

# Design of Integrated SHM System for Commercial Aircraft Applications

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## ABSTRACT

This paper discusses Structural Health Monitoring (SHM) design as a subsystem to the Integrated Vehicle Health Management (IVHM) system of an aircraft. Starting with detection and tracking of damage using active interrogation by elastic waves, we discuss the damage estimation in an SHM system as a Member System within Honeywell's Central Maintenance Computer (CMC) IVHM. The additional SHM data integration described includes: spatio-temporal filtering, damage reporting, and generation of the BIT fault reports in the CMC Member System format. The approach is illustrated for data collected on bonded composite repair patches experiencing crack growth due to cyclic loading.

## INTRODUCTION

As Integrated Vehicle Health Management Systems (IVHM) become more common in commercial aircraft, Honeywell continues to be a leader in this area building on their pioneering success of the Central Maintenance Computer (CMC) for the Boeing 777 aircraft. After labor and fuel costs, maintenance costs represent the third largest expense item for both regional and national carriers with maintenance costs commonly comprising 15-18% of the operational expenses. The CMC helped air carriers achieve maintenance costs reductions at 50% to 80%. The CMC technology is deployed in business and regional jets as a part of Honeywell's Primus Epic avionics suite. A ground tool implementing the technology, AMOSS, is being used for maintenance support of legacy aircraft. Recently the technology has been further extended to support applications on Boeing's 787, the Platform Soldier - Mission Readiness System for the US Army's Future Combat System program, and other applications.

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As existing IVHM systems integrate a growing range of aircraft subsystems such as a Structural Health Monitoring (SHM) subsystem, SHM is experiencing increased interest from a number of communities. In particular, commercial aircraft operators are looking at SHM technology, driven by a desire to reduce structural inspection costs, minimize downtime, and improve operational safety.

In SHM, the mechanical loads, vibration, and environmental conditions experienced by the aircraft can be monitored with strain gauges, fiber optic sensors, MEMS sensors, and accelerometers [7—10]. The aircraft damage state is estimated from the collected data using structural models that might be obtained through extensive and expensive analysis. A more direct estimate of the structural damage state can be obtained by actively interrogating the size and location of damage, such as thinning and pitting by corrosion, fatigue cracks, and impact damage. Unlike the passive sensing that is influenced by the loading and environmental conditions, the interrogation of the structure can be done on demand, when needed [7—10].

Although operational monitoring methods have been in use in military vehicles for some time, direct measurement of the airframe damage state and integration of the damage estimates into an avionics environment is still emerging. Commercial deployment and operational usage can be greatly facilitated by integrating SHM system into aircraft IVHM as a member system. Despite the advancements in the SHM technology, this level of integration has yet to be demonstrated in a commercial aircraft. This paper provides evidence that these capabilities exist. We describe a possible integration path for the SHM subsystem into an existing IVHM system – Honeywell’s CMC. We illustrate this through SHM data integration example for an experiment with repaired composites undergoing crack growth.

## INTEGRATED SYSTEM REQUIREMENTS

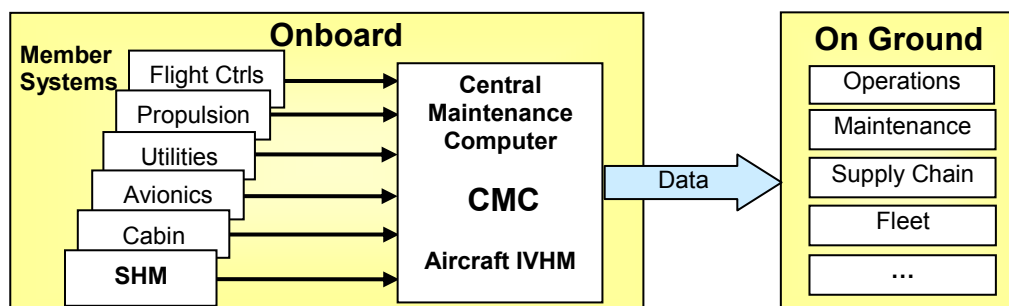


Figure 1. Integrated Vehicle Health Management systems of an aircraft

Figure 1 shows a system level design for SHM as a member of an IVHM system using Honeywell’s CMC. The CMC collects BIT (Built-in-Test) fault reports from multiple aircraft subsystems and provides an integrated assessment of the aircraft’s health-state, see [1, 4]. The subsystems, called member systems, provide fault reports in specified formats, which are then integrated through the CMC. For example, the member systems: SHM, Flight Control, Propulsion, Utilities, Avionics, and Cabin could all report in through the CMC.

