DESIGN AND DEVELOPMENT OF OPTIC FIBER SMART STRUCTURES IN AEROSPACE VEHICLES

Zaffar. M. Khan
Advanced Engineering Research Organization, Wah Cantt, PAKISTAN
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Abstract
As aerospace structures have become more complex and demanding to meet the stringent aerodynamic and propulsive requirements, there is an ever-increasing need to intelligence into them so that they can sense and react to the environments just like birds. To perform these functions successfully a smart system is required that senses the environments, conveys the message to central processing unit and reacts almost instantaneously. Such structures not only monitor their own health but also for warn about onset of failures, fatigue and impending disasters.

This paper will review the optic fiber smart structures with emphasis on their application in aerospace structures. It will discuss advantages, working principle, performance parameters, classification, system architecture and future trends in fiber optic smart structures.

1. Introduction
In the brief history of the aerospace industry, a progressive evolution of new materials and design concepts has occurred from stone to space age. In the quest to fly faster and farther, stronger, lighter and intelligent materials have been developed. These have ranged from wood, aluminum, composites to smart structures as shown in Fig [1] [1];

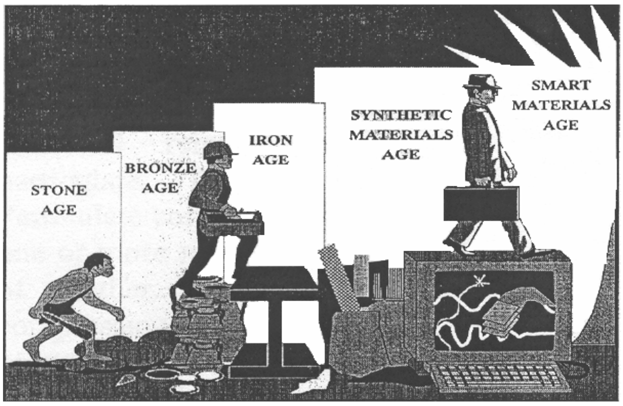

Fig [1]: Evolution of materials during different ages [1].

In early times 5000 B.C. chopped straw was used to toughen mud bricks and Maya potteries to prevent them from cracking. Around 1500 B.C. the consumption of bronze determined the world powers. Much later around 1850 A.D., it was steel followed by the light alloys. The period between 1940 and 1950 A.D. saw maximum consumption of metals and alloys with respect to their relative importance to other materials in terms of their usage at that time. From this point on, the application of metals and alloys in the aerospace industry in particular has been, as a percentage of total material utilized, declining and production of composites has been expanding. Series of experiments at the Royal Aircraft Establishment, Farnborough England by Watt, Philips and Johnson led to the manufacture of high strength, high stiffness carbon fibers and their composites in early 1964. Since then production of advanced composites has been increasing at unprecedental rate of 40 percent per year and is now a multibillion market.

It was demonstrated in 1970s that the attenuation of light in fused silica fiber was low enough to allow long transmission links through total internal reflection. Initial penetration of fiber optic technology into market has been slow due to high cost of components in 1980s. The cost of fiber optic components lowered by 1990s due to their widespread applications in tele communication industry, compact disk players and laser printers etc. In the same time frame, new components such as fiber optic couplers, beam splitters, multiplexing elements fiber coupler, pig tailed and beam-conditioning devices became commercially available.

By year 2000, NASA successfully coupled advancement in fiber optic technology with composite materials and electronics, which led to development of Smart Skin/ Structures. A 'Smart Structure' is able to detect the variations of the external environment and adapt itself, through a network of actuators and sensors embedded inside composites. A Structure may be defined 'Smart' if it presents integrated devices, able to make it interact with the external environment, and is able to learn from experience. The development of smart structures has opened new frontiers in the field of aerospace industry.

