

**A Structural Health Monitoring Workshop Roadmap for
Transitioning Critical Technology from
Research to Practice**

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**Principal Investigator: Aditi Chattopadhyay
Arizona State University (ASU)**

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Workshop on Transitioning Structural Health Monitoring Technology to Military
Platforms

Mark Seaver, Code 5673, Naval Research Laboratory, Washington, DC 20375
Aditi Chattopadhyay, School for Engineering of Matter, Transport and Energy, Arizona
State University, Tempe, AZ, 85287, USA
Antonia Papandreou-Suppapola, School of Electrical, Computer and Energy Engineering,
Arizona State University, Tempe, AZ, 85287, USA
Seung Bum Kim*, School for Engineering of Matter, Transport and Energy, Arizona
State University, Tempe, AZ, 85287, USA
Narayan Kovvali, School of Electrical, Computer and Energy Engineering, Arizona State
University, Tempe, AZ, 85287, USA
Charles R. Farrar, The Engineering Institute, Mail Stop T001, Los Alamos National
Laboratory, Los Alamos, NM, 87545
Matt H. Triplett, AMSRD-AMR-PS-AM, Redstone Arsenal, AL 35898
Mark M. Derriso, Air Vehicles Directorate, AFRL, WPAFB, OH 45433

* current address: United Technologies Research Center, 411 Silver Lane, MS 129-22,
East Hartford, CT 06108a

ABSTRACT

Interest in structural health monitoring/management (SHM) is attracting lots of attention across a spectrum that ranges from sensor developers to end users. The United States military, in particular is making a concerted effort to implement condition-based maintenance (CBM) as a means of reducing the life cycle costs and improving availability of various weapons platforms. In spite of this effort, the majority of installed health monitoring systems are limited to rotating machinery such as engines, transmissions, and other gear boxes. The goal of this workshop was to bring together representatives from military, industry, and academia covering the spectrum from hardware developers to end users and platform managers and have them discuss issues that must be addressed as SHM systems mature to the point that managers will implement them. This paper describes those discussions and highlights important issues that need to be addressed as SHM systems make the transition from laboratory scale demonstrations to real-world use.

INTRODUCTION

Currently, the Department of Defense (DoD) in the United States is focused on reducing the maintenance costs and increasing the availability of their weapons systems. The result is a major push to implement Condition Based Maintenance (CBM) and significant success has been demonstrated in deploying sensors to monitor engine performance. The Health and Usage Monitoring System (HUMS) now deployed on many rotorcraft is a prime example (Moorman, 2010). Such success in engine and transmission monitoring has not been matched when it comes to structural monitoring. Because of this slowness, a group of structural health practitioners felt it important to conduct a workshop that would include the complete spectrum of people involved in implementing CBM on structures including hardware, software, and systems developers as well as program managers at both the research and development (R&D) and weapons platform levels. A major goal of this workshop was to facilitate the two-way discussions between systems developers and end users to ensure that developers understand the requirements and constraints of the end users and that the end users understand the technology capabilities. Such discussions benefit all parties by informing end users of what is possible now and in the future and letting developers know about high-level constraints that must be met for a successful technology transition.

The universe of structural monitoring encompasses a wide variety of sensor systems, analysis methods, and implementation visions. This is illustrated by the many engineering societies that either organize dedicated conferences or include sessions on structural health. Relevant conferences/sessions appear under a variety of names such as nondestructive evaluation (NDE), smart structures, structural health monitoring (or management), prognostics health management, or intelligent materials to name a few. In spite of the high levels of interest within both the R&D and program management communities, progress in getting systems tested beyond laboratory settings is slow. The consensus among the organizing committee for this workshop was that there are two major factors influencing this lack of progress: 1) field tests are expensive, which makes obtaining funding from R&D programs unlikely, and 2) systems have not demonstrated sufficient reliability in the field to convince program management at the weapons platform level that the likelihood of success is sufficient to justify the investment. Because this is a circular problem it will take movement from both ends to create success and one of the ongoing discussions within the community and at this workshop is about how to generate the needed movement.

The workshop consisted of five sessions that targeted problems of interest to all parties. These five were:

- 1) Sensor Systems: Current capabilities and needs
- 2) Data Analysis: Information handling
- 3) Implementation Issues
- 4) Performance Validation and Certification
- 5) Cost Benefit Analysis

Sensor systems are the fundamental building block in assessing structural health. Thus, the opening session was devoted to describing what sensors are capable of both now and in the future. However, sensors are only valuable when the data collected from the sensors is converted into the information needed by the user. There are significant challenges in this arena that span the range from the technological, e.g. how much data is generated and how do you analyze and store it, to human factors, where 'who knows what?' and 'when should they be told?' are key programmatic decisions. The session on implementation issues dealt with how to bridge the gap between lab level results and the field reliability desired at the program level. It is worth reiterating that there is general agreement that this is the area where most transition failures occur. Performance validation and certification is a step that any new technology will have to achieve before it becomes generally accepted. However structural health systems face a daunting challenge because the structures (e.g. ships, ground vehicles, and aircraft) are too expensive to test a statistically significant number. Thus other ways of making statistically valid tests that can be compared across sensors and analysis methods are needed. Finally, should a structural health system make it past the hurdles described in the first four sessions, the final say in implementation will probably be determined by some kind of cost benefit analysis.