A member system is a grouping of hardware and software for the purpose of communicating with the maintenance system of the CMC. Each member system provides fault codes on the status of the line replaceable units (LRU) they contain. Faults within one LRU usually result in fault reports being generated by other member systems due to the impressed system connectivity. The CMC isolates the faults by deducing the root cause from on the observed symptoms. This is based on a CMC Fault Model, which contains relationships between the fault reports, maintenance messages, other effected LRUs, and the connectivity of the LRUs. Over the last two decades Honeywell has been developing and improving a Diagnostic Model Development Tool (DMDT) to collect and validate Fault Models that can be used to isolate the root cause of a failure. Once a Fault Model has been validated, the DMDT tool can produce a loadable diagnostic information file that resides on the CMC for fault isolation and maintenance reporting.

A more detailed view of the structure of SHM Member System is illustrated in Figure 2. A key part of SHM system is the primary sensing system. Though other sensors might be used, Figure 2 shows the active interrogation Smart Layer® sensor system by Acellent Technologies. The SHM Electronics block drives the transducers and digitizes the received analog signals. The SHM Electronics blocks also contain digital processor(s) that compute an estimate of the structure damage in the form of a damage map. The Smart Layer® and SHM Electronics hardware and functionality developed by Acellent are discussed in the next section.

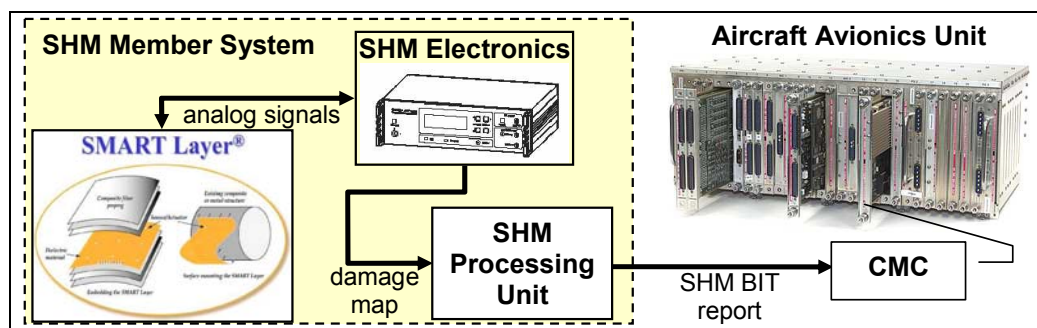


Figure 2. SHM member systems in an aircraft CMC-style IVHM

Most of the existing SHM research work focuses on damage detection using some proposed sensor system. However, the damage map data must be post-processed for IVHM integration. This processing is described further in this paper. Figure 2 shows an SHM Processing Unit that receives the damage map and calculates the CMC fault report. Note that the functionality of the SHM Processing Unit is largely independent on the fundamental SHM measurement mechanism used to obtain the damage map. This unit hosts post-processing algorithms for interfacing SHM with the CMC so that the SHM data can be integrated an onboard maintenance and reporting system.

