BATTERY OPERATED HEALTH MONITORING SYSTEM

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Introduction

The majority of the cost of maintaining aging aircraft structure can be associated with corrosion prevention and control. For Boeing's commercial transport aircraft, approximately 70% of the total person-hours spent inspecting the airframe during a scheduled maintenance is corrosion related, with only 30% for fatigue cracks and other damage. The major portion of the cost of inspecting aircraft for corrosion damage is associated with obtaining access to concealed parts of the airframe. In addition, there is the added cost associated with any incidental damage that is done to the structure while gaining access to these concealed areas. There is a clear need to develop in-situ sensors and the diagnostics and prognostics algorithms to monitor corrosion environments to provide early warning of the onset of corrosion in hidden parts of aircraft.

The battery-operated health monitoring system (BOHMS) is an aircraft flight data acquisition system that has been designed to fill the void in commercially available data recorders to monitor corrosion environments. To perform these functions, a rugged, small and lightweight data acquisition unit has been constructed and is currently being further revised. Running off of battery power, the system will collect flight data autonomously, independent of any aircraft systems. This unit is designed to interface with other data acquisition units, multiple sensor types and placed in remote, hard to access areas of aircraft, spacecraft, launch vehicles, ships and ground vehicles to monitor the health of structural components. The current quantity of sensors capable of integrating with the BOHMS include up to eight electrical sensors and sixteen fiber optic sensors ranging from, but not inclusive of moisture detection, relative humidity, temperature, pressure and static strain measurements.

The BOHMS will be tested on several platforms including military and commercial aircraft. Current algorithm development is being conducted concurrently for military and commercial aircraft. As structure types between some military and commercial applications are similar, corrosion information may be shared and algorithms developed jointly. As a whole, information learned from either military or commercial applications will allow better algorithm development for corrosion predictions.

Another advantage of the BOHMS is that the function of the system is twofold. First, the system may be used as a quick-look inspection method for hard to reach areas. Sealed avionics bays will not need to be opened to determine if moisture is present. Since seals are not broken, moisture is less likely to enter the area. Areas that are hidden will not have to be disassembled, thus saving substantial labor and risk of disassembly damage. The second function of the BOHMS is that of a virtual flight laboratory. The BOHMS can continually take data, which provides essential information for a long-term health management system. Sensor information may be input into an Open System Architecture for Condition Based Maintenance (OSA-CBM), a dual use science and technology program that has developed an industry-military common, open architecture to implement CBM strategies, conformed to the proposed ISO/DIS 13374 standard. The health management system would allow real time operations and maintenance decisions to be made. Thus, maintenance and repairs would be performed on a need basis, rather than a timed basis.

This paper will detail the design of the Battery Operated Health Monitoring System.

Design Requirements

The BOHMS is derived from the "Durability Patch Program", in which the Air Force Research Laboratory (AFRL) Wright Laboratories funded the design, fabrication, and flight-testing of a damage dosimeter. The damage dosimeter was developed to allow a repair design engineer to easily instrument an in-service aircraft to obtain the structural data necessary to properly select damping materials and design a structural repair with incorporating damping materials optimum effectiveness. The design process is shown in figure 1.

