15
Smart Structures

15.1 Introduction

Through evolution, biological structures have become highly optimized both in their mechanical properties (e.g., strength, stiffness, and toughness), and in their ability to sense and respond to the environment—to sense threats, heal damage, and respond to external demands (e.g., adaptive shape and other functions such as stealth).

The active/sensory "smart" behavior of these materials involves the following systems:

- **Sensor**
  - nerve: develops signals from external stimuli: senses overstress, physical damage, temperature, chemical attack
- **Actuator**
  - muscle: provides response to a signal; provides force for movement or shape change
- **Processor**
  - brain: monitors sensor, processes data, provides signal to actuator

Smart behavior of biological structures includes:

- Adaptive shape
  - e.g., for aerodynamic control
- Adaptive stiffness
  - to optimize for loading conditions
- Adaptive strengthening
  - reinforcement deposition to optimize strength and stiffness
- Health monitoring
  - indication of damage or overstress
- Self repair
  - heals damage by local deposition of material
  - re-grows damaged component
- Reversible adhesion
  - ability to form and break strong adhesive bonds at will
- Stealth
  - change in form, colour, and/or pattern

Fiber composites simulate natural materials, such as wood and bone, in forming lightweight, stiff, tough structures. Now there is a rapidly growing interest in simulating selected aspects of this intelligent or "smart" behavior, particularly in aerospace composite structures.

15.2 Engineering Approaches

Based on the discussion of the proceding section, smart structures can be defined as structures that are "aware" of their state and have the ability to respond to changes in the operating environment or to other stimuli in an intelligent way. This ability may be achieved by processing information from sensors and driving actuators or more simply from a built-in response mechanism. The terminology adopted here has been taken from Gandhi and Thompson,[1] and is illustrated in the flow diagram in Figure 15.1. This Figure shows the various sub-systems in a so-called active smart structure that consists of structural health monitoring systems

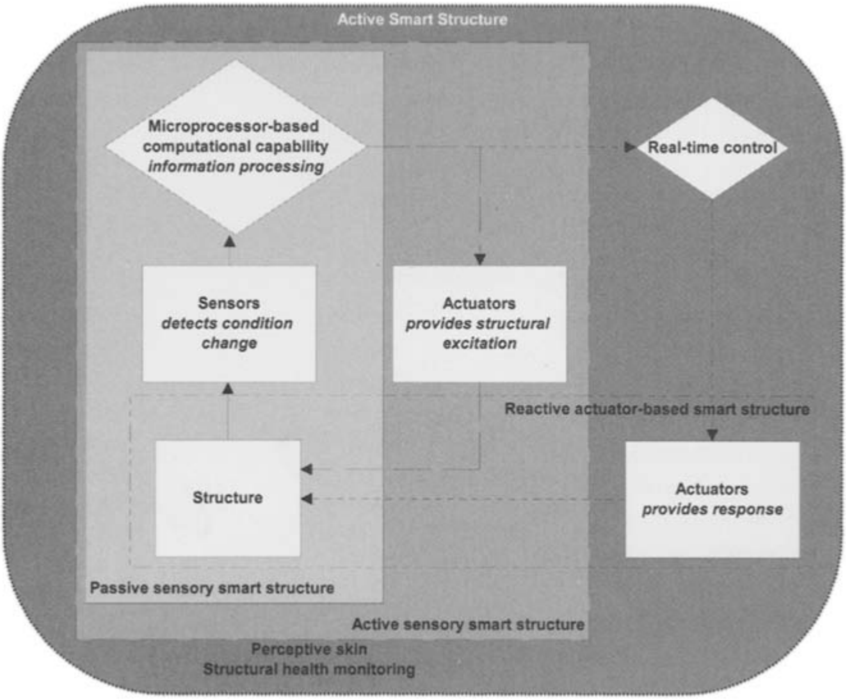


Fig. 15.1 Schematic diagram showing components of an active smart structure—different sensory schemes are indicated.

and the reactive actuator-based smart structure, in other words, systems without an adaptive feedback loop. Systems that incorporate adaptive feedback loops are referred to as active smart structures.

Currently, smart structures are made up of individual sensors and actuators embedded in the material or bonded to its surface, as well as microprocessor and possibly a power source. In the future, these components may be integrated, possibly at the molecular level.

The engineering analogies for the basic smart functions of biological materials are:

- **Sensor**
  - strain: optical fibers, electrical-resistance strain gauges, surface acoustic wave sensors, piezoelectric transducers (ceramic and polymer)
    - * interrogated electrically or optically in the case of passive elements, or by generated charge in the case of piezoelectric transducers
  - chemical: optical fibers, surface acoustic wave sensors, and various ceramics
- **Actuator**
  - piezoelectric ceramic transducers, shape memory alloys and ceramics, magnetostrictive materials, electrorheological fluids, and carbon nanotubes
    - * actuated by electric, magnetic, or thermal (electric current) energy to change shape or produce a force from a power source, generally an amplifier
- **Processor**
  - microcomputer or a built-in response that may simply be included in the sensor or actuator

Appendix A provides a brief description of some current sensor and actuator systems. These elements (not including the power source) may be integrated into free-standing microscopic devices called micro-electromechanical systems (MEMS) or micro-systems. These systems can sense, control, and actuate at the micro scale and function individually or in arrays to generate effects on the macro scale. Micro-systems may also include optical components for sensing and processing; these systems are referred to as micro-electro-opto-mechanical systems (MEOMS).

Polymer-matrix composites lend themselves well to the embedded approach because these elements can be incorporated during manufacture of the component and the mechanical properties of the composite tailored to provide the desired mechanical response for the actuators. Thus, composites are well suited to the formation of adaptive structures (for example, structures able to change geometry). Embedding is possible because the relatively low temperatures and pressures required to produce the materials will not damage the sensors or actuators. However, for existing composite structures and metallic structures (where embedding is not possible), the elements can be attached to the surface of the component. Although this approach is much less robust than the embedded approach, it will be effective for some applications.

In the medium term, it is hoped that the life-cycle costs of airframe structures can be reduced by the application of smart structure technologies for structural health and usage-monitoring and even to extend life. Long-term aims are to develop structures with adaptive shape and other morphological capabilities.