2. Structure of Composite Materials

Composite materials are defined as the combination of two or more manually insoluble macro-constituents that differ in physical form and chemical composition. Composite materials are superior to ordinary engineering materials for a variety of reasons. Notably amongst these are their high strength to weight ratio and high modulus to weight ratio. The ability to tailor their strength properties to fit a particular structural situation and the flexibility of design in terms of reduced part count makes them even more attractive. Composite materials consist of three main elements, the matrix (resin), the structural reinforcement and the interphase. The matrix binds the reinforcement together to allow distribution of load protects the notch sensitive reinforcement from self-abrasion and externally induced scratches. The resin also protects the reinforcement from environmental moisture, chemical corrosion and oxidation. The shear, compression and transverse tensile properties and failure mechanism of a composite are resin dominated.

There are four general categories of structural reinforcement in a matrix, particulate, flake, whisker and fiber. Particulate composites consist of particles of one or more material suspended in a matrix of another. Such composites have good compression strength but have poor tensile properties. Flake reinforcement offers a number of advantages in composites due to their two dimensional geometry. Long and continuous fibers are more desirable in aircraft composite science they impart better structural properties, creep resistance and crack stopping properties. The fiber reinforcement primarily determines the tensile/ flexural strength and stiffness of a composite system. The type, stacking sequence and orientation of the fibers, determines the longitudinal mechanical properties and failure mechanism of a specific lay-up. The four types of commercially available fibers are Glass, Boron, Kevlar and Carbon fibers. The glass fiber reinforced plastics (GFC) are easy and inexpensive to manufacture. The high stiffness property of boron fibers (420 GPa) made possible their early use in primary aircraft structures but they were more expensive due to difficult manufacturing process. Kevlar fibers combine their extremely high toughness with good impact resistance but have poor compression strength. Carbon fibers are the most widely used in aerospace applications because of their best balance of properties in terms of maximum specific stiffness and strength [2].

3. Fiber Optic Sensor Technology

Important aspects of optical fiber design for efficient light coupling are the core diameter, the cladding diameter, the core-to-cladding eccentricity, the overall fiber ellipticity, and the numerical aperture. The core and cladding diameters define the quality, sensitivity and reliability of light transmitted from one fiber to another. The fiber eccentricity provides a measure of how well the core is centered to the actual central axis of the fiber. The overall ellipticity measures the roundness of the outside diameter of the fiber. The numerical aperture is a measure of the half angle of the in coming or out going light cone. The tolerance of each of these parameters combine to define how well two fibers can match up and couple light from one optic fiber to the other.

An optical fiber primarily consists of three concentric cylindrical elements such as core, cladding and coating. Core is the central light transmitting region of the fiber and is made of silica. The cladding can be made of the same material as the core but has lower refractive index. This causes internal reflection of signal within the core. The coating protects cladding/ core against physical damage.

There are discrete numbers of paths called modes, which travel through the fiber at different angel to fiber axis. The wavelength of light and geometry of optic fiber determine the number of modes in given optical fiber. They can be classified into single mode, multimode graded-index and multi mode step-index fibers. Fundamental mode is propagated in single mode fibers. They have typically core diameter of 5-10 micron. Multimode fibers have core diameters of the order of 100-150 microns. This permits transmission of higher order modes having equal travel time due to varying refractive index. The uniform refractive index of step-index fibers having core diameter of 100-150 micron allow transmission of light in different modes and speeds.

Light emitting diodes (LEDs) and laser diodes (LDs) are commonly used in such sensors. LED has low coherence length, broad spectral width, low sensitivity to back reflection and high reliability. They are very useful in intensity type sensors. Laser diodes exhibit high coherence, narrow bandwidth and high optical output. They are more suitable for interferometer sensors such as Mach Zehnder and Febry Perot type sensors. Coupling of sensor with fiber optic has led to pigtailed fibers, which has minimal losses. The detectors could be classified into semi conductor photo diode or avalanche photo diode. Silicon photo diodes are good for visible and near IR wavelength. Avalanche photo diode can sense low light level but need large supply unit and are noisy.