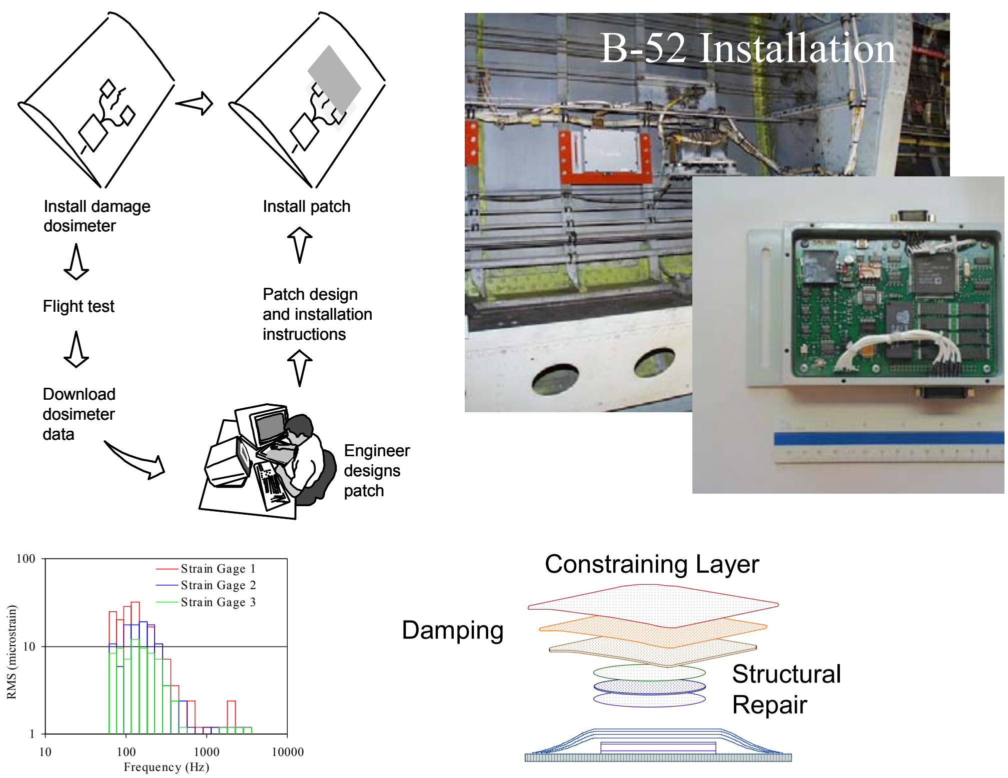

Figure 1. Boeing/AFRL durability patch program developed the Damage Dosimeter that has been flight-tested on B-52, C-130, F-18 and F-15 aircraft.

The damage dosimeter, shown in the upper right corner of figure 1, is a rugged, small, lightweight data acquisition unit that will acquire and store the required data for a damped repair design. Running off of battery power in an autonomous fashion, it is currently configured to measure three channels of strain at sample rates as high as 15 kHz and a single channel of temperature. It merges the functionality of the analog signal conditioning and a digital single board computer on a single card. In order to minimize the impact on an aircraft's normal operations, the dosimeter is a stand-alone device that does not require aircraft power or cooling. This greatly reduces the amount and severity of modifications to the aircraft and certification needed to do in-flight testing on a military aircraft.

The dosimeter was revised and improved upon as the BOHMS to further meet the needs of customers for a small data acquisition system capable of monitoring several different parameters.

Hardware Design

The BOHMS hardware design has leveraged lessons learned from the Damage Dosimeter and has implemented the successful attributes of that design into a new single board computer. The BOHMS includes the main acquisition unit, the sensors and the power supply.

The BOHMS operates autonomously from its own battery supply. Operating from a separate power source relieves the necessities of connecting to the airframe's power bus. The BOHMS's operation is programmable by the user to determine the sampling rate and monitoring period of the BOHMS implementation. This allows the user to determine which and how many sensors are to be monitored and how often. Another advantage is that battery life may be conserved by monitoring static environmental measurements on a long-term basis (for example, measuring a parameter once per hour rather than continuously). The BOHMS's design to operate autonomously also alleviates any flight crew interface. This drastically lowers the barriers to accessing and implementing experiments on aircraft.

Acquisition Unit

The main acquisition board shown in figure 2 performs the functions of system controller (autonomous operation, peripheral power management etc), data acquisition, data conversion (ADC and data manipulation or preprocessing), data storage, time keeping, and provides a user interface to the system.

