

Future Roles of Structural Sensing for Aerospace Applications

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ABSTRACT

The Department of Defence (DoD) is continuously evaluating different methodologies to reduce cost, increase availability, and maintain safety of current and future air vehicle systems. Recently, emphasis has been placed on the development of Integrated Systems Health Management (ISHM) techniques. The ISHM process provides the appropriate architecture to determine system level health based on combined assessments of the various subsystem conditions and, as necessary, interacts with flight control systems to ensure mission success. Since the vehicle structure is one of the most critical subsystem, structural health monitoring (SHM) techniques are being developed. These SHM techniques offer unique benefits for both fielded and emerging air vehicle systems. For fielded vehicles, a major sustainment cost driver in the air vehicle fleet today is unscheduled maintenance. By utilizing SHM techniques, DoD intends to migrate to condition-based maintenance instead of the current schedule-based approach. Condition-based maintenance will enable DoD to meet its objective of improving maintenance agility and responsiveness for quicker turnaround times, increasing operational availability, and reducing life cycle total ownership cost. Emerging air vehicle systems will likely utilize advanced materials and advanced structural concepts. Extensive use of composite materials is expected and, to further complicate matters, the composite structures also may include embedded electronics or sensors. Advanced structural concepts include techniques such as morphing structures, which will be integrated with other vehicle systems such as the flight controls. As a result, assessing the current state of these structures will be critical. Applications for emerging air vehicle structures offer the potential to consider SHM in the design process, rather than having to retrofit a SHM system to an existing structure. The current paper discusses the future role of structural sensing for air vehicle applications.

1.0 INTRODUCTION

The Air Force Research Laboratory (AFRL) is continuously developing advanced aerospace technologies to enable new capabilities for future weapon systems. Some of these advanced capabilities include Persistent Intelligent Surveillance and Recognizance (ISR), Persistent Strike, and Multi-Role Mobility. New weapon

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systems will be required to operate longer, fly faster, and provide more intelligent while performing missions. Current weapon systems are designed with generous margins to account for system uncertainties to prevent premature degradation and/or failures. In most cases, current aircraft are capable of operating years beyond its initial design life. Hence, the average age of aircraft in the Air Force fleet is 30 years old (e.g. KC-135). New weapon systems will push the design margins closer to its performance limits in order to achieve its desired goals. The only way to accomplish this is to minimize the uncertainties in the system's capability by accurately assessing its current health status.

The AFRL has recently instituted a thrust area in Integrated Systems Health Management (ISHM) to mature system's diagnostics and prognostics techniques for potential implementation on current and future air vehicles. AFRL defines ISHM as "any system that collects, processes, and manages health data to assess the current condition of the vehicle and determine its ability to perform a given mission". AFRL's vision for ISHM is to create fully integrated health management systems enabling affordable combat support, maximizing mission capability, and abating secondary damage. To achieve AFRL's vision for ISHM, the subsystems' conditions must precisely be assessed before determining the system level health and capability. Since the vehicle structure is one of the most critical components, advanced structural sensing techniques are being developed for structural usage monitoring, structural health monitoring, and structural shape determination.

2.0 STRUCTURAL USAGE MONITORING

Structural usage monitoring is a methodology of determining actual loading conditions that a weapon system experience during its life. Since new weapon systems are expected to operated at the limits of its design, it is imperative that accurate structural loading and environmental exposure history information is acquired in order to determine current structural condition and remaining useful life. Structural usage monitoring is not a new concept; In fact, it is currently being used on aircraft in the Air Force fleet today (e.g. C-17). The problem with current aircraft load monitoring systems is that loading data acquired from the vehicle is mainly focused on primary structure locations and is too sparse to make a determination on the actual usage loading on secondary structural components. In fact, secondary structural inspections/maintenance is one of the major contributors to the increase of operational and support cost for the Air Force fleet. With these new weapon systems being design more efficiently by virtually eliminating fail safe structure, most of the aircraft will essentially become critical structure. Hence, knowing the actual structural loading conditions of the entire weapon system's structure will become essential to fully understand the integrity of the structure. Structural usage monitoring is determined by using a combination of on-board sensors and structural models as depicted in Figure 1.

