal properties were reversed, the tensile stress in the protective film would rapidly induce failure. And silica is quite stunningly transparent in the near infrared, so that all these bits of information can travel long distances. What is even more helpful is that the dispersive effects in silica at these wavelengths are minimal.

Nature has been helpful here. In the case of silica, we were presented with a material which, if man had designed it, we would have been sufficiently pompous to define it as "smart." The concept of the smart material is ill-defined, though it has emerged as one which responds in a constructive way to its environment. Ideally its response would be adaptive and would show initiative essentially to ensure the survival of material structures incorporating our "smart" component. Perhaps it could go so far as to reproduce. Indeed there are those philosophers amongst us who argue that highly automated factories are on the verge of reproduction.

The biological model, whilst stimulating, is ambitious and probably inappropriate. The material scientist and the engineer who incorporate these materials into structures and systems are both concerned with optimizing performance against engineering criteria. Even the biologist, to whom the engineer is tempted to ascribe influence over life forms, produces material sub-systems with specific properties usually responsive to a particular trigger or resigns himself, even for the genetically cloned Dolly the sheep, to considerable assistance from Mother Nature.

So in the context of this discussion, we must understand what "smart" materials are. Our focus will lie on responsive materials—transducer materials even—where one form of input trigger causes a change in the material's properties, usually in a different physical or chemical domain from the input. The smartness in these materials is in the final reckoning in their design to optimize to specific properties. In some communities, and especially in the smart materials and structures community, these are the smart materials of the title of this chapter.

Often there is another link: the smart material plays its part in the smart structure concept (Figure 1) where the responses of these smart materials are analyzed and controlled from an outside source, typically a computer. Indeed, even the biological precursor needs this control. Admittedly the responsive materials within the biological model have had millions of years of evolution to refine their design. However in order to go beyond a purely mechanistic reaction, some control function must be brought to bear from an external higher authority.

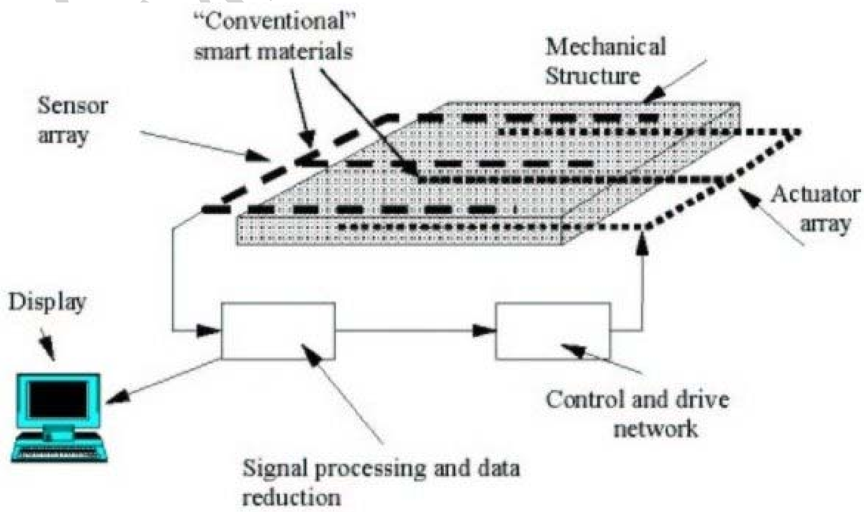

Figure 1. The "Smart" Structure Concept

So this defines our focus. The subject is enormous, so the coverage will be nothing beyond the indicative. However, hopefully it will indicate not only the present state-of-the-art, but also some of the emerging new areas that may prove to be extremely important in the future.

2. Responsive Materials in Engineering

Our smart materials are then primarily transducer materials whose function is to change an input signal into an output. The range of such materials is enormous and Figure 2—a generalization of the sensor cube—indicates the multitude of input and output domains.