Some of the potential applications of smart structure technologies are as follows:

Health and usage monitoring

- Damage detection
  - sensors to measure stress, strain, temperature or life consumption
  - sensors indicating damage size and severity and location over the whole structure
- Environmental degradation (bonded joints)
  - embedded chemical sensors to detect incipient bond degradation
- Internal environment
  - environmental sensors to detect moisture content

Life extension

- Smart repairs
  - bonded patches or reinforcements with damage sensors to detect disbonding of the patch or growth of the repaired damage
- Self-healing materials
  - encapsulated adhesive systems (separate resin and hardener) in composite structures that activate on local damage and react to re-bond the damaged zone)
  - Memory alloys contract on activation to close up the damaged region
- Vibration suppression
  - bonded on sensor/controller/actuator system
    * providing out-of-phase force to increase damping
  - electrorheological fluids to enhance damping

Improved operations

- Signature reduction (acoustic, infrared, radar, visual)
  - active paints—thermochromatic, photochromatic, electrochromatic
    * change color and/or infrared emissivity when stimulated
  - active coatings with embedded MEMS to send out false signal
- Integrated antenna airframe structure
  - embed antenna into composite skins
    * reduce drag, observables, etc.
- Adaptive structures
  - embedded sensor/controller actuator system to modify shape of component
    * wings, helicopter blades, etc.

- Adaptive surfaces
  - use of MEMS to modify surface contour
    * may eliminate need for large hinged control surfaces
- Active noise suppression
  - sensor/controller/actuator system
    * generate a disturbance to cancel out noise (if narrow band)
    * change model shape

15.2.1 Structural Health Monitoring

Figure 15.1 illustrates that structural health-monitoring systems can be classed as two types of systems: passive and active sensory smart structures. The passive sensory smart structure contains only sensors and electronics, with a communication mechanism and potentially some storage and processing capability, which is capable of processing the sensor data in such a way that will provide the operator with structural condition information. These systems are passive to the extent that the sensors are using the structural in-flight loads to detect/monitor structural damage. Active sensory systems contain both sensors and actuators. In this case, the actuators provide a well-defined (known) excitation and the response is monitored by the sensors. This sensing system can be used on demand by the operator, for example, at the beginning or end of each flight.

Current approaches to ensure aircraft integrity for metallic components rely simply on measuring fatigue consumption, achievable through the use of usage monitoring techniques. However, when this approach is combined with continuous damage detection it is called a health and usage monitoring system (HUMS) or structural health monitoring (SHM).

This approach can eliminate or drastically reduce the need for inspection. The ability to detect damage is particularly important for composite structures that are susceptible to impact damage and disbond damage in secondary bonded joints. Here, SHM systems will enable the detection and characterization of this type of insidious damage. The introduction of SHM-based structures may allow less stringent certification requirements, thus reducing the cost of certification of composite structures and possibly reducing certification concerns with secondary bonded structures.

Using smart sensor concepts, damage and damage growth in the airframe and other structural life-related problems would be continuously monitored on-board the aircraft to provide real-time damage assessment. This technology could permit a reduction in inspection and regular maintenance costs with substantial impact on the through-life costs.

The overall goal is for the structural health monitoring system to form a subsystem of a total integrated vehicle health monitoring system (IVHMS).[2] To achieve this goal, significant progress needs to be achieved in the areas of structural health monitoring sensors, data/information processing, diagnostic and prognostic algorithm development, and data dissemination and storage. Current SHM programs are concentrating on the demonstration of various sensor systems, such as optical fiber and piezotransducer systems, through civil flight-testing and the development of design guidelines for incorporation of sensors into composite manufacturing processes.

15.2.2 Improved Aircraft Operations and Extended Airframe Life

Figure 15.1 illustrates that the next category of smart structure (beyond the perceptive structures/structural health monitoring systems) is the reactive actuator-based smart structure that is devoid of sensors and contains only actuators. One example would be a shape memory alloy, actuated temperature fuse. Finally, the fully active smart structure is one that contains sensors, actuators, information processors, and a real-time control capability (i.e., with feedback).

Smart materials and structures technologies can be used in various ways to improve operations or extend life, for example, by:

- Reducing dynamic instabilities, vibrations, and noise by using active vibration and noise control
- Improving aircraft/rotorcraft handling, manipulating lift, or reducing drag by the application of adaptive structures and aerodynamic flow control
- Incorporating conformal antennas to improve aerodynamics and low observable characteristics, as well as reducing fabrication costs by developing multi-functional structures integrated electronics and devices

Excessive vibration and noise may affect the fatigue life of the structure and electrical components and crew/passenger effectiveness/comfort. A number of applications have been identified in which smart structure technologies have the potential to improve structural life and operational performance:[3] tail buffet wing/store flutter, isolation of electronics from forced vibration, helicopter blade/vortex interaction, and blade tracking.

By incorporating actuators within the composite structure to make the structure bend and flex, the concept of shape control or morphing can be applied.[4] The actuators may induce wing warp, camber shaping and/or control surface deformation; they may also produce structures with variable stiffness. Lift/drag of a control surface may also be controlled/improved by changing the flow conditions over the lifting surface. The expected benefits from such concepts are: reduced drag over a broad range of flight conditions, increased payload, greater range, improved aerodynamic performance, and improved low-observability characteristics.

Composite structures allow for fabrication of smart skins that incorporate radiofrequency (RF) antennas, signal processors, and various other types of sensors and devices. One example is conformal antennas, that is, load-bearing structures that incorporate embedded controllable and reconfigurable antennas. Typical military aircraft have a large number of antennas; for example, the

F/A-18 has approximately 70 antenna apertures for radar and communication functions.

Conventional antennas require structural cut-outs, and with their associated structural reinforcements, protrude from the airframe thus degrading aerodynamic performance; weight consequently increases, further adding to operation costs. It has been estimated that up to 50% of an aircraft's surface, if composite, could be used to incorporate RF antenna functions. Potential benefits of conformal antennas include reduced weight and volume, lower observability, reduced power requirements, greater radar and communication range, reduced manufacture and maintenance costs, and improved aerodynamic performance.

15.3 Selected Applications and Demonstrators

To illustrate smart structure applications to composite components, a few examples are discussed below.

15.3.1 Structural Health (and Usage) Monitoring Systems

15.3.1.1 Smart Patch. The application of bonded composite patches to repair or reinforce defective metallic or composite structures is a very effective and versatile procedure.[5] However, airworthiness authorities are often reluctant to certify bonded composite repairs to primary structures because of concerns with the reliability and durability of adhesive bonds.[6] The smart patch approach is being developed to alleviate these concerns and thus facilitate the application of composite bonded repairs to primary structure.