The design of the main acquisition unit was driven by the need to operate in a flight environment on as small a battery as possible. The microprocessor is not only the controller for the system but also the device used to perform the math functions necessary to process sensor data. An *Analog Devices* Digital Signal Processor (DSP*)* was used due to its successful performance on the Damage Dosimeter and the ability to leverage previously developed software. The DSP is more than capable of performing the math functions necessary and has some of the attributes of a microcontroller that were used to implement this design – like user defined pins used to control peripheral devices' power. Data is stored in flash non-volatile memory. This gives the user the flexibility to store data on an acquisition unit with the freedom of not needing a backup battery. Time keeping and Watch Dog operations are performed using a *Dallas Semiconductor* device that provides real time resolution of 0.01 seconds and Watch Dog operations that are programmed to be either a periodic alarm (every 60 seconds for example) or set on a time of day alarm (the top of every hour or the same time every day for example). The Watch Dog alarm is used to determine the standby period for the acquisition unit. When the alarm goes active the acquisition unit powers up and boots the operational code. The microprocessor then decides what mode to operate in and what to perform next; i.e., gather data, wait for the user interface, or power down. The user interface is implemented over a serial port; this allows the use of any PC with a serial port (virtually all) to be used to communicate with the acquisition unit. This provides the opportunity for a portable or laptop PC to be used to connect the user to the acquisition unit for data download or data acquisition configuration changes.

Figure 2. Battery Operated Health Monitoring System Board.

Sensors

The BOHMS has been designed to interface with numerous sensor types (shown in figure 3) separated into two groups; analog output and digital output devices. Analog output sensors are monitored by the BOHMS through an Analog to Digital Converter (ADC). The 12-bit ADC has a reference voltage of 4.096 volts giving the ADC output a resolution of 1 millivolt. Presently, inexpensive yet highly reliable, small and accurate analog electrical sensors are available for temperature, pressure and relative humidity, among others. The BOHMS is capable of monitoring up to eight analog channels at sample rates up to 10 kHz. Any sensor capable of outputting a voltage (or being conditioned to) can be monitored by the BOHMS. For example, a fiber optic system developed by Blue Road Research is capable of transferring wavelength data for Bragg grating sensors into voltage output. Current fiber optic sensor types include relative humidity, moisture, temperature and pressure fiber optic sensors. This sensor system has been incorporated into the BOHMS system.

The BOHMS is also capable of interfacing with up to four serial (RS-232) devices. Any device with a serial port can be communicated with using the BOHMS. Examples of this kind of devices are sensors recently developed by Analatom Incorporated and Luna Innovations. Each of these devices performs measurements when requested by the BOHMS and returns a digital reply. The digital reply can be either stores as a raw value or further manipulated by the on board DSP. Analatom Incorporated has a solid-state sensor system that measures corrosion. Luna Innovations sensor types include Long Period Grating (LPG) sensors and Extrinsic Fabry_Perot Interferometric (EFPI) fiber optic sensors.