In the sections that follow, we will describe each topic and present the discussion, analysis, and any conclusions. We expect the conclusions drawn from these discussions to be the starting point for continued discussion within the structural monitoring community.

CURRENT CAPABILITIES AND NEEDS

Background

The main goal of this session was to provide both sensor systems developers and potential end users with some general guidance as to how advanced different sensor systems are with respect to their uses for SHM. As anyone who has attended conferences with sessions devoted to SHM knows, there are both a wide variety of sensor types and numerous specific implementations of each sensor type touted as having major capabilities for structural monitoring. Because of this diversity, a thorough discussion of sensor capabilities could easily occupy many days and result in a book length description. Thus, this session was limited to a general description of capabilities broken down by sensor type and upper frequency limit. Beneath the admittedly arbitrary limits used during this session and shown in Table 2, there is a lot of underlying information that should be investigated by anyone interested in implementing a SHM system or in developing new or improved sensing capabilities. One place to start such an investigation is by reading section 2, Sensing System Design Considerations for SHM, in the report from Los Alamos National Laboratory describing their workshop on "Energy Harvesting for Structural Health Monitoring Sensor Networks" (Park et. al., 2007). This portion of the report provides a general description of sensor types and capabilities focused on SHM, and some details on a few specific sensor types such as accelerometers, fiber Bragg gratings (FBGs) and PZT sensors.

We've chosen to use a draft revision of the DoD Technology Readiness Levels (TRLs) as listed in Table 1 to characterize the development stages of a sensor system (Graettinger et. al., 2002). Note that this table differs from the standard DoD or NASA TRL list in that it separates hardware/subsystems (HW/S) from software (SW). One major driver for use using the draft version TRLs is because most weapons platforms already have an overall software environment into which SHM software will need to be integrated. Such integration represents a huge effort in software development and testing that would include specified communications protocols for the SHM systems as well as modifications to the platform level software for SHM displays and reports. The effort (and expense) required suggests that early SHM implementations may be best as stand-alone systems. The TRL level table alludes to the software integration effort in the distinction between TRL levels 5 and 6 for software by noting that algorithms run on a processor with "characteristics expected in the operational environment" (TRL 5) as opposed to algorithms run on a "processor of the operational environment" (TRL 6). It should also be noted that the tabulation of sensor systems in Table 2 was focused on hardware status, not software status and does not take into account the preceding discussion.

Sensor Capabilities

Table 2 provides a description of the development levels for a number of systems that sense mechanical parameters using distinctions based on sampling rate. The systems designations were chosen based on distinctions that are often seen at conferences. Conventional systems cover the sensors and sensing approaches that have been used routinely for more than a decade. This includes resistive strain gauges, accelerometers, linear variable displacement transformers (LVDTs), etc. These systems can also be thought of as requiring multiple wire electrical connections and signal conditioning for each sensor. While such systems have a long history of quality measurements, the extensive wiring harness, bulky signal conditioning, and sensitivity to electromagnetic interference make them unlikely candidates for on board SHM. Fiber optic sensors encompass a wide array of types. Here we have focused on multiplexed systems where many sensors can be readily incorporated in a single optical fiber. These include the optical scattering approaches that rely on Rayleigh, Raman, or Brillouin scattering where the fiber itself is the sensor and the limits on multiplexing lie in the time duration of the light pulse or the capabilities of the digitizer (Kersey, 1991). The other main type of fiber optic sensor is the fiber Bragg grating (FBGs) where sensors are manufactured into the fiber at specific locations, with predetermined capabilities such as length and wavelength (Kersey et. al., 1997). There are other types of fiber optic sensors that can be multiplexed such as extrinsic Fabry-Perot interferometers (EFPI), but they are rarely used for structural monitoring. We have not included the interferometric fiber optic sensors, which can offer much higher sensitivities and data rates, but currently require individual demodulation for each sensor resulting in readout hardware that rivals conventional systems in size and weight. Piezoelectric (PZT) strain gauges and accelerometers have been around for decades and thus could fall into the conventional systems category, but it seems more appropriate to include them with the PZT based ultrasonics and impedance methods that are currently being investigated for detecting early stage damage such as sub-millimeter cracks and corrosion since they are rarely used conventionally. We include MEMS as a separate category because while the sensing methods are conventional, the size reductions and possibility of including local digitization can overcome several of the major barriers to real world implementations. As a final category, we include energy harvesting systems. Again, the sensors themselves are based on well known sensing methods: the challenge here is to create a system that eliminates the electrical wires and includes the signal conditioning and digitization in a tiny node using power generated at or near the sensor node. Currently, limits in power generation rates and the power use for radio communications have limited data acquisition/transmission rates to well below 1 Hz.