The smart patch concept consists of a bonded composite repair with the ability to monitor its own health,[7] thus enabling a continuous safety-by-inspection approach to be applied. This approach will allow timely decisions on preventative and scheduled maintenance before failure of the repair or repaired structure.

The specific objectives of the smart patch are:

- To detect disbond growth in the safe-life zone of the patch (Fig. 15.2a), which is unacceptable because damage can grow very quickly
- To monitor damage growth in the damage-tolerant zone, where damage growth is stable and slow

Damage in the damage-tolerant zone may consist of either cracks or delaminations in the parent metallic or composite structure and also disbonds in the adhesive or delaminations in the patch system. Current research[7] is focused on the assessment of new sensing techniques and sensors, which may be incorporated in bonded repair systems, to detect and monitor disbonds in the adhesive layer, delamination in the patch system, quality of the bond, and crack growth rates in the underlying metallic substrate.

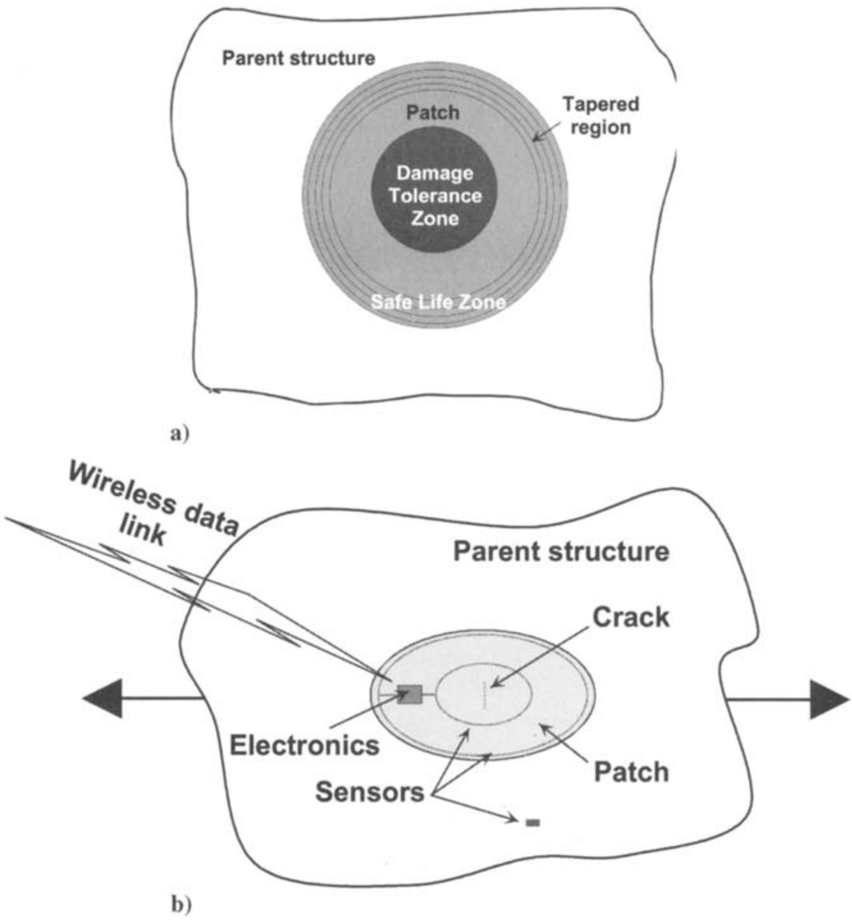


Fig. 15.2 Schematic diagram of *a*) a generic external bonded repair showing safe-life zone (no disbonding allowed in this zone) and damage-tolerant zone (stable disbonding growth allowed in this zone) and *b*) the smart patch concept.

The most direct approach to assess the health of the patch system is to measure the level of load transfer in the safe-life zone (See Fig 15.2a). The concept is to monitor the ratio: (patch strains)/(strain in the component) during service life. Any decrease in this patch health ratio is an indication of disbonding of the patch in this critical end region. There is no requirement to measure the actual loading; disbonding is indicated by the reduction in relative strain. The strain sensors are continually monitored by an on-board miniaturized system that processes and stores patch health information and then transmits these data to an external computer by an infrared link when required, as shown conceptually in Figure 15.2b.

An alternative approach for monitoring the patch is to measure damage directly, as described later.

15.3.1.2 Optical Fiber Sensors: Loads and Damage Monitoring. For embedded optical fiber systems, the interaction between the optical fiber and the host composite needs to be considered from the point of view of structural integrity and also in understanding the response of the sensor due to its embedding. Considerable effort has been directed toward characterizing the effects of embedded optical fiber sensors on the polymer fiber composite.[8] Figure 15.3 is a micrograph of cross-sectioned carbon/epoxy laminates with embedded 150-μm polyimide buffered optical fibers, showing that the introduction of the optical fiber is relatively unobtrusive in terms of fiber and resin distribution in these laminates when the optical fiber is collinear with the reinforcing fiber. Because of the better thermal stability of the polyimide-coated fibers compared with acrylic, these fibers give superior interfacial mechanical properties. In general, as long as the optical fibers are collinear with the reinforcing fibers, and the percentage of the optical fibers is significantly lower than that of the reinforcing fibers, the mechanical properties are not compromised. Numerous static and fatigue studies of carbon/epoxy laminates with embedded optical fibers (when the fibers are collinear with the reinforcing fibers) have indicated no significant variation in the mechanical properties for room temperature/dry and hot/wet environmental conditions.[9,10] From the point of view of understanding the performance of the sensor due to embedding, the

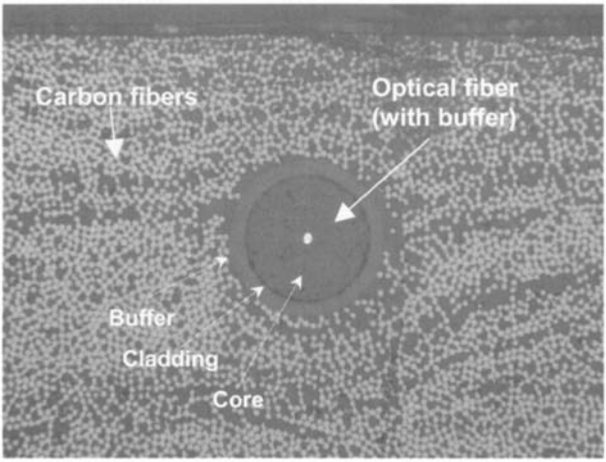


Fig. 15.3 Micrograph of cross-sectional laminates illustrating a polyimide coated fiber in carbon/epoxy laminate. The carbon fibers have typical fiber diameters of 7 μm, the optical fibers have typical core and cladding diameters of 10 μm and 125 μm, respectively, and the polyimide coating is typically about 12 μm thick.