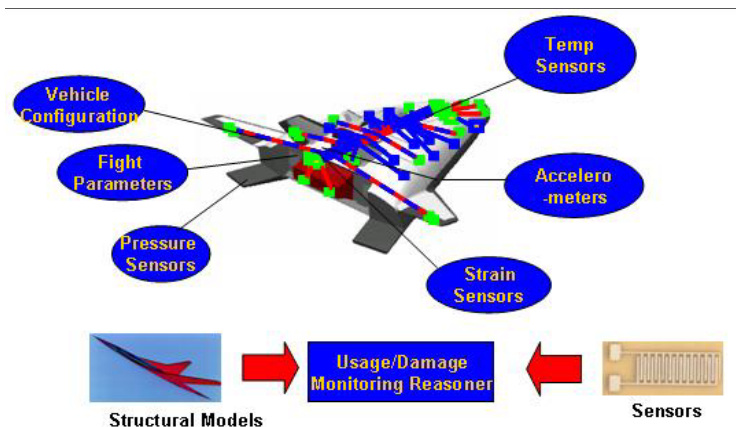


Figure 1: Structural Usage Monitoring

Virtual structural sensing techniques are utilized to obtain measurements at locations where physical sensors are not present. This methodology enables the reduction of on-board sensors required to accurately determine loading conditions.

3.0 STRUCTURAL HEALTH MONITORING

With recent advances in sensor technology, more and more data can be collected from distributed sensors built into structures that monitor conditions beyond loads such as damage states or health. This leads to the development of SHM technology by expanding the load monitoring capability to include damage diagnostics, damage prognostics, and health management for structures. Advanced data processing techniques, diagnostic algorithms, prognostic methods and maintenance/operation processes will be required to be integrated in conjunction with a network of distributed sensors and hardware to form a complete SHM system [1-6]. A schematic description of the SHM system is illustrated in the Figure 2. Load monitoring could be considered as a subset of the SHM system. Accordingly, the SHM system would include three major components: sensor network, software, and hardware. Besides the commonly used sensors such as strain gauges in load monitoring, many advanced sensors such as fiber optics, Micro Electro Mechanical Systems (MEMS) sensors, piezoelectric sensors, and Acoustic Emission (AE) sensors have been considered [1-6]. In addition, actuators/transducers such as piezoelectric (PZT) actuators may also be considered in the system as a part of the sensor/actuator network [1-6].