The horizontal categorization axis was chosen to be data acquisition rate. This choice was based on "conventional wisdom". First, it is widely believed that the length sensitivity of a method scales inversely with frequency. That is, low frequency methods can only detect large amounts of damage while high frequency methods can detect much smaller damage or even possible damage precursors. One way of visualizing this concept is that the length scale of the damage needs to cover a significant portion of the wavelength used for the detection, when the size of the damage is a small fraction (say $< 0.1\%$) of the

wavelength, even interacting with the maximum amplitude region of the detection wave results in minimal signal. The result is no change in the measurement and no detection of damage. Based on this concept, we expect that low frequency methods, and we'll arbitrarily pick 500 Hz for a data rate, should not be considered for many type of damage detection but should work well for loads (fatigue) monitoring, shape sensing, and for modal analysis. Although we will not discuss them here, there is an extensive literature investigating approaches such as tuned excitation, nonlinearity detection, etc. that may provide improved damage detection capabilities while using low frequency systems. Second, as indicated above, the structural information provided by a measurement system depends strongly on the data acquisition rate. The low frequency data critical for fatigue monitoring or global shape sensing in many instances cannot be provided by high frequency systems because they don't offer the high accuracy and long term stability needed for static or quasi-static measurements. Similarly, the kinds of self-calibration required for static measurements preclude the high frequency operations that may provide early damage detection capabilities. In between are measurements of impulsive events such as wave slamming in ships and bird or stone impacts in aircraft that require a moderate frequency response (5 - 20 kHz) when it is important to capture the peak forces accurately. Finally, the upper frequency distinction (<500 kHz vs >1 MHz) comes from the sense that Lamb wave detection focused on the lowest modes (A_0 , and S_0) and acoustic emission work will occur at frequencies below about 500 kHz and that there will be significant hardware and performance differences as frequency capabilities are extended above a Megahertz.

Needs

Because of the DoD-wide push for condition based maintenance (CBM and CBM+), there is strong interest in structural monitoring and automated damage detection on the part of end users. In fact, several weapons platforms that are currently being developed (such as Joint Strike Fighter (JSF) and Littoral Combat Ship (LCS) have structural monitoring requirements. The specifics of how structural monitoring will be implemented is not clear, although in the case of JSF it will include few if any structural sensors and the fatigue monitoring will rely on recorded flight parameters. The lack of clarity in implementation relates strongly to sensor system development and the lack of confidence on the part of program managers and platform developers that appropriate sensor systems have reached an adequate state of development (e.g. hardware $\geq$ TRL 6). Thus, the needs discussion was focused on how to provide convincing evidence of hardware readiness and reliability. The consensus was that there are two critical aspects in demonstrating that a sensor system has reached the maturity needed for inclusion in a weapons platform. These are:

1. Reliable performance must be demonstrated through incremental demonstrations

Once a system has shown strong promise in traditional laboratory tests such as crack growth from an EDM notch on a dogbone test article, impact damage on flat plates, lamb wave detection of holes drilled in plates, etc., it should be tested on structures that are larger and more complex using more realistic types of damage. Examples might be large panels with lap joints and/or stiffeners, curved surfaces, or materials with varying thickness. Analysis methods and sensors should also be tested for temperature sensitivity.

Success at this stage indicates TRL 4-5 depending on the degree of structural complexity and the sophistication of the hardware. It is worth noting that multiple DoD agencies have ongoing SBIR efforts with similar goals.

The next performance stage involves limited field-testing. On the hardware side, this can require dramatic changes in hardware as systems that work well under the ± 2 °C, constant humidity conditions in a laboratory get challenged by cooking for hours in direct sun at 35 °C, experiencing condensing humidity or rain, freezing, dust, etc. In fact, a routine problem in moving from the lab into the field is the difficulty of reading a laptop screen in direct sun. One benefit of limited field-testing is that it keeps costs down by minimizing the amount of time that personnel have to be deployed and the associated travel costs. Following a very successful limited field test hardware can be considered to have reached early TRL 6 and program managers may be willing to consider its use in their efforts.

The final demonstration of hardware readiness is a long-term field test where the system is operated by military personnel with occasional advice/oversight from the developer. The fact that the system must be operated by military personnel makes including automated operating procedures and straightforward user interfaces necessary. A successful long-term field test provides strong support that a system is ready for real-world use and will facilitate the inclusion of said system in the platform development process.