fiber is considered as an elastic inclusion within the host, and therefore the interaction between this inclusion and the host needs to be considered when interpreting data from the sensor. For example, a significant difference has been observed between the sensitivity of embedded and surface mounted metal-coated optical fibers.[11]

Rugged and non-intrusive connection systems for optical fiber sensors are required for these systems to be accepted. Therefore, either embedded optical fiber connectors and/or (embedded) wireless communication systems will need to be installed, allowing robust connection on demand without interfering with the measurand.

One of the earliest uses of optical fiber systems was to detect impact damage and monitor damage growth in aramid fiber/epoxy in the leading edge of the DASH-8 aircraft.[12] In this case, special sensitized optical fibers were embedded within the composite leading edge that was fractured after an impact event that exceeded a certain threshold value. The fibers only fractured within the immediate vicinity of the impact site. Thus, when HeNe laser light was transmitted through the fiber, light was emitted from the fiber-fractured ends. Thus, the impact sites were observed visually by significant leakage of laser radiation at these sites. Without treatment, these silica optical fibers can withstand significant shear and in-plane stresses sustained during impact damage without breaking; these fibers break at much higher strains (~5%) than do most structural materials. Therefore, the most difficult aspect of this technique is in the application of surface treatments that sensitize the fiber to break at a given consistent strain level.

Fiber Bragg grating sensors (see Appendix A) provide a quasi distributed, non intrusive, accurate, and reliable measurement of temperature, strain, and pressure. A fiber Bragg grating system was used on the DC-XA prototype[13] (Delta Clipper experimental advanced re-usable rocket program) to monitor loads on ground tests and during takeoff of several highly stressed components. The system enabled the ground personnel to achieve readily understood (in graphical format) load and temperature distributions of the advanced structural components in the vehicle.

A successful application of the fiber Bragg grating system has been applied to yacht composite masts[14] where 60 optical fiber strain sensors were embedded in 12 separate optical fibers at various locations throughout the rig. Figure 15.4 shows the optical fiber Bragg grating sensors being embedded in the carbon/epoxy masts during fabrication. A total of 43 sensors were monitored in real time, at a rate of about 500 times per second, with most sensors measuring strains within the range of 3500 $\mu\varepsilon$ and some sensors measured extreme strains ($\pm$ 15,000 $\mu\varepsilon$). The system was constructed using several optical fibers and a demodulation system with several channels in parallel, which were multiplexed electronically (Fig. 15.5). These systems have been successfully used to monitor loads in the mast for design information (allowing reduced weight, size, and cost) and to enable optimal safe performance during race conditions.

Fig. 15.4 Fiber Bragg grating sensors being embedded in carbon/epoxy composite yacht mast during construction.[10]

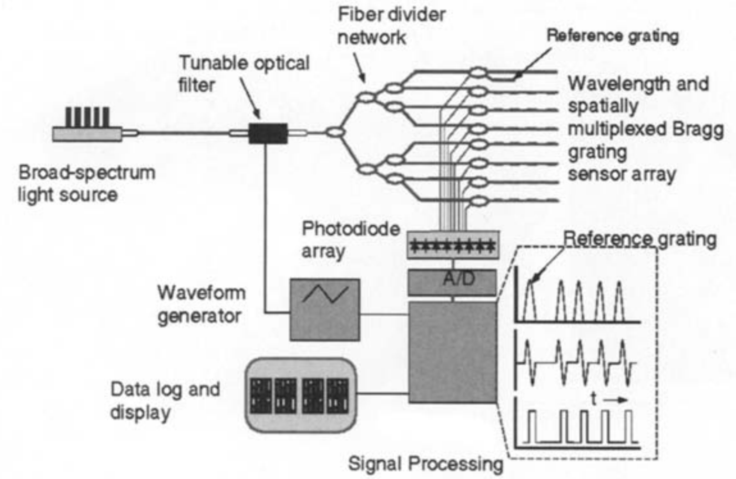


Fig. 15.5 Fiber Bragg grating strain sensor interrogation system architecture used to monitor the fiber Bragg gratings embedded in the carbon/epoxy yacht mast.[10,14]

15.3.1.3 Piezotransducers: Damage Detection/Monitoring. Low-profile piezotransducer elements for sensing and actuation offer an encouraging alternative in situ structural health monitoring (i.e., an active sensory smart structure) system for composite structures. Generally piezoelectric ceramic PZT wafers (See Appendix A) are used for actuation because these materials offer excellent force transfer to the structure, and either piezoelectric film or ceramic transducers can be used for sensing. These materials are preferred over conventional electrical resistance-foil strain gauges because they do not require an external power source; instead, they generate charge when a strain is applied, whereas conventional strain gauges require external power to operate.

The piezotransducers can be either embedded or surface-mounted. These elements offer at least three modes of interrogation: electro-mechanical impedance, transfer function, and stress-wave (or acousto-ultrasonic) technique modes. To date, the stress-wave technique offers the most promising approach as a wide-area damage detection and monitoring system. The excitation of elastic stress waves is relatively straightforward given the broadband frequency response characteristic of piezoelectric ceramic materials. The elastic stress waves travelling through the structure will be reflected/diffracted and subject to wave mode conversions by material and structural discontinuities (such as disbonds, delaminations, etc.) as shown schematically in Figure 15.6. The system can then detect and possibly characterize the damage by monitoring and analyzing the change in the reflected or transmitted signals.