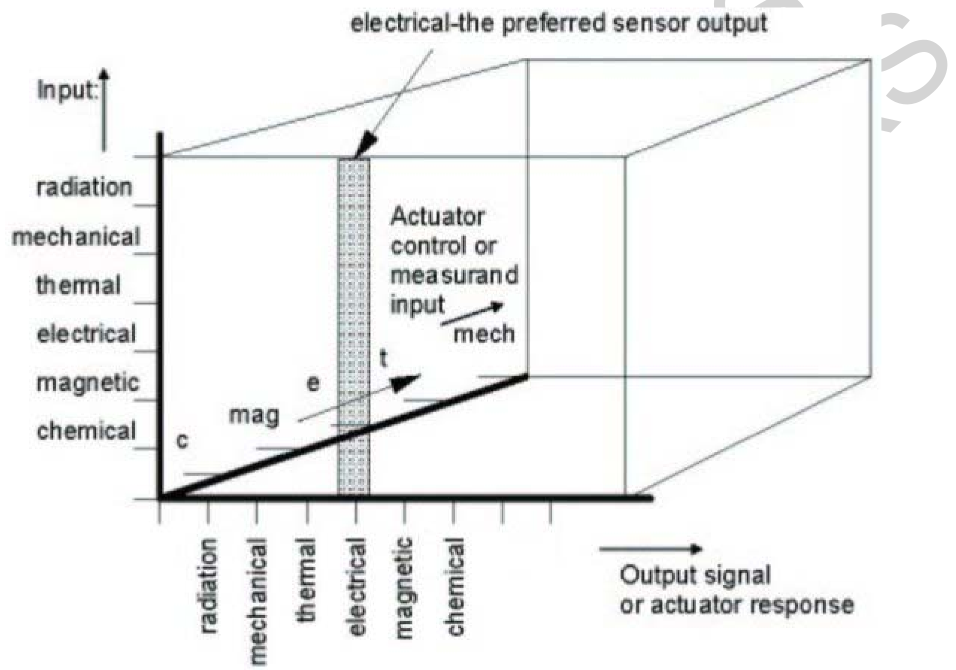

Figure 2. The Sensor Cube

In the context of engineering structures, our smart materials will augment rather than dominate the basic structural properties of the engineering artifact. The smart material will then typically participate in a sensing operation, which takes an input trigger and converts this trigger to an electrical signal. Alternatively, in an actuation function in which a control signal will be applied to a source of energy, which will convert to the required output form in the actuation system. Again typically the source of energy will be electrical and the controller will be an electronic amplifier. However the concept can readily be generalized to controlling chemical or hydraulic energy. For example both animals and automobiles consume hydrocarbon (or carbohydrate) fuels with mechanical, electronic or electro chemical control (Figure 3).

These material systems all have the feature that they respond to external intelligence—the computer —be it silicon based or biological gray matter. A basic characteristic of structural systems of this nature is that the sensor and actuator are effectively add-on extras to the original engineering structure. In this case, we are essentially adding the dimension of intelligence to a relatively conventional structural concept. In principle, we can go further into structural design, which incorporates responsivity. In effect, this is building a computer program—a response function—into the material itself. The transducer then becomes an essential mechanical component within the entire structure.