It is strongly recommended that a sensor system developer have successful results from at least one of these types of demonstrations before they approach a program office offering a solution for that particular platform.

2. Performance results must be comparable across sensor systems

Because each sensor system offers specific advantages and drawbacks, it is important that the end users be able to evaluate performance with respect to their specific requirements. Thus, program offices must be able to evaluate system performance demonstrations across multiple sensor systems with respect to problems that are specific to that platform. In the nondestructive evaluation (NDE) world, one way of addressing this issue is through probability of detection (POD) measurements. However, proper POD results in NDE require measurements on large numbers of test samples based on a factorial or partial factorial experimental design (MIL-HDBK-1823, 1999). Such designs would be cost prohibitive in structural monitoring. Thus, the SHM world needs to come up with a comparable approach that is based on statistical testing. Another approach that describes both POD and probability of false alarms (PFA) in a single plot is the receiver operating characteristic (ROC) curve (Swets, 1988). However, again a best practices evaluation would be cost prohibitive. Currently, research is underway looking into combining measurements with modeling (model assisted POD or MAPOD) in an effort to control the costs of POD studies while minimizing any reduction in statistical quality (Thompson, 2001). Solving the problem of getting a statistically valid assessment is a critical step in the acceptance of SHM systems by the DoD.

Another way of providing sensor system comparison is to hold joint demonstrations. Because of the difficulties involved in setting up known and reproducible damage in a complex structure or in conducting field tests, it can be time and cost effective to include

multiple systems in a single round of tests. Since all systems are looking at the same events, performance comparisons are simplified.

Demonstrating System Performance

The emphasis on robust demonstrations of system performance in the last section makes it important that sensor system developers become aware of any upcoming large-scale structure demonstrations so that they can explore the possibilities of piggybacking sensor performance on these tests. Learning about such demonstrations requires knowing the right people and asking the right questions, which is not easy for someone outside of the military R&D structure. It is also possible, usually by collaborating with DoD researchers, to persuade program managers to set up shorter capability demonstrations when they target known problems or desired capabilities.

In the Army and Navy (including the Marines) program offices exist for specific weapon platforms. In the Navy, this means finding the PMA (A for aircraft) or PMS (S for ships) responsible for a particular platform, e.g. the navy's PMA-253 is responsible for developing a new heavy lift helicopter. Navy supporting labs include the Naval Research Laboratory, the Surface Warfare Centers, Undersea Warfare Centers, Naval Air Stations, etc. In general, it is the scientist/engineers at these centers who know what the program offices are interested in and the history of investigated solutions. The Naval Research Lab (NRL) is the navy's basic research lab and while its researchers individually have knowledge and connections with the program offices, those connections are generally not as strong as the Warfare Centers and Air Stations. Similarly, the Army has Research and Development Engineering Centers (RDECs or RDCs) with good connections to the program offices. In the Army, the Army Research Laboratory (ARL) does both basic and applied research with the quality of a researcher's connections to program offices depending on the individual. A system developer's chances of success in getting program office funding are significantly enhanced through working with military scientist/engineers towards solutions that will solve a program office problem. Thus, getting support for a large-scale laboratory or small field demonstrations in the Army or Navy usually requires collaborating with DoD researchers and approaching specific program offices.

In the Air Force, it is the Systems Program Offices (SPOs) overseeing particular platforms that set up large-scale tests. Most of the Air Force's research occurs at the Air Force Research Laboratory (AFRL) with most researchers at Wright-Patterson Air Force Base, near Dayton, OH and a contingent in the Space Vehicles Directorate at Kirkland Air Force Base, near Albuquerque, NM. It is the scientists/engineers at these locations who will be aware of upcoming tests on a case-by-case basis. Mark Derriso at AFRL, Dayton is setting up a large-scale structural health monitoring test bed with the goal of providing a facility where SHM capabilities can be demonstrated and compared. Much of the design and construction of that facility have been completed, but the details of how access will be granted and how funding for such tests will work are still being discussed. Once those are finalized, the information will be broadcast to the SHM community.

Capabilities and Needs Summary

In summary, while it is clear that the military's push toward condition based maintenance has unlocked the door for structural sensing, it is not clear that sensing systems with suitable weight and power characteristics have demonstrated appropriate levels of readiness. The consensus was that there are multiple sensor systems/types that are approaching the readiness levels that can facilitate deployment on military platforms for structural monitoring but that most of these systems need to undergo additional testing to demonstrate capabilities under real-world conditions. It is also clear that both sensor reliability and sensitivity will need to be demonstrated before a system can be accepted.