Fiber optic sensors are based on measurement of optical parameters and are well suited for digital control, smart response in linear/ non-linear region with minimal long-term drift losses. The main advantages of optical sensors are in terms of speed, safety, security, sensitivity, shielding, compactness, bandwidth and versatility. Fiber optic sensors offer an all-passive dielectric approach that is often crucial to electrical isolation, elimination of conductive paths in high-voltage environments and is compatible with placement in host materials. The lightweight and small size of these devices is critical in such areas as in aerospace engineering. Coupled to the issue of size and weight is their immunity to electromagnetic interference. Conventional electrical sensors often require heavy shielding which significantly increasing cost, size and weight. Environmental ruggedness provides key opportunities for fiber optic sensors, including high-temperature operation and all-solid-state configurations capable of withstanding extreme vibration and shock levels. Complementing these attributes are high sensitivity and bandwidth of fiber optic sensors. When multiplexed into arrays of sensors, the large bandwidths of optical fibers offer distinct advantages in their ability to transport large data files [3].

4. Sensor Classification

The sensitivity of optic fiber sensor to external stimuli is deliberately enhanced for maximum change in optical parameter. The fiber not only acts as modulator but also as transducer. The environmental effects such as shock wave lead to changes in geometry i.e. size, shape and optical properties i.e. refractive index, mode conversion parameters. Since amplitude, frequency, phase or polarization characterizes light, the change of one/ more of above parameters can be quantified and calibrated to give desired output as indicated in Fig [2].

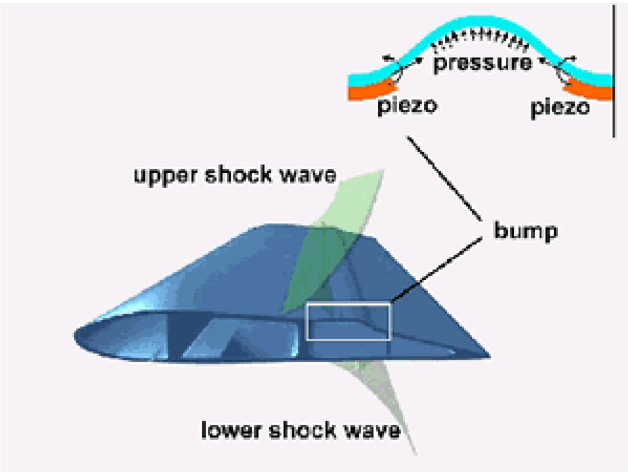

Fig [2] Microbend sensor on aircraft wing to determine shock wave.

A sensor can be classified weather it is intensity, phase, frequency or polarization sensor. The intensity sensors are basically incoherent in nature and are simple in construction. The phase or frequency sensor requires interferometric techniques, which are coherent in nature and complex in design. Fiber optic sensors can also be classified on the basis of their application i.e., physical, chemical and biomedical sensors. Fiber optic sensors are also categorized as being either extrinsic or intrinsic. Extrinsic fiber optic sensors have an optical fiber for carrying a light beam to and from a unit that modulates the light beam due to environmental response. Intrinsic sensors measure the modulation of light by an environmental effect within the fiber [3].

4.1. Intensity Sensors

Bending a fiber leads to increase in signal losses. By placing this fiber in an area that has environmentally induced vibrations, the light propagating through the optical fiber is amplitude modulated. This property can be commercially exploited by placing the fiber in accelerometer to measure mechanical vibrations.

A conventional microbend sensor consists of a fiber that is pressed and bent between two corrugated plates. The deeper the bends, the larger the coupling of radiation from guided to radiated modes, and the lower the intensity of optical signal through fiber as shown in Fig [3] [3];

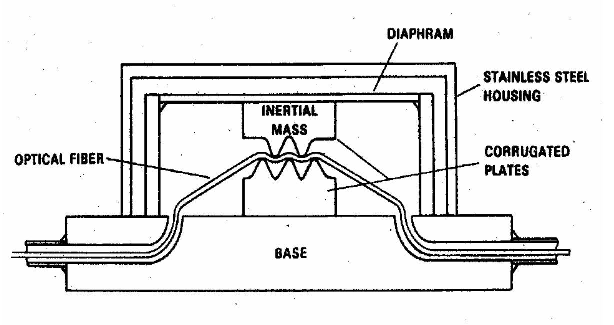

Fig [3] Optic fiber sensor for vibration measurement.

