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Prognostics and Health Management (PHM) / Condition Based Maintenance (CBM)

Dennis Hoffman
Email: d.hoffman@ieee.org

PHM Overview

What is it?

- **Diagnostics** – is the process of determining the state / ability of an item to perform its function(s)
- **Prognostics** – is predictive diagnostics which includes determining the remaining life or the time span of proper operation of an item
- **Health Management** – is the capability to make appropriate decisions about operational use / system configuration and maintenance actions based on diagnostics / prognostics information, available resources, and operational demand.

Facets of PHM

- Fault Detection
- Fault Isolation
- Advanced Diagnostics
- Prognostics / Condition-Based Maintenance
- Useful Life Remaining Predictions
- Component Life Tracking
- Performance Degradation Trending
- Selective Fault Reporting
  - Only tells operator what NEEDS to be known immediately
  - Informs Maintenance of the rest
- Aids in Decision Making and Resource Management (Operation and Maintenance)
- Fault Accommodation – Reconfiguration, Operational Execution
- Information Reasoners

Goals of PHM

- Enhance System Availability, Mission Reliability, and Safety
- Reduce Maintenance Manpower, Spares, and Repair Costs
- Eliminate Scheduled Inspections
- Condition-Based Removals vs. Time-Based Removals
- Maximize Lead Time For Maintenance and Parts Procurement
- Automatically Isolate Faults
- Eliminate / Minimize False Alarms, CNDs (could not duplicate), and RTOKs (retest OK)
- Provide Real Time Notification of an Upcoming Maintenance Event
- Catch Potentially Catastrophic Failures Before They Occur
- Detect Incipient Faults and Monitor Until Just Prior to Failure
- Opportunistic Maintenance To Reduce Down Time

PHM Implementation

- The ability to monitor has been around for a long time, but now we have the technology to really do something with it.
  - Ability to Predict Future Health Status
  - Ability to Anticipate Problems and Required Maint Actions

    - Advanced Heuristics / Algorithms / Processing Power
- Evolution of Diagnostic Capabilities Coupled with the Added Functions, Capabilities, and Benefits offered by New Technologies
    - Maximize Benefit from Limited Specialized Sensors
    - Take Max Advantage of the “Smart” Digital End Products
- PHM is Designed into the End Product
- Reaches across the entire Product – System of Systems Architecture and Design
- New Technologies are being Researched and being Released
- Hardware and Software Utilized for Implementation

Prognostics and Health Management

Prognostics and Health Management is an advancing field that is finding broader and broader uses to monitor and to provide early indications of pending system failure. An example of this broader acceptance and appeal was a segment of the TV program, Wired Science, focusing on structural monitoring. Their segment covered two areas of structural monitoring: bridges and aircraft airframes. Articles covered by the show and posted on the PBS Wired Science web site are provided below (under Structural Monitoring) as well as the web site addresses.

Structural Monitoring

Getting Structures to Inspect Themselves

Every man-made structure can fail. And when we're talking about something like a bridge or an airplane, the results can be catastrophic – like the I-35 bridge that collapsed in Minnesota last August. Because bridges are inspected at regular intervals, that sort of structural failure is extremely rare. But what if they were smart enough to monitor themselves and sound a warning before they were stressed through their limits? It may be possible, thanks to a technology called "structural health monitoring", which involves placing sensors inside a structure that can communicate its vital signs to inspectors. A rigid structure grows weaker every time it flexes or stretches. Each time a vehicle passes over a bridge, the structure vibrates, straining some parts. When this stress cycle weakens a structure beyond its endurance limit, the result is one of the biggest threats to the structural health of planes and bridges: metal fatigue. Visual inspections can spot fatigue after a bridge passes its endurance limit. But permanent sensors can monitor the amount of stress before the structure reaches that limit. That frees up inspecting agencies' limited resources to focus only on the bridges that actually need attention. A wireless system built by a company called **Microstrain** lets civil engineers monitor bridges via the Internet, using technology originally developed for smart knee implants. Sandia National Laboratories is **developing similar technology** to keep tabs on aircraft. That could be a boost for passenger safety, as well as the airline industry's bottom line, as taking a plane out of service for inspection costs them $100,000 a day. Engineers see a day when such sensors will be hidden in everything from trains and trucks to ships and buildings – tiny sentinels working around the clock to prevent disasters.