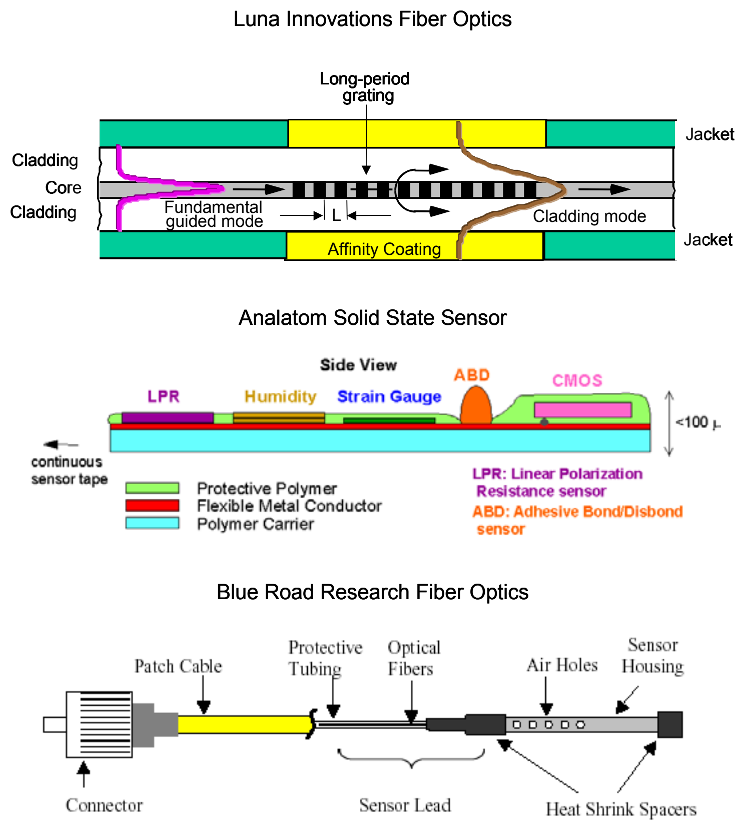

Figure 3. Various Sensor Types Incorporated into the BOHMS.

Power Supply – Battery

The BOHMS can operate on a DC power supply as low as 8 VDC and as high as 40 VDC. Efficient operation, or low power draw, was a primary consideration during the design of the BOHMS. As a result, power consumption during data gathering operations is less then 1.5 watts.

The standby current necessary for BOHMS operate is less then 300 μA. Duracell D2/3A cells were chosen for the battery supply, primarily due to their success in the Damage Dosimeter flight test program. The batteries are not rechargeable but are readily available and inexpensive (about 3-4 dollars per cell). Twenty cells are chosen to power the BOHMS through a typical experiment, four packs (5 cells in series) in parallel. The battery is implemented in a custom aluminum box lined with polyethylene foam for vibration isolation as shown in figure 4.

Figure 4. Battery Operated Health Monitoring System Unit Battery Pack.

Software

The BOHMS's operational software program was written in C to allow the code to be easily maintained. Although the software that is embedded in the BOHMS is C compile-able the low-level device drivers are written in assembly code for the DSP. The device drivers are; however, C callable. The device drivers were written in assembly language for two reasons: First, they are more efficient, and second they can be reused in many different configurations mitigating the need to be maintained. The embedded code was designed to be easily modified since the use of the BOHMS will change slightly from application to application (see figure 5). Each function of the BOHMS is modularized and program variables (such as sample rate, etc) are visible at the top-level program. For example, the user may set a threshold function on the measured parameters. If the threshold function is surpassed a second sample rate may be used. This may be beneficial in such areas as pooling water around clogged plugs. Once water is detected it is advantageous to know how long the water is there before evaporation. By modifying the sample rate from perhaps once every hour to once every ten minutes a better understanding of how long the water is contacting the metal may be achieved. Modification of the BOHMS's embedded code is accomplished by the program variables via a windows user interface program. The BOHMS's operational code resides in onboard flash that makes the boot code and the operational code modifiable in-circuit. This gives the user the ability to upgrade the BOHMS software in the field using a PC and the user interface without the need to open the BOHMS unit or replace parts.