The response of intensity sensor, expressed as differential voltage per unit change in perturbation is given by,

$$S = (qI_0Rm)$$

Where $m = [\Delta I / (I_0 P)]$

q=Detector's Responsivity

R = Load resistance

I_0 = Optical power reaching detector when there is no modulation

m = Normalized modulation index

ΔI = Change in optical power as a result of modulation by perturbation P

The intensity sensors have low cost but they have variable losses in optical components, which leads to experimental error [4].

4.2. Spectral Sensors

The experimental errors may be reduced by spectral techniques such as blackbody radiations, absorption/ fluorescence and dispersive elements. Thermal radiation is transmitted in an optical fiber with blackbody cavity.

As the body heats up, it emits infrared radiations, which are coupled through optic fiber to detector, which has narrow bandwidth. The ratio of output of both detectors determines the spectral envelope in relation to applied temperature range. In case of fluorescent sensors, the light pulses stimulate the fluorescing region, which determines the environmental effect. A grating can also be written into the fiber by imaging the laser beam in ultraviolet region to form an interference pattern, which changes its spectral response when strained.

4.3. Sagnic Sensor

Sagnic fiber optic interferometers are used to sense rotation, time varying acoustic, quasi-static strain and distributed strain. All optical gyros rely on Sagnic effect to measure rotation. Sagnic effect implies that the light is split into two counter rotating light signals in a ring. The interference leads to rotationally induced phase shift as given below;

Clockwise path = $2\pi R + wRL/c$

Counter clockwise path = $2\pi R - wRL/c$

Net path difference = $2wRL/c$

Rotationally induced phase shift = $2wRL/\lambda c$

Where

R = Radius of ring

w = Rotational speed

L = Length of path

λ = Wavelength of optical signal

c = Speed of light

The rotational induced phase shift is balanced by introduction of frequency induced phase shift, which renders the number of fringes to be equal to $2Rw/\lambda n$. All optical rotation sensors for guidance and control applications rely on same effect to measure rotation. A single mode fiber spatial filter and polarizer are placed between the input/ output fiber beam splitter and central fiber optic beam splitter to ensure that both counter propagating beams traverse the same path in the fiber optic coil. The two counter propagating beams mix and fall into detector, which is used to monitor the intensity changes caused by rotationally induced phase changes between the beams. The sensitivity of sensor can be enhanced through close loop feed back as shown in Fig [4].

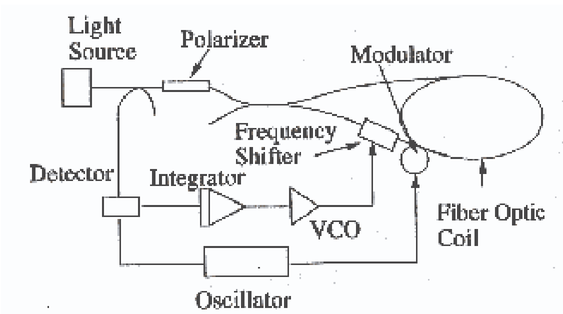

Fig [4] Close loop fiber optic gyro based on Sagnic effect

The detector detects, integrates and passes signal to voltage-controlled oscillator (VCO). The VCO is connected to frequency induced phase shifter, which locks on to the balances the rotationally induced phase shift. This allows the gyro to operate around middle of the sensitivity quadrature.

4.4. Mach-Zehnder Sensor

The Mach-Zehnder Interferometric sensors exploit the interference of two light beams. With this class of sensors two coherent beams are created from a single light beam by employing a beam splitting device. The beams are then coupled into two single mode fibers, which are designated the ‘reference arm’ and the ‘sensing arm’. The sensing arm is subjected to mechanical deformation while the reference arm is generally protected from the strain field as shown in Fig [5].