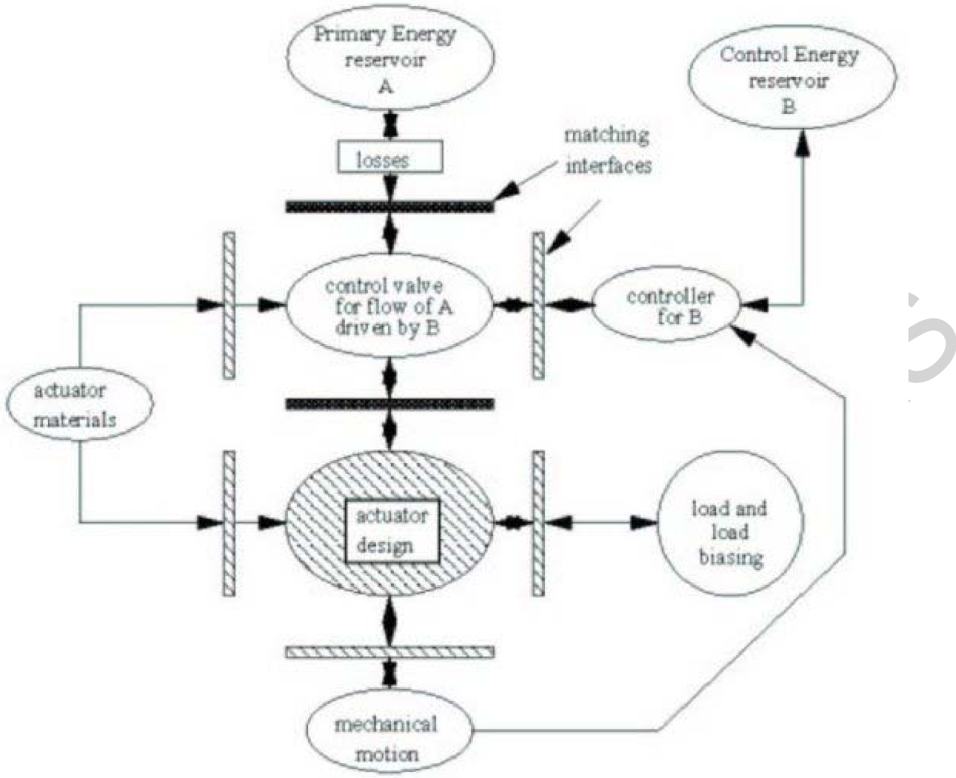

Figure 3. Matching Criteria and Conversion Interfaces in Actuator System Design

Finally it is useful to pause briefly and reflect that our aim with most "smart" structural artifacts is usually to complement the engineering need, rather than imitate the biological model. Our biological precursor is typically very versatile and very adaptive provided of course he or she is kept in a tightly constrained operating temperature range and is neither subjected to very large mechanical forces nor asked to move heavy objects. Even the adaptivity is challenged. The biological model needs books and computers to remember things and pieces of paper with which to plan and communicate. Further, our biological precursor gets bored and irritated through repetition.

So the engineer has a role to complement rather than compete. The remainder of this article looks at just a few of these complementary roles and highlights how material developments play a very important role in determining not only the evolution of the "add-on" intelligence but, more important, how our intelligent design of material systems can help us realize new and very high value functions. We shall first look at instrumented structures to see how these benefit from improvements in sensor and, to a lesser degree, actuator techniques and then progress into a discourse on current and emerging smart material technologies.

3. Instrumented Structures: Add-ons for Smart Materials

The first stage in making a material "smart" is to equip it with the necessary facilities to enable it to communicate what it is doing and link this information into a suitable observation system, which is capable of reacting to the information. Much can be done at the simple level where the observer is human and the reaction is to send out a repair team.

Our physiological model includes within it a nervous system, which reaches every important part of the materials fabric and is capable of gathering and processing information from this nerve system. A sensor array can perform this function only if it is sufficiently complex to sample all the essential data. Such arrays (strain gauges, thermocouplers, etc.) have been available for decades but only to attach to the surface of a material. Further their use has been inhibited by the burden of point to point wiring for each individual sensor element.