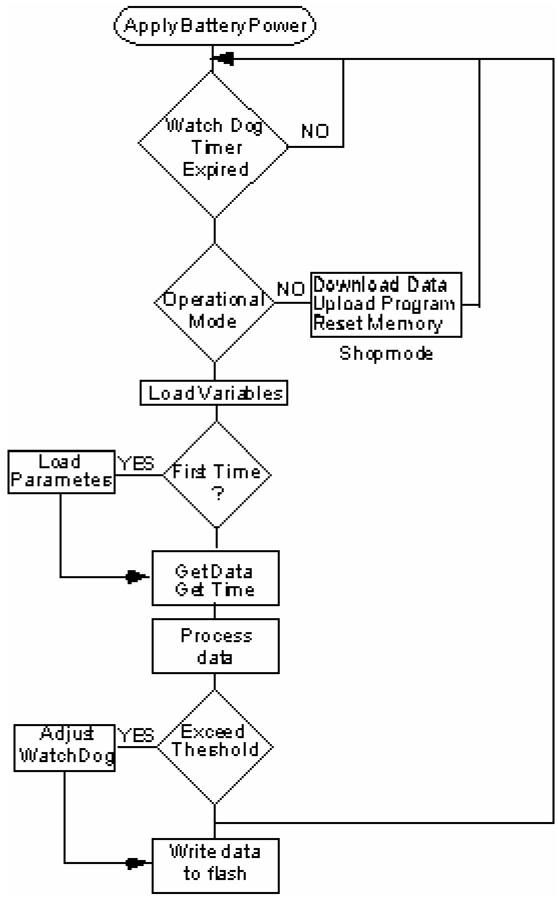

Figure 5. Top Level Flow-Chart of Code.

Data gathered from the sensors is stored in non-volatile memory. The data can be preprocessed by the DSP in the BOHMS. This can be a simple scaling or a more complex function given the data as a variable; for example, a Power Spectrum Density for strain data. Preprocessing the data before storage makes the most efficient use of the non-volatile memory, by reducing the size of the information needed to be stored. The data stored can be the raw value from the sensor or the converted to engineering value calculated using the data as an input. For example, a temperature sensor's voltage output could be converted to degrees Kelvin before storage. This reduces the need for post-processing the data by the engineer. The BOHMS has 4 Mbytes of flash memory, of which 64 Kbytes are reserved for the boot and operational program. An example of a data record for a typical experiment would be two analog relative humidity sensors (2 bytes each), two analog temperature sensors (2 bytes each), one analog pressure sensor (2 bytes), the reference and sensor data from the Blue Road Research sensor (2 bytes each), the measurement of the Analatom sensor (2 bytes) and eight sensor data points from the Luna Innovations devices (2 bytes each). Each data record is appended with ten bytes for time of day data (MM:DD:HH:MM:SS) and a short header and footer for data integrity and post processing capabilities. This makes the data record length 50 bytes. The available memory for data storage is 4,128,768 bytes. If a data record were recorded every five minutes the BOHMS memory would have storage to run for 286 days!

Conclusions

Flight Testing

Currently, flight validation testing is proceeding under cooperative agreements with Delta Air Lines to monitor problematic areas in aircraft where liquid can pool or cause problems such as under floors of lavatories and galleys, inside insulation around doors and in bilge areas. Delta Air Lines is providing the environmental data and assessments on how the systems can be incorporated into their O&M processes. A parallel ground test validation program is also being carried out at Boeing to evaluate system reliability and integration issues, and validate corrosion predictive models and algorithms on structural components in an accelerated corrosion environment.

Recommendation for Future Improvements

As with any prototype system hardware development, initial testing has allowed the maturation of the technology while showing areas that can be improved. Some current improvement areas include:

- Increased Non-volatile Memory – Currently 4 MB of memory is sufficient for short term testing durations but additional memory will need to be installed as more sensors are involved and longer testing durations are required.
- Additional Sensor Development – While a wide range of sensors are currently available, several sensors would greatly enhance environmental monitoring. Some of those sensor types include pH, chloride ions and metal ion detection.
- Size and Power Reduction – As with any system on a vehicle, the lighter and smaller the better.
- Extend Temperature Range of Demodulation Units and Sensors – Peripheral Electronic units currently operate from 0-60C. For maximum flexibility in placement of these units in vehicles, (space, military or commercial), the temperature range should be extended. Many of the sensors also do not function below freezing. New methodology needs to be developed to monitor in extreme cold environments.
- Continual Integration with OSA-CBM – As the long-range goal of this system is to develop an integrated health management system, an eye should be kept on state-of-the-art sensors and data architecture.