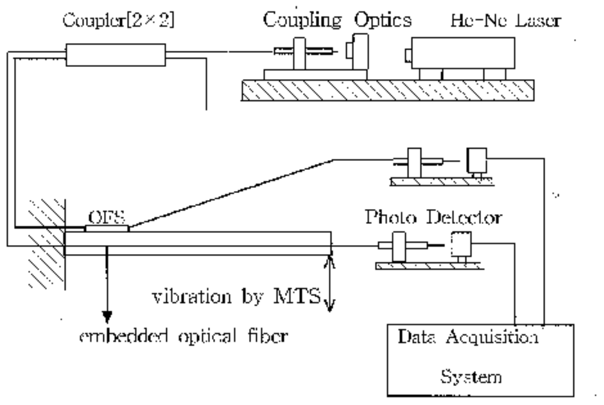

Fig [5] Layout of Mach Zehnder Sensor

Thus the optical wave-guide, subjected to mechanical deformation experiences a change in the optical path length of the light beam. This difference in the optical path length of the two beams results in a relative phase shift between them. This is detected by observing the shift in the fringe pattern upon recombining the two beams. The output from this interferometric sensor is an assemblage of fringes, which can be transformed into a signal by a slitted photodiode arrangement. The fringe pattern is detected by the slitted photodiode and is manifested as a series of impulse function-like electrical signals in response to the excitation provided by each fringe as it moves across the face of the slit arrangement. Then sensitivity and dynamic range of Mach-Zehnder sensor is enhanced by introduction of a modulator as part of active feedback.

5. Integration of a Fiber Optic Sensor with Composite Materials

One of the most common manufacturing defects in production of thick structural composites is layer waviness. This imperfection is characterized by out of plane undulation of layers or group of layers within multidirectional laminate. The layer waviness defect, characterized by wavelength (λ) and amplitude (δ), leads to significant reduction of its compression strength. The poor compression strength of carbon-epoxy composite materials seriously limits its design performance. It is extremely difficult if not impossible to detect above defect by conventional ultrasonic, X-rays and other techniques. Optic fiber microbend technique is employed to detect layer waviness defect in composites.

Single, double and triple wave formation having varying amplitudes were produced in IM7/8551-7 carbon-epoxy prepreg having cross-ply orientation in a single step fabrication procedure. The waviness in cross ply laminates was accomplished by removing two thin strips of prepreg material from adjacent 90^0 plies, rolling them into cylinders and placing them above and below the 0^0 layer. The multiple wave formations were produced by repeating the given wave pattern in the laminate. The entire assembly was bagged, vacuum-sealed and placed in auto clave. Application of 550 kPa (80 psi) pressure, 180^0 C (350^0 F) temperature and vacuum for duration of 2 hours cured the test laminate having embedded optic fiber. After debagging one end of the embedded optic fiber was connected to light emitting diode and the other end of optic fiber was connected to the optical power meter for monitoring the intensity of laser light. The optical signal was launched and recorded by power meter through the optic fiber that was microbent in the carbon-epoxy laminate over strips of prepreg having multiple wave formation and varying amplitude as shown in Fig [6].

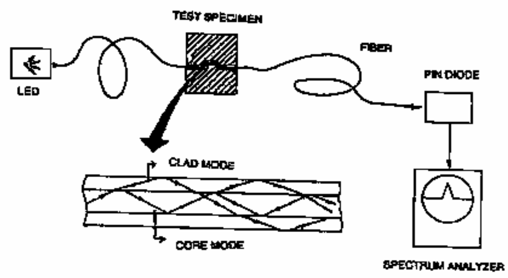

Fig [6]: Schematic showing microbend optic fiber sensor embedded in composite materials

After the test, the specimen was sliced across the wave using fine diamond coated disk saw. The amplitude (δ) and half wavelength (λ) of the sliced wave in the cut carbon-epoxy section were examined using optical microscope.