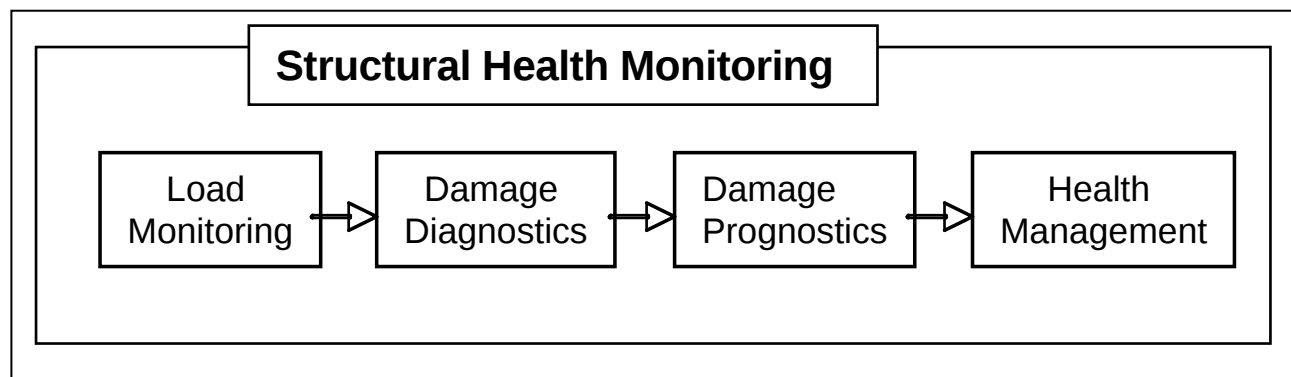


Figure 2: An Overview of Structural Health Monitoring Technology

A SHM system with sensors that only used for collecting data is typically referred to as a passive system, while a system with built-in actuators, which is designed to produce diagnostic signals is referred to as an active system [1-6]. The passive system is most effective in monitoring environmental changes to the structures such as external loads, temperature, etc. The active system is more effective on detecting cracks, damage and anomalies. With an appropriate diagnostic software and hardware, a SHM system could be designed for a particular application with the required level of detection capability. In general, SHM detection capability is typically classified into four levels [1-16]:

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Level I: event detection,
Level II: location detection,
Level III: quantification,
Level IV: residual effect.

For each application, the system shall be designed to target a particular level of detection. For instance, if damage due to impact is the primary concern, then a Level-I SHM system shall only need to detect if damage is present, not the damage location or the severity of the damage. If damage location is also required, then the system must be designed to a Level-II capability. Level-III is to assess the extent of damage, and the Level-IV is to determine the effect of such damage on the structure in terms of remaining life or residual strength. Similarly, this classification can be applied to monitoring impact loads or fatigue cracks.

Figure 3 illustrates a potential application of a SHM system for detection of impact damage in a space transportation vehicle. For example, if a foreign object impacts the surface of the vehicle which is equipped with a Level-IV SHM system. Upon impact, data generated from the built-in sensors will be processed and used to identify the impact event and location. Local built-in actuators may be used to diagnose the damage and to quantify the damage state. Once the damage state is determined from the Level-IV system, the results shall be integrated with a prognostic analysis such as finite element modelling to predict the residual strength and remaining life of the structure which will aid in determining the proper decision on the subsequent mission [8-12].

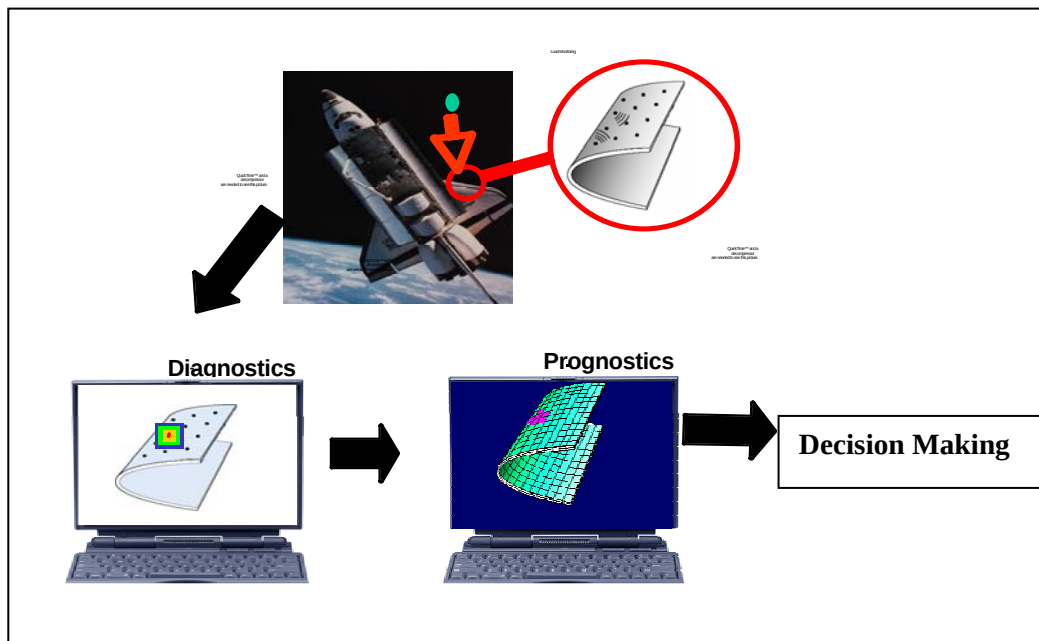


Figure 3: An illustration of a Level-IV SHM system for impact damage detection.