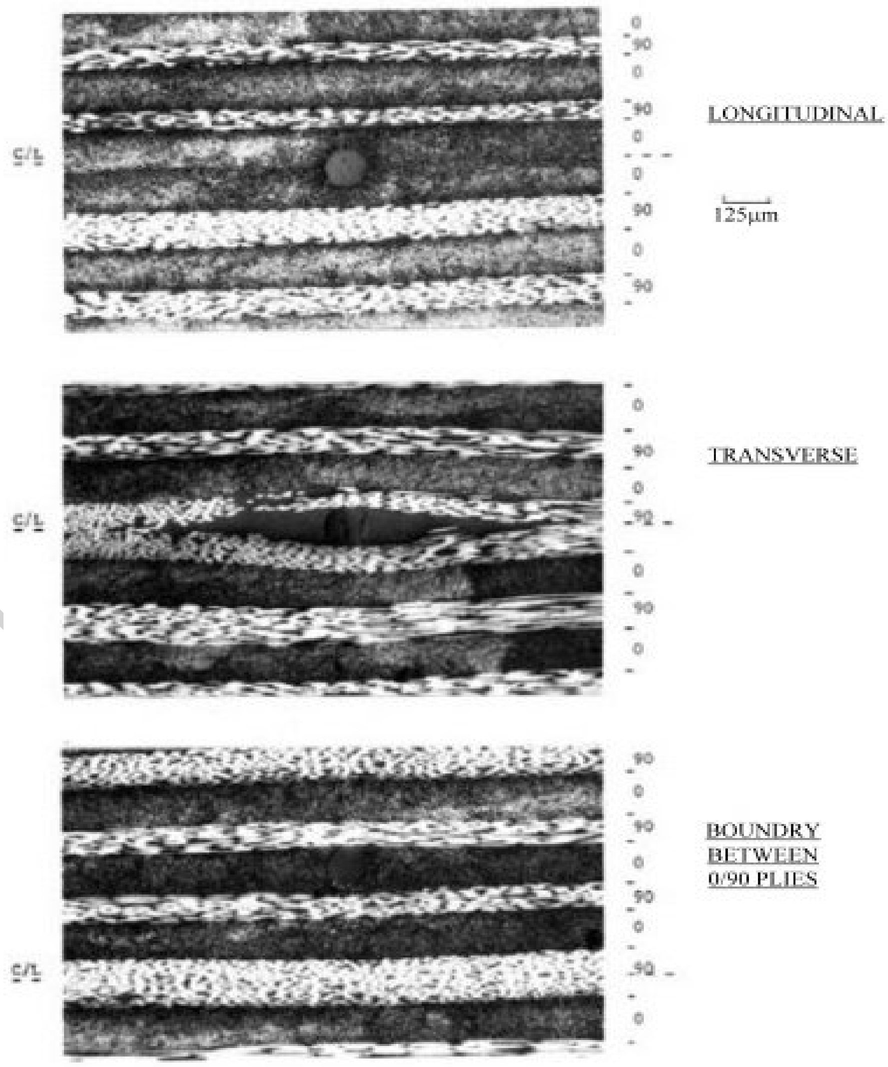

Figure 4. Optical Fibers Embedded in Carbon Fiber Reinforced Composite Coupons

Since 1985, there has been immense activity in fiber-optic sensor systems, which address both inhibitions of the conventional sensor array mentioned above. The optical fibers can be attached to or embedded within a wide range of materials (Figure 4). In particular, they are compatible with carbon and glass fiber composites and can withstand the mechanical strain ranges, which characterize these relatively new materials. Fiber sensors can also be attached, suitably protected, to the surface of structures or incorporated into assemblies such as ropes, tethers and moorings (Figure 5).

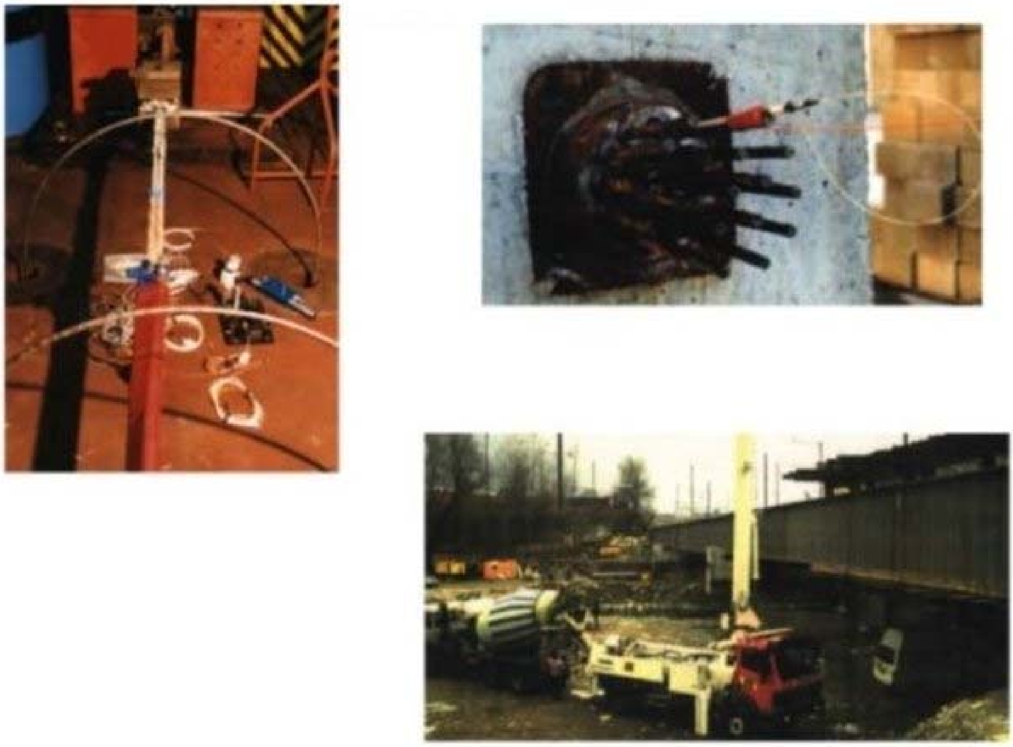

Figure 5. Some Practical Applications of Optical Fiber Sensors

Additionally, the optical fibers can function as an array of sensors with sensing sections located at identifiable points along the fiber. These functions can be realized as, for example, Bragg gratings, distributed Brillouin scattering systems, distributed Raman for temperature measurements, or integrating section by section length measuring systems. Full details of these sensing approaches can be gleaned from the bibliography. Their basic features are shown in Figure 6.