## **SHM SENSING SYSTEM**

Acellent Technologies has developed a network of distributed piezoelectric sensors/actuators embedded on a thin dielectric carrier film called the SMART Layer®, see [5, 6]. The SMART Layer® technology has both active and passive sensing capabilities via the embedded piezoelectric transducers. This sensor network is used with a portable diagnostic unit called the SMART Suitcase™ to query, monitor and evaluate the condition of a structure. The SMART Suitcase™ incorporates all of the functionality of the SHM Electronics block in Figure 2. In Active Sensing Mode, the SMART Suitcase™ actuates the transducers to generate pre-selected diagnostic signals and transmit them to neighboring sensors. The responses can be interpreted in terms of damage size and location or material property changes. In Passive Sensing Mode the SMART Layer® sensors can continuously monitor the sensors to detect anomalous structural events. Both modes permit real-time structural analysis and evaluation along with constant collection of structural data and information while the structure/vehicle is in service. Specifically the system can:

- Obtain real-time, in-service, data on the integrity of an aircraft structure
- Identify visible and invisible damage in metal and composite structures
- Assess damage data from structural anomalies including: i) fatigue cracks in highly loaded metallic fittings, ii) delaminations and disbonds in composite components, iii) deterioration in bonded joints and iv) projectile impact damage.
- Reduce inspection and structural maintenance costs by providing an easy tool for maintenance personnel to assess damaged and take preventive action

The SMART Layer® can be as thin as 2 - 4 mil and as a result has little weight. Typical sensor sizes range from 0.125-0.25” in diameter with thickness of 0.01-0.03”. The sensor network layers can be either surface mounted on both metallic and composite structure using an adhesive such as epoxy or embedded inside the composite structures during manufacturing by placing the sensor film between plies during lay-up.

## **MONITORING OF A COMPOSITE REPAIR PATCH**

Acellent conducted tests at Wright-Patterson Air Force Base as part of a program to evaluate candidate structural health monitoring technologies for bonded composite repair patches. The goal was to detect crack growth under the bonded composite repair during fatigue cycling. The coupons were 0.19” thick unclad 7075 series aluminum, and each was fabricated with a 0.25” diameter through hole in the center of the specimen, and 0.10” EDM notches on each side of the hole. All specimens were cut into dog bone shapes to minimize the probability of failure at the grips. Each coupon was patched on one side only. The patches consist of pre-cured Boron/epoxy 5521 with fiber direction of all plies parallel to the load application direction, i.e., the length of the specimen. Each coupon was cycled in tension until specimen failure. A square SMART Layer with eight piezoelectric sensors was designed for the coupon specimen, see Figure 3. The load was cycled in

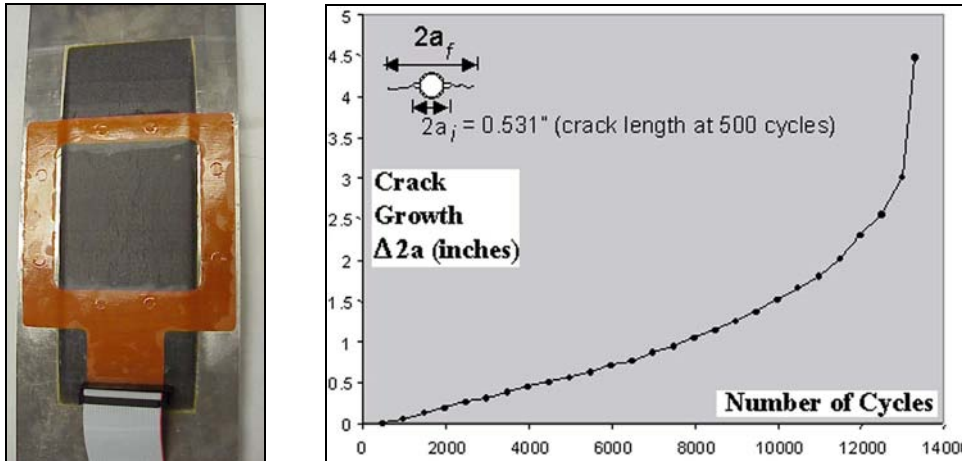


Figure 3. Damage growth under the bonded composite repair patch.

tension between 1 and 26.4 kips at 5 Hz, and data was collected every few cycles. As the number of cycles increased, the crack under the repair patch grew, Figure 3.