4.0 STRUCTURAL SHAPE MONITORING

Advanced structural concepts are being considered for future air vehicle applications to improve performance. For example, two advanced concepts under investigation are morphing structures and structurally embedded conformal array antennas. A brief discussion of these techniques, along with the potential benefits derived from incorporating structural sensing technology, is given below.

Morphing refers to the ability to change a structure's geometry (e.g. reshape a wing profile) to enable efficient flight over a range of conditions without sacrificing performance. Morphing offers the potential to expand an aircraft's flight envelope and may offer significant vehicle mission-level benefits. Figure 4 shows an example of a morphing structure. Such structures rely on an accurate assessment of the current position or state of the structure. The state of the structure is assessed using sensors, and actuators are used to deform the structure into the desired geometry. In a sense, morphing structures are already very similar to SHM systems in that the state of the structure is sensed to detect the current shape or condition. It may be possible to incorporate SHM directly into a morphing system, where a single sensing system is used to control structural morphing and to detect any structural damage.

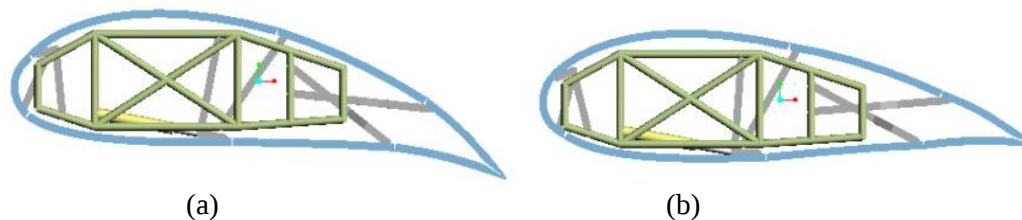


Figure 4: Morphing Wing Concept

An example of a morphing wing concept to change from a highly cambered wing design (a) to a lower camber design (b) for reduced aerodynamic drag is shown in figure 4.

Conformal array antennae refer to curved antennae composed of multiple individual antennae elements arranged on a curved surface. For improved radar performance, large, high-gain antennae are desired. However, it is difficult to install such antennae on most current airframes without severely increasing the aerodynamic drag. One solution under consideration is to incorporate the conformal array antennae into load-bearing structures, such as the aircraft skins. Figure 5 shows an example of a conformal array antenna. Such antennae could be fabricated from composite materials with the individual antennae elements embedded in the structure. However, the performance of the material system would likely degrade. A SHM system would prove useful to verify the integrity of the structure. In addition, a modified SHM system could assess the health of the antennae to detect damage, such as broken electrical connections, which may inhibit the antennae performance but would not affect the structural integrity.