These approaches address the physical state of the material under test and typically measure strain and temperature. Usually the strain measurement will require some correction for thermal interference, but this is readily incorporated into the strain monitoring algorithm. Sometimes, for example, for underwater or underground measurements, the environmental temperature is constant and corrections are not required. The chemical state of a structure is also extremely interesting, especially if corrosion parameters can be addressed. Historically, such measurements have proved to be very difficult since most chemical sensors have limited long-term reliability. There are however some emerging fiber-optic technologies which facilitate distributed chemical measurements. In particular, these systems can detect changes in humidity within a structure, the presence of unexpected hydrocarbons and, in other manifestations, changes in the local pH. These techniques are not nearly so well established as the strain and temperature systems, but also offer promise for another dimension of information concerning structural properties.

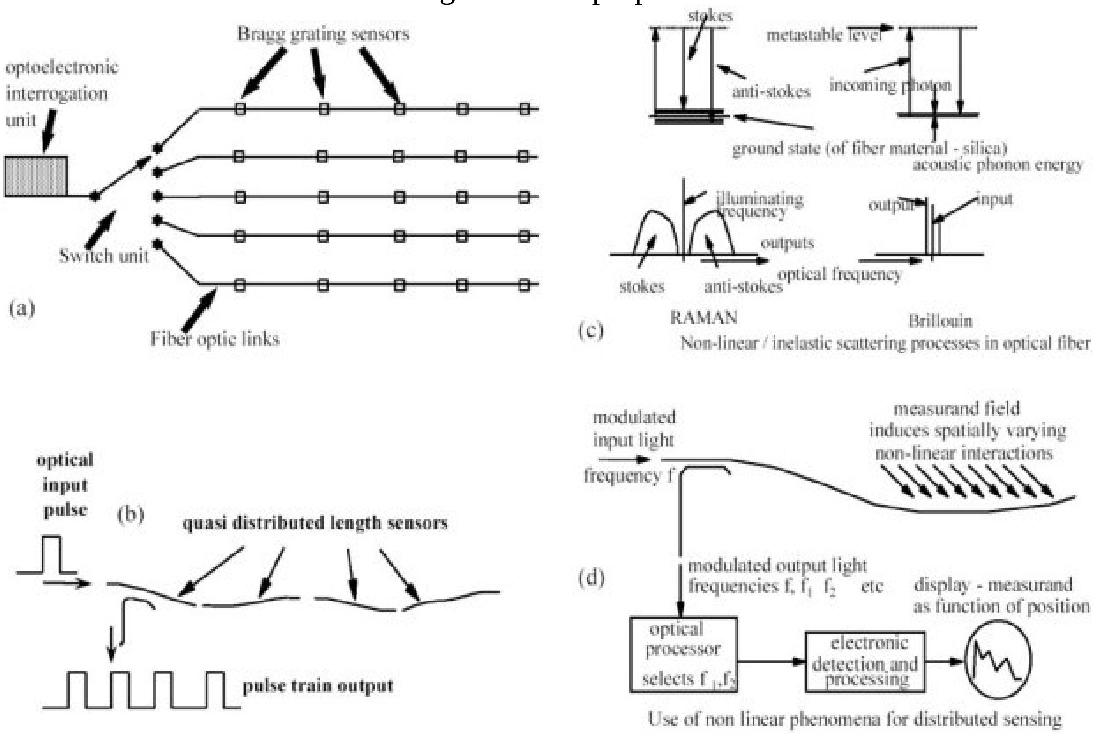

Figure 6. Some Architectures for Optical Fiber Sensors

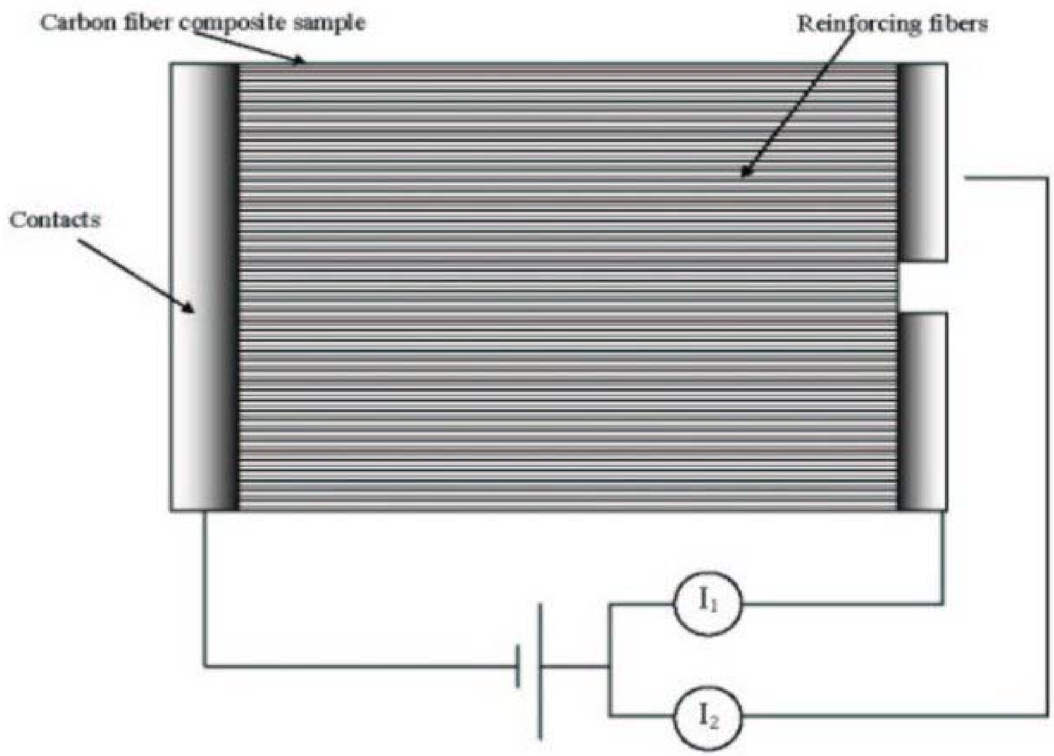

Figure 7. Simple Technique to Monitor the Integrity of a Carbon Fiber

Further technologies have also been considered for structural sensing and indeed some major structures have been instrumented with more traditional sensing methods, especially in the civil engineering domain. These traditional fault sensors such as LVDTs, strain gauges, inclinometers and thermocouplers must all be attached to the structure and wired individually to a data collection point. Systems of over 1000 sensors have been reported, so there is considerable complexity in the wiring harness, power supplies and communication system, which can be simplified using the fiber- optic techniques described above.

Of the new techniques for structural sensing, acoustic emission analysis is particularly promising for detecting fatigue in metallic and fiber/matrix based structures (see Composite Defects and their Detection). In carbon fiber structures techniques such as measuring the resistance of the carbon within the structure hold considerable promise and this concept can be extended into the domain of the sensing textile in which the resistance or other electrical properties measured in a matrix format on an array of points can give information concerning the integrity of the textile structure shown conceptually in Figure 7.