Sensor systems can be categorized into various types, which we subdivided by data acquisition rates. The data rates are important in structural monitoring because low data rates limit systems to loads monitoring and/or modal analysis, neither of which provide high sensitivity to small amounts of local damage. Intermediate data rates will be needed for impact detection, wave slamming, and other impulsive events. High data rates offer the ability to detect ultrasonic waves, which can be useful for detecting the early stages of damage.

INFORMATION HANDLING

Session Goal

The goal of the Information Handling Session was to identify and discuss critical integrated structural health monitoring (ISHM) challenges in processing data obtained from sensor measurements. Such challenges include storing and retrieving raw data, extracting relevant damage features (converting data into information), processing feature-based information, detecting the presence of damage, and estimating pertinent damage parameters. The Information Handling participants concentrated their discussion on three main issues: data management, data standardization, and data processing architectures.

Data Management

The DoD has multiple health monitoring systems currently deployed, focused largely on the health of engines and drive trains as well as their use. These systems collect vast amounts of data from installed sensors or during scheduled inspections, making data management one of the largest problems in already fielded systems. Data management issues include storage and transmission costs, maintaining data integrity, and adequate processing to convert data to useful information. In a keynote presentation, the Army indicated that it has installed condition-based maintenance (CBM) functionality on 1458 of its 3366 aircraft (Smith, 2010). Specifically, these aircraft were wired for rotor smoothing, drive train health, exceedance monitoring, structural health, engine health, or logbook interfacing. However, the CBM systems are generating terabytes to petabytes of data every month. Storing, translating and processing such large amounts of data is extremely expensive, since current systems have limited onboard processing capability and the data is generally analyzed offline. In addition, since the data changes hands up to twenty-three times between the collection and analysis stages, ensuring data integrity is almost impossible. Finally, the data collected does not always contain useful

information. In order to reduce the cost of data transmission and storage, lossy compression was used as a data management technique. However, much broader data management methodologies need to be used to achieve successful ISHM in real systems in the near future.

The Session participants had several suggestions on how to improve data management in health monitoring. These suggestions include;

- Although high performance computing has been used to solve computational problems such as large-scale matrix inversion using supercomputers and computer clusters, it is now being modified to deal with the new technological demands of data intensive processing. As a result, within the next five years, high performance computing technology may be available to alleviate the data management problems we are facing today.
- There are other research areas that are more mature in dealing with very large data sets than the ISHM area. It would be beneficial to study what methodologies these areas employ in solving their data management problems. Examples of these research areas include monitoring and investigating credit card fraud, data collection and analysis by the US census bureau, and outbreak monitoring by the US Centers for Disease Control (CDC).
- One approach to data management is replacing conventional processing with intelligent processing methodologies. Examples of these methodologies include: (a) using compressive sampling, instead of conventional sampling, to reduce the amount of data collected by the sensors; (b) devising techniques to intelligently discard the unimportant data before transmission; (c) developing data fusion techniques when multiple sensors are used; (d) employing adaptive processing to learn/gain knowledge from past data in order to improve future knowledge; (e) automating the system to reduce the need for large data sets and more importantly removing multiple human interactions (and thus multiple sources of error due to data handling).

Data Standardization

Currently, there is no process for developing and agreeing upon technical standards in the area of health monitoring. The lack of a common data interface is a challenge that current systems are facing, and the diversity in data collection platforms and data formats makes comparison difficult. As a result, it would be good to have a steering committee or working group that can recommend or design a standard data format. For example, this would help us learn not to collect data that was not useful and collect new types of data that could provide new or more meaningful information. The structural health monitoring community has a working group called the Aerospace Industrial Steering Committee (AISC) that is already looking into various other implementation issues. Data standardization might also be included under their auspices. In addition, session participants suggested that we should investigate data standardization practices in other, more mature, research areas.

Data Processing Architectures

It is important that ISHM methodologies, algorithms, and standards developed today remain compatible with the expected advancements in hardware configurations. In particular, algorithmic solutions need to be proposed that will take into consideration possible architectures that will be available in the future to implement those solutions. The hardware five years from now, built for dealing with large amounts of data, can be quite different from what we current have available. Also, advanced algorithms and software must be designed to take advantage of new hardware configurations. Note that a significant body of work exists for non-ISHM systems that could be adapted for use in ISHM systems. There are many applications where tools have already been developed to deal with large amounts of data with efficiency and speed. That experience should be drawn upon and used for guidance. We are currently capable of identifying only 5-10% of failure modes using CBM; the target for the next five years is to increase that number to 90%.

IMPLEMENTATION ISSUES OF CURRENT RESEARCH

The discussions on implementation issues focused around three main topics, each summarized below. During the discussion an additional topic was mentioned, the definition of implementation. Numerous ideas for an appropriate definition were discussed. These include: 1) Implementation occurs when an SHM system reaches TRL 8. 2) A system is implemented only when it is used on multiple aircraft, ships, or ground vehicles. 3) Implementation is when the system has been institutionalized e.g. maintenance credit established. Suffice it to say that SHM implementation can only occur when it is technologically mature and being utilized as an integral part of a larger system. The following discussion topics and ideas address issues associated with the implementation of SHM.