One of the inherent advantages of the stress-wave arrangement over the strain-based load transfer approaches, just discussed, is that it does not require a priori

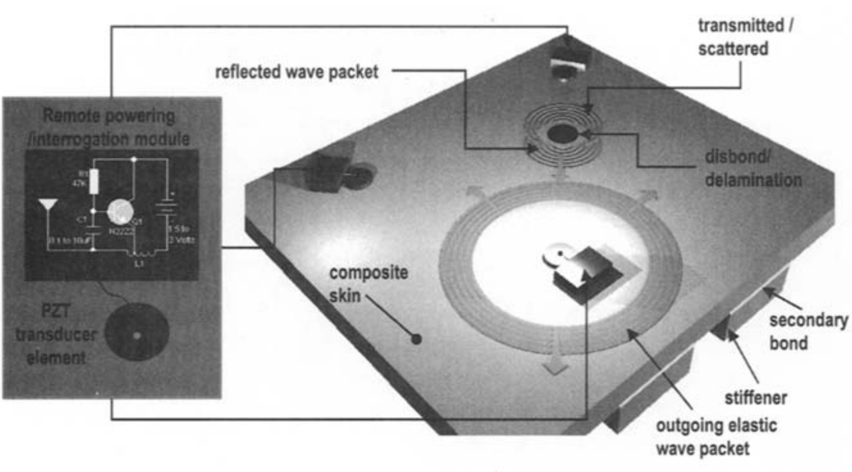


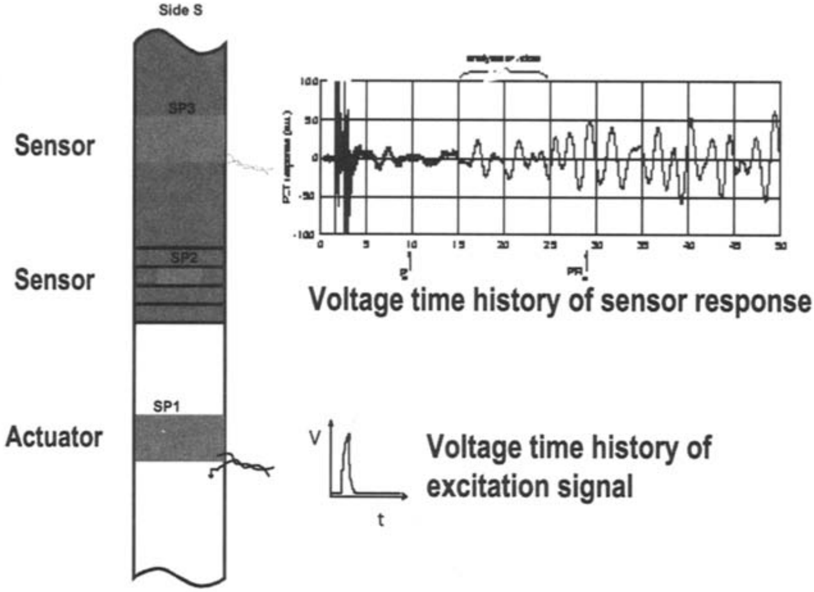
Fig. 15.6 Schematic diagram illustrating the stress-wave concept where piezotransducers are used to generate elastic stress waves that enable global structural health monitoring with low sensor density.

knowledge of the likely location of damage initiation and should therefore allow for a lower sensor density where large structures are considered. The broader sensitivity range also provides a better basis for the quantitative assessment of disbond growth. Some examples on the application of the stress-wave technique are given in the following.

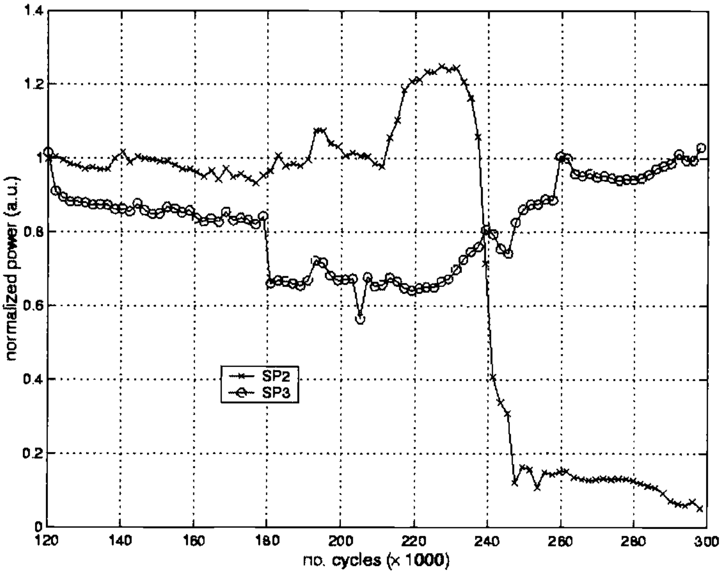
Studies on composite bonded repairs have shown the excellent sensitivity of the stress wave technique to detect disbonds in secondary bonded joints.[7] In this study, the approach was to excite elastic stress waves in the host by applying a short voltage pulse to a piezoelement, SP1, surface-mounted to the metal substrate some distance from the patch edge as shown in Figure 15.7a. Part of the elastic energy is transmitted through the bond-line into the patch and received at the two piezoelectric sensor locations (SP2, located on step 3 of the patch, and SP3, located on the far-field region of the patch). Damage in composite bonded repairs was assessed by monitoring the transmitted sensor power (P) within a prescribed time window. The response at sensor SP2, as shown in Figure 15.7b, reflects a high level of sensitivity to disbond growth and correlates well with the strain gauge results.

Significant progress has been achieved in the development of the Stanford Multi Actuator Receiver Transduction (SMART) layer that consists of an array of piezoelectric ceramic wafers encapsulated within two layers of Kapton sheets,[15] as shown in Figure 15.8. The Kapton layers incorporate the copper tracks for the electrical connectivity. These SMART layers can be embedded or surfacemounted on the composite component for process control and/or damage detection. One piezotransducer (actuator) generates controlled repeatable diagnostic (acousto-ultrasonic) signals, and the resulting response is detected by the neighboring piezotransducers. By analyzing the resulting response, an indication of the state of cure (for process control) and size and location of damage sites (for structural health monitoring) can be ascertained. The SMART layer has been incorporated in composite bonded repairs and successfully used to detect and monitor crack growth in the metallic substructure.[16] Alternatively, this SMART layer can be used passively to detect noise from impacts that might occur to alert the operator to impact damage.