A technique was employed that uses the Mean Signal Amplitude (MSA) to calculate Damage Index values for each actuator-sensor path. The MSA of the scatter signal is compared to the MSA of the baseline signal and a corresponding Damage Index is calculated. The values for each path were used to generate images of the damage growth under the bonded composite repair patch in Figure 4. These images provide a visual representation of the location of structural changes and can be used as a qualitative measure of damage size.

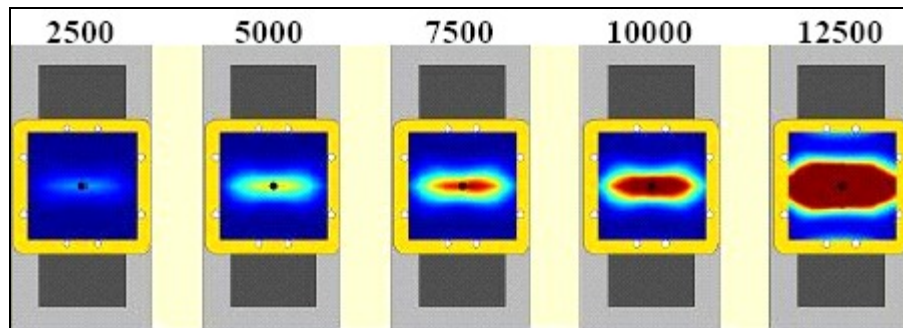


Figure 4. Images of damage under the bonded composite repair patch for different cycle counts.

## STRUCTURAL DAMAGE TRACKING AND REPORTING

Consider the SHM Processing Unit in Figure 2. This unit takes a structure damage map established by the SHM Electronics and computes an SHM Fault Report implementing the data processing functionality necessary for SHM integration into IVHM. Let us assume a scenario where the structure inspection is initiated after each flight when the aircraft with the SHM system is on the ground.

The damage map data after every 100 cycles is passed to the algorithms in the SHM Processing Unit for post-processing.

The experimental data were collected in a laboratory experiment at room temperature. A separate test was used to establish the thermal variation sensitivity of the estimated damage map. The temperature variation can be partially compensated by using temperature information in the damage map computation. Still, temperature non-uniformity and the calibration errors result in uncompensated residual variation. Based on the available data, we modeled the variation by convolving a ‘white’ noise signal with an exponentially decaying 2-D spatial kernel. The characteristic spatial correlation length was set to 5 pixels. The noise was obtained with a random number generated as spatially uncorrelated 3-D array of variables uniformly distributed on  $[-1, 1]$ .

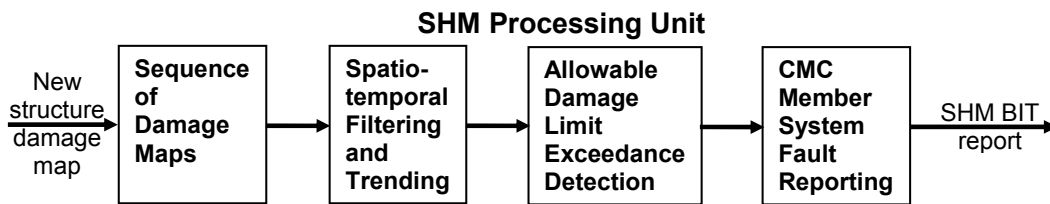


Figure 5: Functional blocks of SHM Processing Unit

The functional blocks of the SHM Processing Unit are shown in Figure 5. The input data are damage maps collected and estimated by the SHM sensors and SHM electronics after each aircraft flight. The maps could be collected in different locations and different weather conditions and, therefore, are subject to environmental variation. The SHM Processing Unit looks at a time sequence of the damage maps to discriminate between real damage and the environmental variation. By applying a spatio-temporal filter, the useful damage estimate can be enhanced and the noise (environmental variation) reduced. The filtered damage estimate should be then compared against the allowable damage limit set by the airframe manufacturer in consultations with regulatory authorities.