Results of the light transmitted through optic fibers having single, double and triple wave formation in the laminate indicated that as the severity and wave formation of wave increases the intensity of light decreases. It was found that bend with radius of less than 2 cm cause significant losses, which can maximize microbending sensitivity. The greater the wave intensity and formation of microbend, the more were losses in the optical fiber signal as indicated in Fig [7].

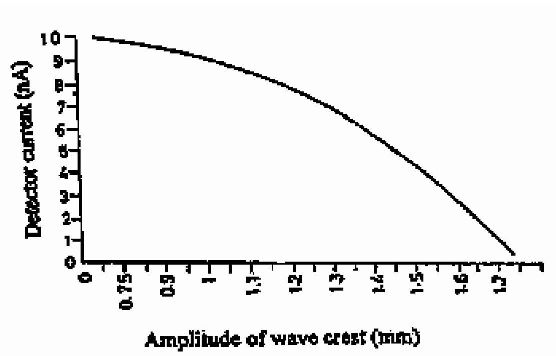

Fig [7]: The variation in detector current with respect to amplitude of optic fiber.

The fiber optic microbend assessments methodology offers good possibility of using above technique for detecting the layer waviness defect in smart structure used in aircraft wing and fuselage as shown in Fig [8] [5].

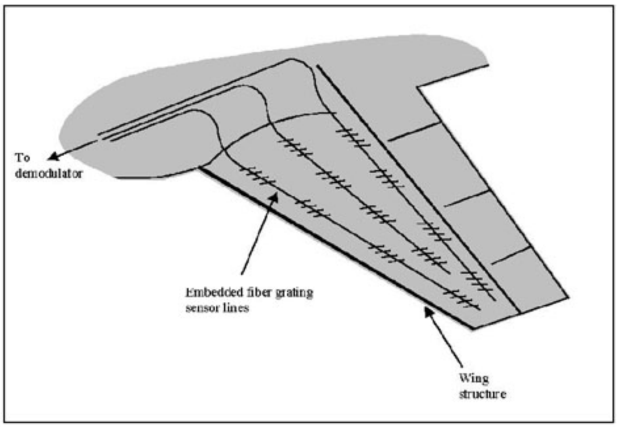

Fig [8]: Fiber optic sensors array embedded in aircraft wing to detect layer waviness.

6. Aerospace Applications

Initial application areas of fiber optic smart structures include the manufacturing and processing of parts, introduction of simple health monitoring and structural control systems such as icing indicators, vibration and localized strain monitoring systems. They also include automatic maintenance systems that perform preflight and post flight assessments of the aircraft. These systems are used to improve and simplify repair procedures and provide in-flight structural integrity warning systems. Finally fiber optic smart structures evolved into an integral part of smart aircraft, which exhibit self-healing characteristics, real time flight corrections, and repair in flight and automatic flight control systems. The health-monitoring philosophy is directed towards increasing aircraft performance through the integration of sensors, microprocessors, data transmission links and flight control systems to provide a viable dynamic interface with the external flight environment as shown in Fig [9] [6].

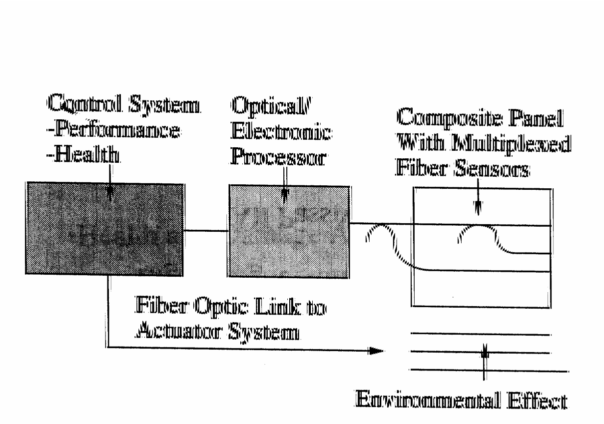

Fig [9]: Schematic of fiber optic sensor system.