Figure 1 In the back of a commuter jet used as a testbed at Sandia, Dennis Roach and Ciji Nelson examine piezoelectric sensors placed on a printed circuit board for mounting to an aircraft structure.[1]

Sensors may monitor aircraft for defects continuously, see Figure 1

Networks of sensors mounted on commercial aircraft might one day check continuously for the formation of structural defects, possibly reducing or eliminating scheduled aircraft inspections. Like nerve endings in a human body, in situ sensors offer levels of vigilance and sensitivity to problems that periodic checkups cannot, says Dennis Roach, who leads a Sandia National Laboratories team evaluating some of the first sensor systems for aircraft. "With sensors continually checking for the first signs of wear and tear, you can restrict your maintenance efforts to when you need human intervention," he says. Structural health monitoring, or SHM, techniques are gaining the support of airframe manufacturers, airlines, and regulators, he says. SHM incorporates into the aircraft structure itself nondestructive inspection (NDI) technologies currently used in manual inspections – to scan for small cracks in the airframe, for example. Such inspections are strictly regulated to maintain a high degree of aircraft safety. Widespread adoption of SHM could significantly reduce maintenance and repair expenses for commercial aircraft, now estimated at about a quarter of the fleet's operating costs, says Roach. Those costs are rising as the aircraft age, many well beyond their design lifetimes. Ground crew technicians might plug a laptop or diagnostic station into a central port on the aircraft to download structural health data. Eventually "smart structures" fitted with many sensors could self-diagnose and signal an operator when repairs are needed. Ultimately an integrated network of sensors could monitor not only structural elements, but also the health of electronics, hydraulics, avionics, and other systems.

Extension of NDI

The SHM sensors being developed or evaluated at Sandia can find fatigue damage, hidden cracks in hard-to-reach locations, disbonded joints, erosion, impact damage, and corrosion, among other defects commonly encountered in aging aircraft. The work is an extension of Sandia's Airworthiness Assurance Program, which for years has focused on development and evaluation of NDI (nondestructive inspection) technologies to aid human inspectors as they go over an aircraft frame or fuselage skin inch by inch looking for the consequences of aging. Boeing's recent incorporation of an in situ, or permanently-mounted, crack-detection sensor into its NDI standard practices manual for Boeing airframes is the first time a manufacturer has adopted SHM (structural health monitoring) techniques – evidence that the industry is ready to consider new ways of ensuring the safety of aircraft beyond NDI-assisted human inspection, says Roach. Several other commercial airlines working with Sandia are considering SHM applications and are working with Boeing and the Federal Aviation Administration (FAA) to use embedded crack

[1] (Photo by Randy Montoya) Download 300dpi JPEG image, "vacuum.jpg," 6.5MB (Media are welcome to download/publish this image with related news stories.)

detection sensors to address specific maintenance requirements. “When we set out to do NDI, in the back of our minds we knew that eventually we wanted to create smart structures that ‘phone home’ when repairs are needed or when the remaining fatigue life drops below acceptable levels,” he says. “This is a huge step in the evolution of NDI.”