Novel acousto-ultrasonic (elastic stress wave) generation and detection techniques were developed to generate 2D maps of damage and failure in composite structures.[17] Phase-delayed multi-element low-profile piezoelectric ceramic actuators were designed and fabricated to generate selected ultrasonic Lamb waves, within carbon/epoxy and glass/epoxy fiber epoxy laminates. The detection of the ultrasonic response was achieved using surface-mounted interferometric optical fiber sensors. Advanced signal processing was then used to detect defects and achieve enhanced images of the defect. A multivariate outlier analysis was used to detect changes in the signal that corresponded to damage, that is, generated the damage index. A visual representation of impact damage was then achieved using a mapping technique. This study also showed that the passive listening mode is also an effective technique to detect impact damage in composite laminates.



a)



b)

Fig. 15.7 ***a*) Schematic diagram of skin-doubler specimen (Chapter 9), representing the termination of a repair patch, showing typical time varying voltage signals to the actuator and from the sensor; *b*) signal power versus number of cycles for piezoelectric ceramic sensor SP2 and SP3.**

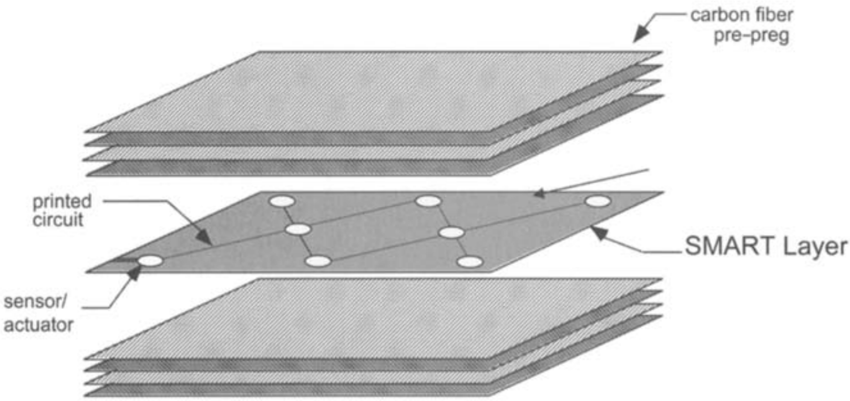


Fig. 15.8 Schematic diagram illustrating the piezoelectric sensor network, or SMART (Stanford Multi-Actuator Receiver Transduction) layer, embedded in a carbon/epoxy laminate. Taken from Ref. 15.

15.3.2 Active Smart Structures

15.3.2.1 Vibration Suppression. High-performance aircraft, especially those with twin vertical tails such as the F/A-18, are commonly subject to an aeroelastic phenomenon called buffeting when the aircraft flies at high angles of attack. These high-performance aircraft are often required to undergo maneuvers involving high angles of attack, and under these conditions unsteady vortices emanating from the wing and the fuselage impinge on the twin fins, causing substantial buffet loads. These loads result in oscillatory stresses, which may cause significant fatigue damage that may restrict the capabilities and availability of the aircraft.

Design of aircraft to accommodate these buffet loads is a difficult task. Therefore, the use of piezoelectric ceramic actuators in conjunction with active structural control to alleviate damaging buffet induced strain (and therefore increase the fatigue life of vertical tails) is a possible solution to this important design issue.

To demonstrate this technology, a full-scale test was conducted on the vertical tail of an F/A-18. Piezoelectric ceramic actuators were attached to the composite skin of the starboard fin,[18] as shown in Figure 15.9. The fin was tested in a rig, which generates representative static and dynamic flight loads on the airframe, as well as maneuver loads. In this study, it was demonstrated that at maximum control gains, the active buffet load alleviation system was able to reduce the overall root mean square (rms) strain level over the control bandwidth from 0 to 100 Hz. The tests were carried out at a number of different flight conditions where, at the nominal flight condition, the critical strain was reduced by 51%, whereas at the penultimate severe flight condition, the reduction was 15%.

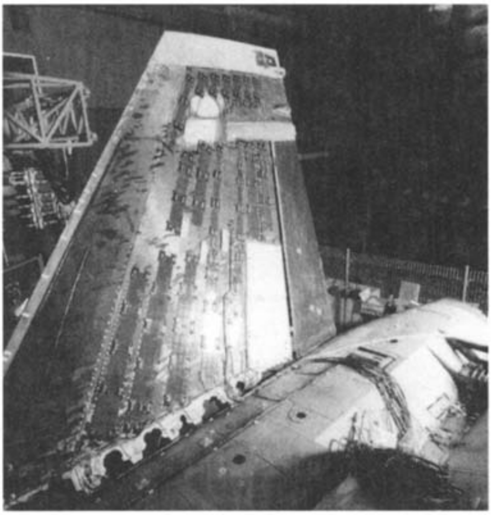


Fig. 15.9 This photograph shows the piezoelectric ceramic actuators, bonded to the carbon/epoxy composite skin of an F/A-18 fin to reduce vibration response of the fin due to buffet loading.

Figure 15.10 shows a comparison of strain density as a function of frequency between the open-loop and closed-loop configurations at the nominal flight condition. From these results, it is estimated (taking into account usage rates) that if the current active buffet load alleviation system were installed on an F/A-18, the increase in life would be approximately 70% or, in other words, 4000 hours could be added to the life of the tail.

15.3.2.2 Damage Mitigation. Shape memory alloy (SMA) wire (See Appendix A) actuators embedded in a hybrid composite system have been demonstrated to provide active damage control.[19] In this case, the SMA wires were embedded in a composite material, making the SMA wire an integral part of the overall system. The basic approach was to elongate inelastically the SMA fibers before being embedded (the SMA fibers are constrained from reverting to their original length during the curing process). Upon heating the wires beyond their transition temperature (by passing an electric current through them), the wires were activated, causing them to revert to their original length thus changing the stress and strain fields in the specimen. The aim here is to change the stress field around areas of high stress concentration to reduce the effective stress intensity factor and reduce crack growth. This concept was experimentally demonstrated by embedding elongated SMA (nickel-titanium alloy, NiTi) fibers in a photoelastic epoxy material. When the SMA fibers, which were located about 0.5 mm ahead of a crack, were activated, a reduction of 24% in the stress intensity factor was measured.[19] Similar studies were conducted with NiTi fiber/epoxy