The operation of the blocks in Figure 6 is illustrated below for the fatigue crack growth data. The spatio-temporal filter used in this work has the form

$$u(t+1) = u(t) + K ** [y(t) - G ** u(t)] - S ** u(t), \quad (1)$$

where  $y(t)$  is a 2-D ‘raw’ damage map obtained at time  $t$ ,  $**$  denotes 2-D (spatial) convolution,  $S$  and  $K$  are two spatial FIR operators in the filter,  $G$  is a FIR operator describing blur model respectively. A new 2D estimate  $u$  at time  $t+1$  is computed from the estimate  $u(t)$  and the map  $y(t)$ . The spatio-temporal filter was designed as described in [2, 3]. The optimization-based design of the FIR operators  $S$  and  $K$  attempts to satisfy filter performance, robustness, and spatial boundary constraints.

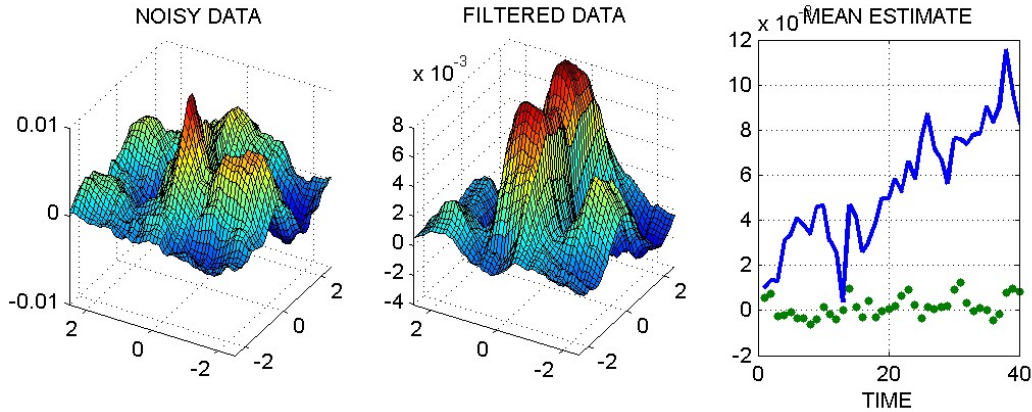


Figure 6: Results of spatio-temporal filtering and trending.

Figure 6 shows the results of applying the spatio-temporal filtering to the crack growth data. The left plot shows the damage map  $y(t)$  contaminated by adding the variation; the map corresponds to the update cycle  $t = 40$  (loading cycle 4000). The middle plot shows the deblurred and de-noised data, the filter output  $u(t)$ . Finally, the right plot shows the mean value of the filtered data in the crack area (solid line) and outside of the crack area (dotted line) for each of the 40 update cycles.

In a CMC-style IVHM, each LRU is responsible for providing fault codes into the CMC as a single or double bit message. At a first glance it seems attractive to consider defining the pixels within the binary image damage map as LRUs. However multiple fault codes are needed for each LRU to enunciate detected damage of the structure, SHM sensor/system failures and connectivity failures. Since the number of pixels in a damage map is very large, this requires using an excessively large set of fault codes in the DMDT modeling tool and the resulting loadable diagnostic information file.

One alternative is to collect and process the data with multiple data concentrator dedicated to local region of the inspected structure, e.g., a part of the SHM electronics shown in Figure 2. The fault code could enunciate the presence of damage within the local region through an additional separate protocol after the SHM concentrator had calculated the damage position. To define the damage location within the local region, BITE data in the form of a shop fault strings could be used. This data would enhance the LRU level fault detection and provide the maintenance personnel with additional LRU damage specific detect attributes such as intensity, location and number of connected regions etc. Maintenance actions and flight deck effects could be associated with the data concentrator fault codes through the loadable diagnostic information file that resides on the CMC. These would provide detailed information about the detected damage for the ground maintenance personnel performing repairs as well as any necessary pilot specific information.