Risks of SHM Implementation

In general there are two major sources of risk in implementing any new system. These are: 1) the maturity and reliability of the technology, and 2) the programmatic risk associated with the cost and schedule for integrating the technology into the final system.

In order to address risks associated with maturity and reliability, iterative approaches are needed to incrementally demonstrate the technology. While this is true and small demonstrations are positive, to convince decision makers, step change demos are needed to truly show the maturity and reliability of SHM systems. The Army's CBM program, to collect and analyze rotorcraft vibration data, has shown the value of health monitoring for a few applications. High confidence in reliability and effectiveness is needed in addressing all the important failure modes. If some important failure modes are left out, it may not be worth the investment. The use of mature and reliable SHM provides an opportunity to reduce safety factors and therefore system weight. The weight and space

requirements of an SHM system are likely to be a risk as many military platforms are already weight/space constrained.

In order to overcome the programmatic risks, there must be a push and/or pull for the technology and it needs to be clearly shown that SHM can reduce the maintenance burden. Push and/or pull needs to come from generals, maintainers etc. One of the main reasons to implement SHM is to reduce the maintenance burden, which in turn can reduce life cycle cost. Evidence of the life cycle cost reduction and push/pull for the technology may be able to convince program managers that the cost and schedule risk associated with SHM are manageable.

Transition from Traditional Maintenance to Health Monitoring-logistics Plan

Logistics plans will be critical to transition from traditional maintenance procedures to health monitoring based maintenance procedures. One important aspect of the transition will be the need to work more closely with maintainers. During the transition phase it may be necessary to have the two maintenance approaches working in parallel. In addition, modifications to maintenance contracts and manuals will be needed. In order for a full transition to occur, policy changes will be required for the logistics infrastructure.

Existing Systems and Platforms Amenable for Demonstration to Ease Integration

Successful demonstrations are very important if implementation of SHM is to occur. Two basic approaches to demos have been attempted. One approach is to instrument numerous platforms and take data, the amount of which can be very large. The data can then be analyzed by various methods to determine if anomalies are present. It was pointed out that for this approach to be successful management of expectations is critical, i.e. success criteria must be defined in advance. Previous large-scale demos have failed due to ill-defined success criteria. The second approach is to utilize smaller iterative demos to build up to a successful full-scale demonstration system. Both approaches can be valuable. For example, the C-17 has been targeted for a potential demonstration platform and funding avenues are being explored by the Air Force. The C-17 demo is planned to be more like the first approach, that is; instrument, collect, analyze data, and learn as you go. It was also suggested that corrosion detection and unmanned aerial vehicles (UAVs) may be good areas for demonstrations. Other important aspects discussed included a central repository for test results, cooperation among DoD laboratories, and "marketing" of SHM technology.

Conclusion

For SHM to be implemented, i.e. institutionalized with logistics and maintenance plans and maintenance credits, push from maintainers and/or pull from high ranking officials will be needed along with a change in the maintenance culture. The push/pull is not likely without successful iterative small-scale demos in addition to large-scale data intensive demos. It is critical for these demos to have well defined success criteria, a central repository for demonstration results, and cooperation between the DoD labs.

PERFORMANCE VALIDATION AND CERTIFICATION

The session discussion was focused on methods for the validation and certification of candidate systems and the identification of a process for transitioning research to practice. It was recognized that researchers would have to understand the real-world challenges and needs of the application and to communicate and work closely with the end-users. It is critical that the research be coupled with the requirements.

It was suggested that it would be better to proceed in small steps and first demonstrate the advantage of the proposed approach on a specific component. For example, while ageing aircraft are a current problem of high interest, there are currently no standard test specimens on representative structures. The Federal Aviation Administration (FAA) has standard NDE test specimens. While there are no standard specimens within the military, outer wing panel tests have been used upon request. Mark Derriso of the Air Force Research Laboratory (AFRL) is working on the development of a standard test bed.

The real proof of validation for justifying implementation would be to demonstrate that the method meets current performance requirements on an actual structure, with a building block process that considers variability issues of real data and provides quantitative results (e. g. a probability of detection study for the FAA). It was pointed out that some organizations such as the FAA could be in a good position to validate the capabilities of a test system.

A comparison would also be required with existing methods. One example of an existing system is the Health and Usage Monitoring System (HUMS) developed for use as a diagnostic tool for rotating machinery (Moorman, 2010). However, based on maximum flight loads instead of probabilistic loads, the HUMS system is not FAA certified and does not fit currently with the Navy's needs. Nevertheless, HUMS is an existing health monitoring system that is being implemented and can serve as a model for other candidate systems. Indeed, it should be pointed out that the Navy does have some HUMS systems and is evaluating their performance and use.