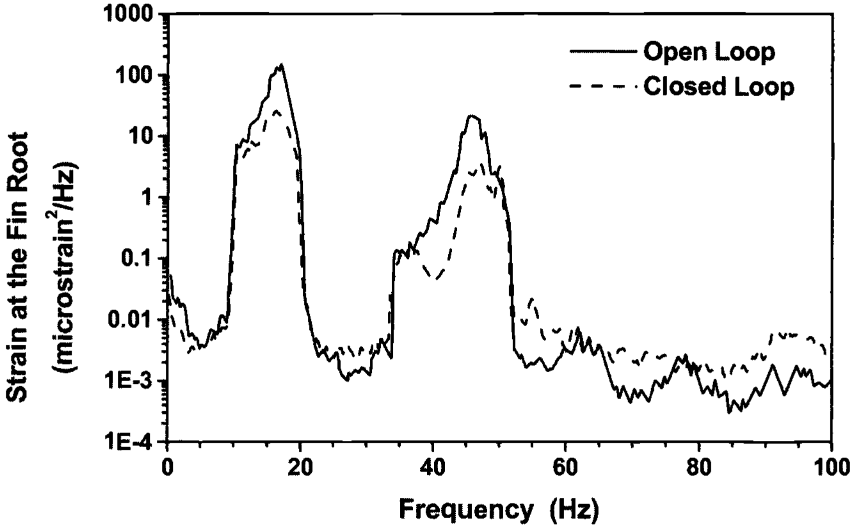


Fig. 15.10 Comparison of open-loop and closed-loop strain response at the root of the vertical fin.

specimens with the SMA fiber located at various distances ahead of the crack.[20] Four different pre-strain levels were studied (0%, 1%, 2%, and 5%) at various crack lengths. Experimental results showed the drastic reduction in stress intensity factor when the SMA wires were activated. The degree of reduction in stress intensity factor depended on the level of pre-strain and the compressive stress domain size between the crack tip and the fiber. Reductions of up to 50% were measured, using photoelastic techniques, when the fiber was 0.2 mm ahead of the crack and with the 5% pre-strained fibers. Figure 15.11 shows the fringe pattern before and after the SMA fiber is activated with the fiber about 2 mm ahead of the crack tip. In this case, a reduction in the number of fringes of about 1–1.5 can be observed, and because the stress intensity factor for crack opening mode I is proportional to the number of fringes,[20] this represents a reduction of about 25–33% in the stress intensity factor. Embedded pre-strained SMA fibers have been used to provide restoration forces to enhance the post-buckling behavior of composite plate structures.[21] Experimental studies showed that quite low volume fractions of SMA fibers significantly reduced the out-of-plane displacements in composite panels. This study concluded that many buckling critical aerospace structures could benefit from such adaptive SMA-based control systems, particularly when mechanically loaded structures are exposed to elevated temperatures—for example,the next generation of supersonic aircraft.

15.3.2.3 Shape Adaptive Structures and Flow Control. A recent Defense Advanced Research Projects Agency (DARPA)-sponsored Smart

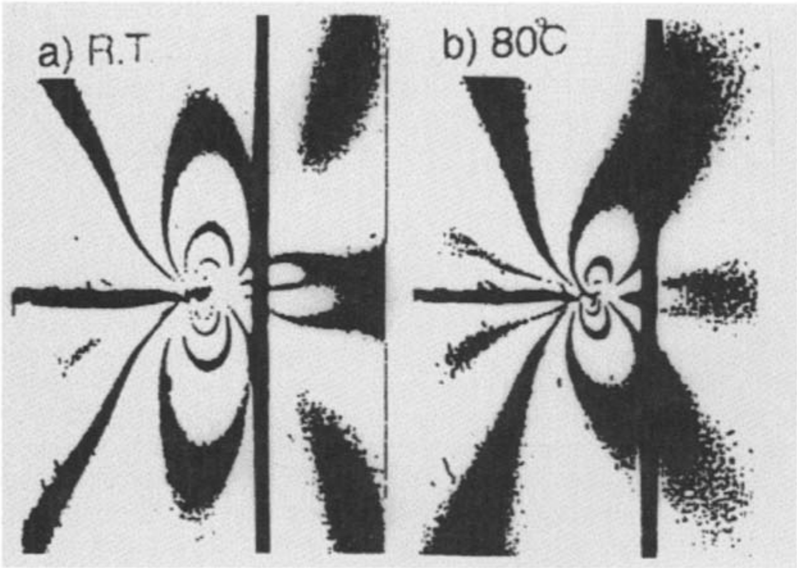


Fig. 15.11 Photoelastic fringe patterns observed at a side notch in a NiTi wire/epoxy resin specimen loaded at 300 N, at room temperature and 80°C (i.e., with the NiTi wires activated).

Wing Program investigated incorporating integrated actuation mechanisms, based on SMA and piezoelectric-based actuators, to replace conventional hinged control surfaces to provide variable optimized aerodynamic shapes for a variety of flight conditions.[4,22] The concept is shown in Figure 15.12.

Initial activities focused on the development of a SMA torque tube in a 1/6 scale F/A-18 wing to achieve twist within the wing and also SMA wire tendons to actuate the trailing edge. Optical fiber pressure and strain sensors were included in this demonstrator. The demonstrators focused on two variations of the smart wing on a scaled unmanned air combat vehicle, the first incorporating SMA-actuated leading edge and trailing edge control surfaces and the second using an ultrasonic piezoelectric motor to drive a control arm to manipulate the trailing edge. A 30% scale model of an unmanned air combat vehicle was fabricated with one wing using conventional control technologies and the other with smart control surfaces.

The unmanned air combat vehicle consisted of aluminum spars, bulkheads, ribs, and longerons, with glass/epoxy skins. The SMA-based hingeless control surface system used SMA tendons, demonstrated the benefits of this technology compared with conventional designs. However, because of the slow response of the SMA (in seconds), only quasi static conditions could be achieved. In maneuver situations where higher responses are required (i.e., typically require about 60° of deflection per second), an actuator with higher bandwidth is

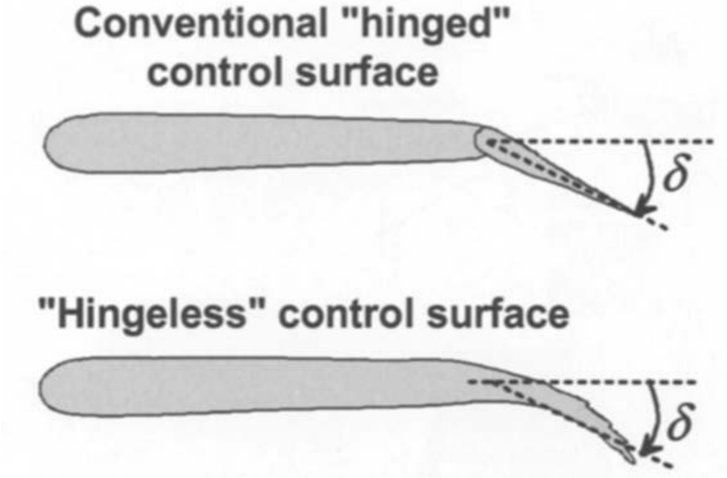


Fig. 15.12 Schematic diagram of conventional "hinged" control surface and "hingeless" control surface (i.e., morphing structure).

required. To this end, various actuators were investigated, including actively cooled SMA, electro-active polymers, piezo-hydraulic pumps, and ultrasonic piezoelectric motors. The final design used an ultrasonic piezoelectric motor to achieve a hingeless control surface with a response of up to 80° deflection a second and deflections up to $\pm 20°$.