The signal processing necessary for implementing the above described vision includes detection and characterization of the connected damaged regions. To achieve that, the filtered damage estimate maps are further processed with two-dimensional wavelet filtering and hard thresholding to arrive at a 2-D binary image. The damaged areas are characterized by finding and labeling the connected

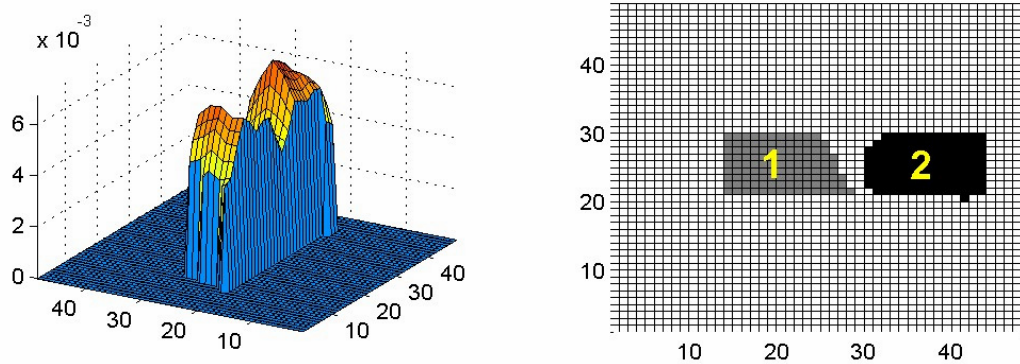


Figure 7: Results of wavelet filtering and damage area detection

components in this binary image. The wavelet filtering results and the labeled connected components are shown in Figure 7 for the filtered data (the middle plot in Figure 6).

## REFERENCES

1. Felke, T. 1994. "Application of model-based diagnostic technology on the Boeing 777 airplane," *Proceedings of 13th DASC., AIAA/IEEE Digital Avionics Systems Conference*, pages 1—5.
2. Gorinevsky, D., Boyd, S., and Stein, G. 2003. "Optimization-based tuning of low-bandwidth control in spatially distributed systems," *American Control Conference*, Vol. 3, pp. 2658—2663, Denver, CO, June 2003.
3. Gorinevsky, D. 2005. "Feedback Loop Design and Analysis for Iterative Localized Image Deblurring," *IEEE Conference On Decision and Control*, Seville, Spain, December 2005
4. Ramohalli, G. 1992. The Honeywell on-board diagnostic and maintenance system for the Boeing 777. *Proceedings of 11<sup>th</sup> IEEE/AIAA Digital Avionics Systems Conference*, pages 485--490, October 1992.
5. Shawn J. Beard, Amrita Kumar, Xinlin Qing, H.L. Chan, Chang Zhang, Teng K. Ooi, Practical Issues in Real-World Implementation of Structural Health Monitoring Systems, *Proceedings of SPIE on Smart Structures and Material Systems*, March 2005.
6. Shawn Beard, Peter X. Qing, Michael Hamilton and David C. Zhang, Multifunctional Software Suite for Structural Health Monitoring Using SMART Technology, *Proceedings of the 2nd European Workshop on Structural Health Monitoring*, July 2004, Germany.
7. Structural Health Monitoring-Current Status and Perspectives, Chang, F.-K. (Editor), Technomic Publishing, Inc., *Proceedings of the First International Workshop on Structural Health Monitoring*, Stanford, CA, September 18-20, 1997.
8. Structural Health Monitoring-2000, Chang, F.-K. (Editor), Technomic Publishing, Inc., *Proceedings of the Second International Workshop on Structural Health Monitoring*, Stanford, CA, September 8-10, 1999.
9. Structural Health Monitoring-The Demands and Challenges, Chang, F.-K. (Editor), CRC Press, *Proceedings of the Third International Workshop on Structural Health Monitoring*, Stanford, CA, September 12-14, 2001.
10. Structural Health Monitoring-From Diagnostics, Prognostics to Structural Health Management, Chang, F.-K. (Editor), Destech Publishing, *Proceedings of the 4th International Workshop on Structural Health Monitoring*, Stanford, CA, September 12-14, 2003.