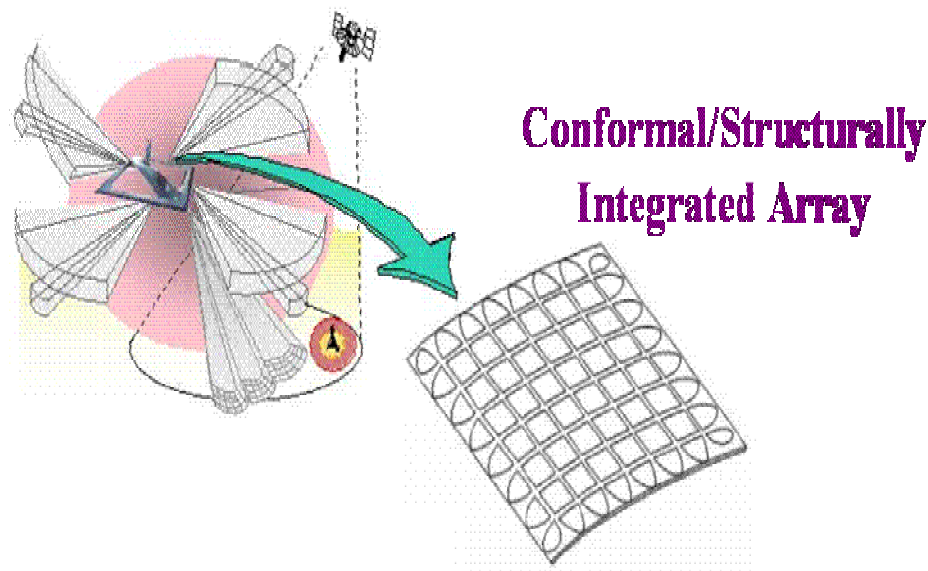


Figure 5: Conformal Array Antenna Concept

5.0 DESIGN WITH STRUCTURAL SENSING

It is clear that structures with a built-in sensing capability have superior advantages over traditional structures due to improved state awareness, enhanced safety and reliability, minimized operation and maintenance, and added multi-functionalities. Structures with sensing capability can detect and monitor their physical health conditions in any given environment and can determine an optimal course of action to maximize their performance and operation with minimal risk in safety. With proper sensing, the performance of many other added functional capabilities such as shape control, smart antenna, noise reduction, and flow control could be significantly improved or enhanced.

Furthermore, it was reported that if the SHM system could be considered at the initial design stage, it could result in a major paradigm change in the structural design for the next generation aircraft and spacecraft [4,5]. Instead of relying upon uncertainties and safety factors in the design process, the new design with an appropriate SHM system could lead to much more reliable structures without overly conservative weight penalty. As shown in the Figure 6 below, a design with structural sensing leads to more benefits, possibilities and potential with a future of more “intelligent” structures [17-18].