Another method of achieving aerodynamic control (without the use of hinged control surfaces) is by manipulating the aerodynamic boundary layer over the wing using MEMS technology.[23] The concept of active conformable surfaces is illustrated in Figure 15.13. The concept is to wrap the flexible smart skin, with distributed micro-sensors, micro-actuators, and micro-electronics (referred to as the M^3 system), around the three dimensional leading edge of a delta wing. Shear-stress sensors detect the location of separation of the leading-edge vortices and then (through the built-in micro-electronic circuitry) the micro-actuators manipulate the thin boundary layer around the leading edge to control the aerodynamic forces and reduce drag on the delta wing. Figure 15.3 shows two types of actuators that are under investigation, viz. flap and bubble actuator.[24] Current activities involve the trials of the MEMS shear stress sensors on the NASA Dryden F-15 and on a delta wing unmanned aerial vehicles.[23]

15.3.3 Multi-functional Structures

Composite materials allow the integration of RF antennas into load-bearing aircraft structures. Recently, a multi-disciplinary program has involved the development and ground testing of a conformal load-bearing antenna structure[25] to improved aircraft operational effectiveness (increased stealth, reduce weight,

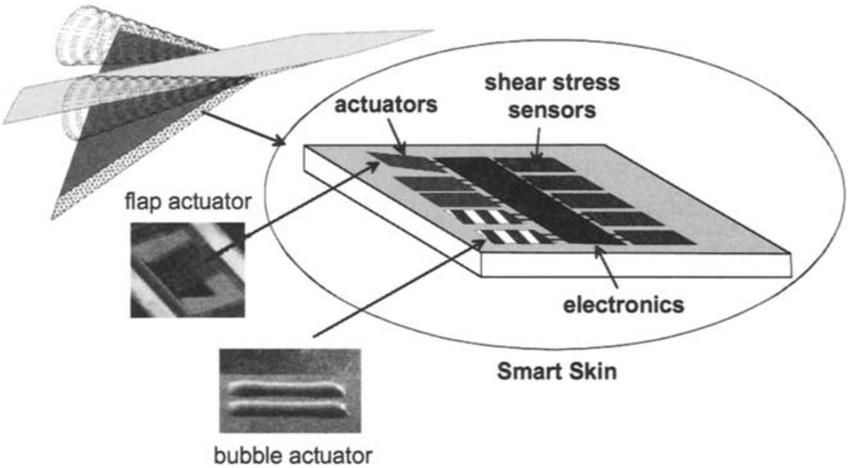


Fig. 15.13 Schematic diagram showing planned use of MEMS (combined sensors and actuators) to control leading edge vortices. Taken from Ref. 24.

drag, radar signature, communication range, and electronic warfare capability). One antenna can now undertake multifunctional roles, whereas before several antennas would have been required. Various sites around the aircraft may be used (e.g., wings, tails, empennage). Testing has shown significant (orders of magnitude) improvements in operational performance of antennas over conventional antennas' configurations (e.g., improved range from 40 to 200 miles). Structural issues like buffets mean that antennas must be robust. Also, high-frequency antennas need to be compensated for spatial deformation, therefore structural vibration effects can be significant. Another key issue for such structures is the durability and repair. Testing to date has shown that structures with embedded antennas can withstand static strains up to 4700 $\mu\varepsilon$.

15.4 Key Technology Needs

To be practicable, smart applications must be rugged and unobtrusive; they must not increase the burden on an aircraft's monitoring system nor on the pilot and ground staff. They must be able to withstand severe operating conditions for prolonged periods and be able to operate under temperatures ranging from $-50°C$ to over 100°C. Some surface-mounted systems will be exposed on the outside of the aircraft and will need to withstand aerodynamic stresses, sunlight, moisture, other aircraft fluids and erosion.

The key technologies for the development of many of the smart applications lie in the elements: sensors, actuators, and control and power systems.

Current sensors and actuators are much too large and generally too fragile, particularly in the case of piezoelectric actuators, which are prone to cracking and burn-out when used to produce large forces. The current generation of piezoelectric systems lack the force required to make shape changes or to develop sufficient loads in many practical situations.[26] Magnetostrictive transducers allow higher forces than the piezoelectric materials and should prove to be more robust; however, they are heavy and have significantly high power requirements. Clearly, further technological breakthroughs are required for these elements.

There is also the necessity for rugged miniaturized microprocessors (and associated instrumentation) that can be embedded in the component or bonded to its surface (or nearby) and, where data transfer are required, for low-power, long-life, robust, wireless systems. Small power units that can be mounted in, on, or close to the smart structure are a major requirement for applications involving actuators—mini fuel cells are a possibility.

For low-power requirements such as structural health monitoring, it is highly desirable for the system to be self-powering, thus avoiding the complications and the increasing problems associated with the use of batteries. One promising approach[7] is to use piezoelectric materials to harvest power from energy sources (e.g., dynamic straining) in the parent structure, as is being developed for the smart patch described earlier. To avoid the need for battery power in the smart patch, a self-powered (piezoelectric film-based) patch health-monitoring system was developed.[7] This system operates by using the electrical power generated by the straining of the structure. The piezoelectric transducers convert the dynamic strain to electrical energy to power the electronics, which interrogate the piezoelectric film sensors, and process and store the patch health data on a non-volatile memory.

Large-scale use of sensors (for example, extensive use of optical fibers with Bragg gratings) for health monitoring brings with it problems of data presentation.[26] The need will be to present the information to ground staff as pictorial maps, ideally indicating changes from the original state.

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