A full qualification plan and cost-benefit analysis is required before the proposed condition based maintenance method can be fully adopted. To be feasible, the health monitoring framework, which includes installation, use, and maintenance, must be cheaper than replacing parts! To complete validation, a handbook, such as MIL-HDBK-1823 (1999) is required that provides guidance (not standards) to users.

Contacting the appropriate agency is a step toward demonstrating advantage and feasibility. Each service has a certification/qualification team, for example, the Aeronautical Systems Center (ASC) for the Air Force and the System Program Office (SPO) for the Navy. However, this step is necessary only after multiple successful demonstrations and is likely to be overseen by the program office.

COST BENEFIT ANALYSIS

The scope and context for the Cost Benefit Analysis session was to consider attributes for a CBM approach to health management. The session participants explored the following three questions to help focus the discussion:

- What is cost and benefit?
- Are cost benefit studies beneficial?
- What limits the use of cost benefit studies?

What are Costs and Benefits?

There was a consensus that Business Case Analysis (BCA) language should be used to describe value because the term “cost” is often associated only with direct dollar savings. Using BCA language better implies the inclusion of measures that are difficult to characterize in terms of dollars such as increased reliability or reduced unscheduled maintenance. It was indicated that the aircraft structural integrity program (ASIP) descriptions of CBM would provide good insight and direction for specifically defining costs and benefits as part of a BCA. Other industries quantify measures that are not directly related to dollars and the SHM community may be able to leverage this knowledge to quantify various non-cost performance measures for DoD or any SHM applications. It was agreed that it is important to talk to the customer in a language that they use. For instance, Cost Effectiveness Analysis (CEA) is the term used in the propulsion technology area. Using the customers’ language may help answer the question of how to estimate value for benefits that are difficult to quantify. It was agreed that the level and application should be identified to determine whether the use of SHM systems is beneficial or not. It was also pointed out that the SHM community should look at other programs where automated monitoring technologies are being used, for example, programs that include rotating machinery or HUMS systems. The structural monitoring community can learn from those experiences about how they performed a BCA.

Are Cost Benefit Studies Beneficial?

The general consensus was that a BCA would be required in order to persuade maintainers and program managers to advocate for new SHM technologies. BCA should be part of an overall trade study approach. If the magnitudes are uncertain, but consistent across options, then the relative differences can be used to down-select specific options for increased development and analysis. The presentation made by Chris Smith of the Army appeared to demonstrate a BCA (Smith, 2010), and it would be useful to take a closer look at what has been implemented by the Army. Investigating BCA cases about how SHM technologies could be used to manage an airplane past its design limit is of particular interest to the Navy perspective. The AFRL Hot Spot program was suggested as an opportunity where a BCA could be demonstrated in the context of an application under study.

What Limits the Use of Cost Benefit Studies?

Many agreed that much of the SHM community’s advertised/projected capabilities have not been sufficiently proven. Thus it would be very helpful to demonstrate capability first

using programs such as the aging aircraft. Acquisition programs will set requirements, but until proven in the field, the requirements will have limited insight for success. It was indicated by many participants that the approach for program integration and business case demonstration should focus on taking incremental steps through small demonstrators. Demonstrations should prove capability, and a BCA should be part of the process. The SHM community needs to clearly identify all the possible benefits associated with new SHM technologies and aggressively evaluate potential value regardless of the readiness of the technology. This would provide the incentive for development and application. Since specific applications provide limited value in a larger context, it was suggested that the use of a few representative business case examples extrapolated across an entire weapons platform could provide a more aggregate business case assessment. It should be noted in making a business case that the complete elimination of false calls is not necessary. What is required is that false negatives be eliminated. False positives, on the other hand, can be tolerated to the point that the business case fails. Finally, it was pointed out that the SHM community needs a good success story with demonstrated benefits. At that point, other DoD programs will start to request their own versions of the system and ask for added capabilities. Such a success will ease making a business case for other SHM systems.

SUMMARY

Overall, it should come as no surprise that there is considerable interest in SHM within the DoD as all services spend a significant fraction of their annual budgets on maintenance and support. However, it is also true that for every DoD platform both already deployed and under development, there is fierce competition for space on the vehicle in terms of weight, size, added capabilities, and cost. Thus, the wide spread transition of SHM technology to DoD platforms will take many years. However, it is starting to happen and there will be opportunities to solve specific problems in the near future. Finding these opportunities requires talking various DoD people including weapons systems program management, R & D program management, and individual researchers.