These last techniques are inferential meaning that they do not take a direct measurement of the parameters of interest but monitor some property such as acoustic emission under controlled loading or the elements of the resistance array. Therefore to determine the necessary sensing information requires a processing algorithm and computing power of some substance. Both of these have become available at very competitive costs within recent years and tools such as wavelet analysis, higher order spectral analysis, neural networks and knowledge based systems are readily incorporated into the sensor.

These bolt-on smart materials augment the capability of conventional engineering structures by incorporating sensor arrays and data processing capability. Their principal use lies in condition monitoring. The “actuator” is the human being dispatched with investigative tools to identify and usually correct the fault highlighted by the sensor array.

There are however a few “passive actuators” which respond to applying corrective action to structural conditions. Most of these involve mechanical dampers: variations on the theme of shock absorbers designed to dissipate energy harmlessly from the material. Here, the art lies in maximizing the energy dissipation capabilities and for large structures utilizing plastic flow in ductile steels and even the phase change in materials such as shape memory alloys and viscoelastic materials which show very high specific energy absorption densities. In some cases, it is even feasible to control the damping, for example, in electro and magneto-rheological fluids. These last damping systems offer the next stage in the process refining the available response to suit the particular environmental and structural conditions.

4. “Conventional” Smart Materials

The term “smart materials” is often interpreted as meaning transducer materials which convert mechanical signals to electrical signals or vice versa. Indeed sometimes the implication goes further into focusing on only “hard” transducer materials which have high stiffness comparable, for example, to that typical of metals such as aluminum. In this section, we shall briefly examine the basic properties of some of these conventional smart materials.

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