Millions of multiplexed sensors are required on large space structures. Because of the huge processing requirements, the system architecture consists of two classes of fiber sensors. The first set of distributed fiber sensors are used to localize an event such as impact damage and the second set of fiber sensors are used to support detailed assessment. The fiber sensors are multiplexed into "strings" of fiber optic sensors through an optical switch. The fiber demodulator is used to extract the data from the sensors in the string being accessed. The data is formatted and transmitted to a signal processor, which in turn transfers the data to be vehicle health management bus/ damage assessment system as indicated in Fig [10].

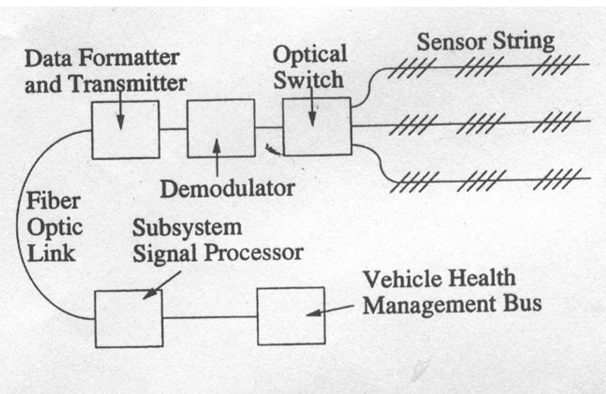

Fig [10] Modular architecture of aerospace vehicle smart health management system,

NASA, Department of Defense, and other organizations are deeply involved in research work regarding development of smart technologies, which will revolutionize aerospace vehicle design philosophy.

Major demonstration programs have addressed structural health monitoring, vibration suppression, shape control and multifunctional structural concepts for spacecraft and launch vehicles, aircraft and rotorcraft. The demonstrations have focused on showing potential system-level performance improvements using smart technologies in realistic aerospace systems.

Some recent work related to smart vehicle technology has focused on the development of composite systems having active distributed actuation systems, fiber optic and compact integrated sensor systems. Current trends aim at the atomic and molecular level to synthesize new materials that are functionally smart such as molecularly imprinted polymers and other materials that contain inherent receptors for information. Other efforts are integrating diverse sensors on a single substrate, and working on practical techniques to fabricate them.

Self-healing material concepts have received increasing attention in recent years. For example, self-healing plastics use material that has the ability to heal cracks when fracture occurs. Shape memory alloys in composites can stop propagating cracks by imposing compressive forces, resulting from stress-induced phase transformation. 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 more functions as indicated in figure [11].

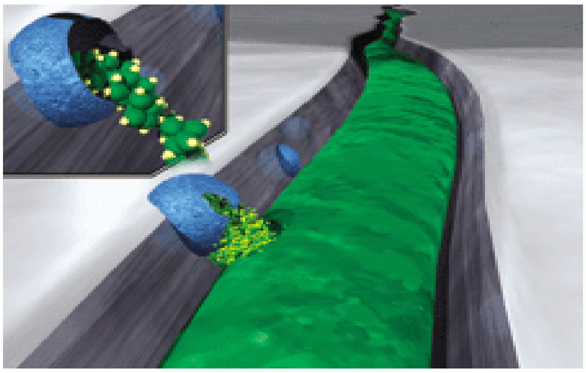

Fig. [11] Microcapsule releasing a healing agent in smart material [6].

Controlling fundamental mechanisms in fluids has long been the focus of intense effort. Recent applications of airflow sensing and intelligent control to air vehicles include improving performance by increasing lift or reducing drag generated by a surface and maneuvering through the use of fluidic devices. Current activities aim at understanding the physics associated with the shock wave formation in high-speed flight and developing designer fluid mechanics tools for all types of flow control—flow separation control, vortex control, laminar flow control, turbulent drag reduction, anti-noise, mixing enhancements, combustion control, circulation control, and favorable wave interference [6]. A suite of high-payoff sonic boom mitigation technologies is being explored for reducing the sonic boom overpressure to an acceptable level to people on the ground (less than 0.3 pounds per square foot). Techniques include airframe shaping, heat addition, particulate injection, leading-edge plasma generation, temporal and spatial variation of lift distribution, and adaptive flow control.