In the meantime, there are particular steps in the development process that system developers need to understand and handle carefully. These include:

- 1) Knowing the appropriate language and this includes a realistic assessment of TRL levels.
- 2) Demonstrated success in testing on appropriately complex structures certainly in the lab and probably under field conditions.
- 3) Careful evaluation of capabilities, costs, and benefits including some sense of how the benefits will be achieved. The consensus was that Business Case Analysis offers a better approach than a straight Cost Benefit Analysis.
- 4) Understanding the needs and restrictions for each platform and how the proposed system would fit into the maintenance regime.

Having quality responses ready for these topics puts a developer in position to approach program officials with a higher likelihood of success.

The authors and workshop attendees acknowledge that there is not a single path to success. However, we feel that taking into account the discussions and recommendations described in this article will help facilitate the transition of SHM from the lab into full acceptance.

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Table Captions

Table 1: Proposed technology readiness levels (TRLs) for the DoD including software.

Table 2: Development levels for a number of systems that sense mechanical parameters based on sampling rate criteria.

Technology Readiness Level	Description
1. Basic principles observed and reported	HW/S: Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties. SW: Lowest level of software readiness. Basic research begins to be translated into applied research and development. Examples might include a concept that can be implemented in software or analytic studies of an algorithm's basic properties.
2. Technology concept and/or application formulated	HW/S/SW: Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3. Analytical and experimental critical function and/or characteristic proof of concept	HW/S: Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. SW: Active research and development is initiated. This includes analytical studies to produce code that validates analytical predictions of separate software elements of the technology. Examples include software components that are not yet integrated or representative but satisfy an operational need. Algorithms run on a surrogate processor in a laboratory environment.
4. Component and/or breadboard validation in laboratory environment	HW/S: Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of ad hoc hardware in the laboratory. SW: Basic software components are integrated to establish that they will work together. They are relatively primitive with regard to efficiency and reliability compared to the eventual system. System software architecture development initiated to include interoperability, reliability, maintainability, extensibility, scalability, and security issues. software integrated with simulated current/legacy elements as appropriate.
5. Component and/or breadboard validation in relevant environment	HW/S: Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include high fidelity laboratory integration of components. SW: Reliability of software ensemble increases significantly. The basic software components are integrated with reasonably realistic supporting elements so that it can be tested in a simulated environment. Examples include high fidelity laboratory integration of software components. System software architecture established. Algorithms run on a processor(s) with characteristics expected in the operational environment. Software releases are Alpha versions and configuration control is initiated. Verification, Validation, and Accreditation (VV&A) initiated.

6. System/subsystem model or prototype demonstration in a relevant environment	HW/S: Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment. SW: Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in software demonstrated readiness. Examples include testing a prototype in a live/virtual experiment or in a simulated operational environment. Algorithms run on processor of the operational environment are integrated with actual external entities. Software releases are Beta versions and configuration controlled. Software support structure is in development. VV&A is in process.
7. System prototype demonstration in an operational environment	HW/S: Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft. SW: Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in a command post or air/ground vehicle. Algorithms run on processor of the operational environment are integrated with actual external entities. Software support structure is in place. Software releases are in distinct versions. Frequency and severity of software deficiency reports do not significantly degrade functionality or performance. VV&A completed.
8. Actual system completed and qualified through test and demonstration	HW/S: Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications. SW: Software has been demonstrated to work in its final form and under expected conditions. In most cases, this TRL represents the end of system development. Examples include test and evaluation of the software in its intended system to determine if it meets design specifications. Software releases are production versions and configuration controlled, in a secure environment. Software deficiencies are rapidly resolved through support infrastructure.
9. Actual system proven through successful mission operations	HW/S: Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions. SW: Actual application of the software in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last bug fixing aspects of the system development. Examples include using the system under operational mission conditions. Software releases are production versions and configuration controlled. Frequency and severity of software deficiencies are at a minimum.

Table 1.

Data Rate uses	< 1Hz Shape Loads Mode	< 500 Hz Shape Loads Mode	< 20 kHz Impacts	< 500 kHz Lamb waves Acoustic Emission	≥ 1 MHz Ultrasonic waves Acoustic Emission
Sensor type					
Conventional (strain, acceleration, deflection)	TRL 9	TRL 9	TRL 7	TRL 5 - 7	?
Multiplexed FBGs*	TRL 5 - 9	TRL 5 - 6	TRL 3 - 6	TRL 3 - 4	N/A
Other multiplexed Fiber Optic Sensors* (scattering, EFPI, etc.)	TRL 5 - 7	TRL 4 - 7	?	?	?
MEMS	TRL 5 - 7	TRL 5 - 7	TRL 3 - 4	?	?
PZT	TRL 6 - 9	TRL 6	TRL 6	TRL 5	TRL 3 - 5
Wireless	TRL 3 - 5	TRL 3 - 5	N/A	N/A	N/A
Energy Harvesting	TRL 3 - 5	N/A	N/A	N/A	N/A

Table 2.