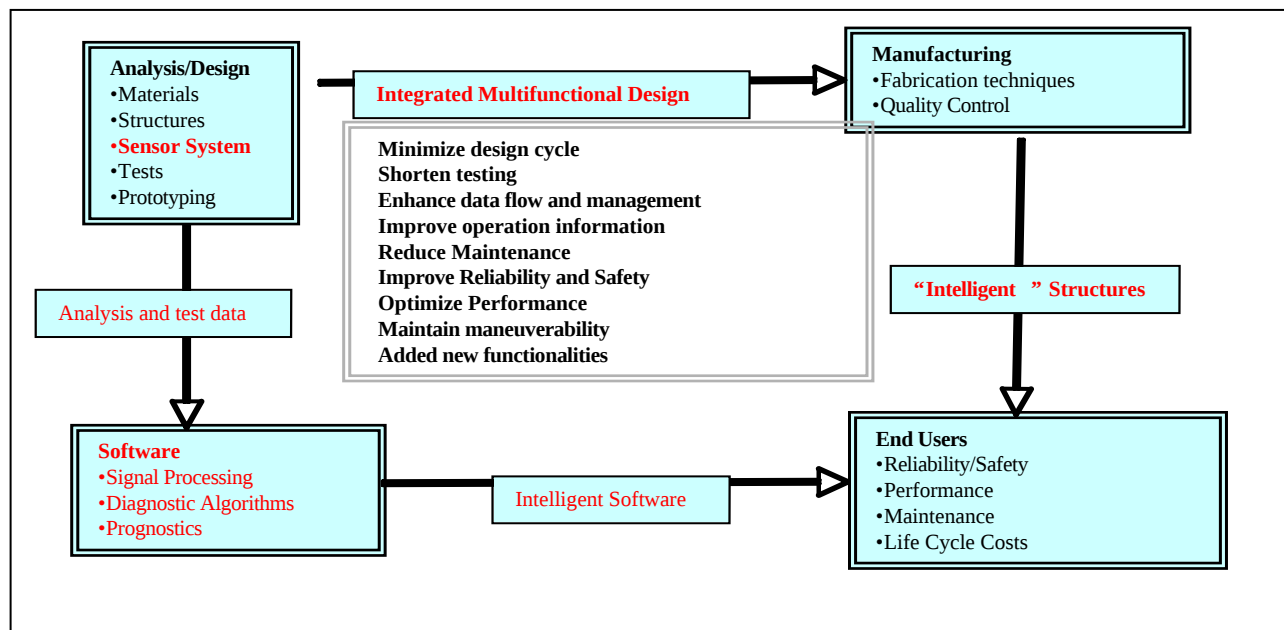


Figure 6: SHM-embedded design flow and potential benefits

6.0 STRUCTURAL SENSING CHALLENGES

The basic components of structural sensing include sensor network, software, and hardware. As shown in Figure 6, in order to implement the sensing technology into structures, it becomes an integrated multifunctional structural design issue, not simply a sensor installation problem, which involves reliability and durability, quantification, validation and certification. Traditional design methodologies may have to be modified and updated to accommodate the new technology from design to implementation. New design methodology suitable for the integrated multifunctional structures may also need to be developed. The material properties, dimension, configuration, and operational environment of structures may affect significantly how a structural sensing system shall be designed and implemented in order to achieve the objectives which involve optimal sensor/actuator placement, number of sensors and actuators, appropriate algorithms for maximizing the system performance, and hardware design, etc. Accordingly, key challenges in implementing the structural sensing technology shall include [18-19]:

- 1) Reliability and durability: The integrated sensing system must be reliable and durable. Not only sensors themselves, but the network, interface between structures and the sensors must be able to sustain and remain functioning in the environments that the structure is expose to. Durable/reliable sensors, advanced interface materials, and embedding/integrated manufacturing techniques are critical needs.
- 2) Quantification: The sensing capability must be quantifiable for its targeted level of application. Relating sensor measurements to physical changes in structures with a high probability of detection (POD) is still a major challenge.

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- 3) Validation: Adequate experimental and numerical methods are required to validate the system reliability and probability of detection. Traditional Non-Destructive Evaluation (NDE) and destructive testing techniques for laboratory applications may not be adequate for evaluating the integrated multi-functional structures in the field on large scale components. Improved or new test methods, techniques, and equipment may need to be developed.
- 4) Certification: Existing certification procedures may not be adequate to accommodate the new design methodology and validation techniques for the highly integrated structures. Therefore, existing procedures may need to be modified or new procedures might need to be developed.

7.0 CONCLUSION

Sensing is the most basic and fundamental element in the design of “intelligent” structures with multi-functional capabilities. With smart sensing, structures can sense, monitor, diagnose and detect their health and physical conditions in any given environment and can respond effectively to optimize their performance, enhance safety, and minimize operation cost. A design with the structural sensing capability may result in major paradigm change on how we design structures in the future. The key challenges in developing structural sensing capabilities for implementation include: reliability/durability, quantification, validation and certification.

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SYMPOSIA DISCUSSION – PAPER NO: 5

Author's Name: M.M. Derriso

Question (A. Paolozzi):

- 1) Is the USAF space vehicle manned? What are the connections with NASA reusable launch vehicle studies?
- 2) Is USAF developing high temp sensors for thermal protection systems or similar applications? If yes, of what kind?

Author's Response:

- 1) The vehicle is planned to be unmanned. The Air Force will take into assessment NASA's experiences.
- 2) Yes, research is currently going on to determine the SOTA. We will use the result of this study as a point of departure.

Question (V. Agarwalo):

On SHM-suggested use of sensors in structures and composite patches, the question is how are these sensors powered to monitor structural health on a continuous basis. Using wired system plugged in the electrical system is labor intensive and cost prohibitive.

Author's Response:

Sensors are currently being applied on the surface of aircraft structures today. Once the sensors are installed, they remain on the vehicle until they need repair. The concept is to plug in to the sensor system when structural assessment needs to be performed. This process takes less than 5 min to complete. The process is much less labor intensive than the current NDE methods. The sensors are powered from a device the size of a laptop. Data is not collected in flight to perform the assessment. The approach has the potential of saving the Air Force millions of dollars in Ops cost.

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