Indirect reduction of sonic boom amplitudes can also be achieved by decreasing vehicle gross weight, or increasing vehicle lift-to-drag ratio by maintaining supersonic laminar flow. In addition, the use of intelligent propulsion control systems is being explored for efficient, reliable operation of the complex supersonic inlet/engine/nozzle system. The smart wing is defined as a wing whose shape parameters such as the camber, wing twist, and thickness can be varied to optimize the wing shape for various flight conditions. Complexity and weight penalty of the actuation mechanisms have excluded its practical implementation. Recent development in MEMS technologies could potentially overcome the shortcomings of previous designs.

The fiber optic sensors also support the sub systems of launch vehicles such as cryogenic tanks, rocket nozzles, fairings, solid rocket booster casings, and inter stages. Fiber sensors are filament wound directly with the pre-impregnated material, which monitor the consolidation process and subsequently nondestructive evaluation of tanks. Sapphire sensors are used to detect rocket nozzles exhaust temperatures for areas of excessive burning. They also augment separation systems between stages and are used for vibration control and acoustic damping of the payload and other key components. Space-based platforms must be extremely light in weight and yet rigid. Fiber optic smart structures for this type of platform manifest themselves in the form of health monitoring systems that assesses changes in the structural integrity of the platform due to such events as docking, impacts or orbited aging. Fiber optic smart structures are used in combination with actuator systems for vibration control in order to isolate critical areas requiring a zero-g environment and to damp out oscillations that degrade pointing and tracking accuracy. The potential exists for building fiber optic damage assessment systems directly into the walls of the structure to monitor the location and severity of an impact and also exhibit self-healing characteristics. Other features include distributed acoustic sensors to locate gas/ fuel leaks and radiation, electromagnetic, pressure and temperature sensors [7]

7. Future Prospects and Potentials

As the structural complexity increases, the coupling between design, analysis and manufacturing processes becomes more and more inextricably intertwined. Therefore the integration of actuators, sensors, processors, and structures for smart nano/ microstructure applications mandates the evolution of sophisticated manufacturing process-driven design, analysis, and synthesis methodologies such as MEMS. It is anticipated that the quantum leaps in manufacturing technologies packaging and environmental considerations will lead to successful evolution of this class of materials.

The application of biological concepts and principles has led to emergence of biomimetics, neuromimetics and neuromorphic engineering. The cross coupling of bio-, nano-, and info technologies will mimic the bird's flying as indicated in artist's sketch in Fig [12].

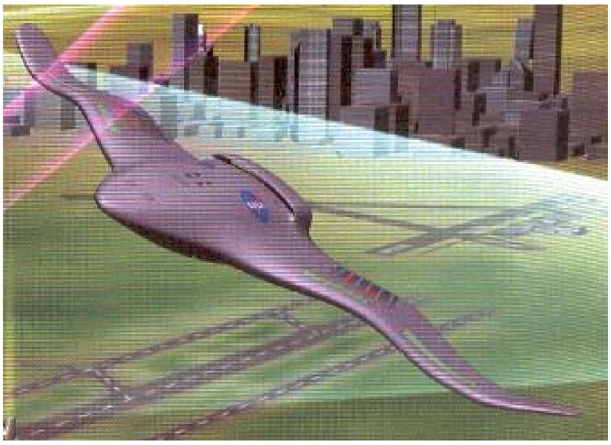

Fig. [12] Artist's vision of smart aerospace structure [6].

Molecularly designed materials have the promise to be much lighter than aluminum yet stronger than steel. Their maximum strain could be 25% higher than traditional structural materials. Wing's surface made from these materials will be covered with tiny embedded sensors and actuators. They could morph and continuously deform for different phases of aircraft flight.

The advancements in design and manufacturing techniques at the atomic level will diminish the boundaries between sensors and actuators. These attributes permit a substance to be synthesized with self-adaptive abilities at the nano/ micro level.

8. Acknowledgement

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