Growing demand

“Sandia is part of a group formed in November 2006 – the Aerospace Industry Steering Committee for Structural Health Monitoring – to address the growing demand from the aerospace industry for standardized procedures and certification requirements for SHM. The international group includes manufacturers, regulators, government agencies, the military, universities, and Sandia. The Sandia team already has developed or evaluated several types of inexpensive, reliable sensors that can be mounted on aircraft structures, typically where flaws are expected to form. “If I usually get fatigue damage in this area above a door, that’s where I am going to install a crack detection sensor,” Roach says. One promising SHM sensor, a Comparative Vacuum Monitoring (CVM) sensor, is a thin, self-adhesive rubber patch, ranging from dime- to credit-card-sized, that detects cracks in the underlying material. The rubber is laser-etched with rows of tiny, interconnected channels or galleries, to which air pressure is applied. Any propagating crack under the sensor breaches the galleries and the resulting change in pressure is monitored. The sensors – manufactured by Structural Monitoring Systems, Inc. (SMS) – are inexpensive, reliable, durable, and easy to apply, says Roach. More important, they provide equal or better sensitivity than is achievable with conventional inspection methods, he says. The CVM sensors were tested in a lab and validated on three commercial aircraft beginning in April 2005. Boeing’s inclusion of CVM technology in its Common Methods NDI Manual, an aviation industry first for NDI, is the culmination of a comprehensive, two-year validation program by Sandia in cooperation with the FAA, Boeing, SMS, a number of US airlines, and the University of Arizona. Work on additional applications for Southwest, Northwest, and Delta Airlines is underway. Sandia also is developing or evaluating a variety of other sensor systems. Technologies being considered include flexible eddy-current arrays, capacitive micromachined ultrasonic transducers, piezoelectric transducers that can interrogate materials over long distances, acoustic emission sensors, embedded fiber optics, nickel strip magnetostrictive sensors, and conducting paint whose resistance changes when cracks form underneath SHM techniques also could monitor the structural well-being of spacecraft, weapons, rail cars, bridges, oil recovery equipment, buildings, armored vehicles, ships, wind turbines, nuclear power plants, and fuel tanks in hydrogen vehicles, Roach says. Sandia already is applying SHM to a variety of structures. “There is recognition that SHM’s time has come, an opinion you would not have heard from many people a few years ago,” says Roach.

Figure 2 Dennis Roach with a Comparative Vacuum Monitoring (CVM) device showing galleries etched into the sensor's underside.[2]

PHM Professional Organizations

IEEE Reliability Society

The IEEE Reliability Society is the IEEE's home for Specialty Engineering disciplines such as PHM Engineers. The Reliability Society has within its Technical Operations a Committee focusing on all aspects of PHM and encompassing all the broad disciplines required to make PHM implementation successful.

Society for Machinery Failure Prevention Technology

The Society for Machinery Failure Prevention Technology (MFPT) was formed to gain understanding of the processes of mechanical failures and to devise methods of accurately predicting mechanical failures. The Society was organized under the leadership and sponsorship of the Office of Naval Research as the Mechanical Failures Prevention Group (MFPG). The MFPG was formed primarily as a mechanism for effective interchange of technical information among segments of the scientific and engineering communities in order to gain a better understanding of the processes of mechanical failures. The anticipated result was to reduce the incidence of mechanical failures by improving design methodology, to devise methods of accurately predicting mechanical failures, and to apply the increased knowledge of the field to current problems. Improved reliability, greater safety, and economic savings were among the obvious goals to be achieved through a better understanding of mechanical failures. The original objectives continue to form the basis for the activities of the current MFPT Society Technical Committees.

PHM Conferences

New PHM Conference

The IEEE Reliability Society (RS) has established and will sponsor its first International Conference on Prognostics and Health Management in October 2008 (Marriott Tech Center,

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[2] (Photo by Randy Montoya) Download 300dpi JPEG image, "circuit2.jpg," 8.5MB (Media are welcome to download/publish this image with related news stories.)

Denver, Colorado, October 6-9, 2008, http://www.phmconf.org). Many of current conferences only had a track associated with PHM, focus only a a segment of PHM, or are very aerospace oriented. The Reliability Society's PHM Conference will be an annual conference focusing on all aspects of PHM and emcompassing all the displines, suppliers, and researchers necessary for PHM to be successful. The Reliability Society's PHM Conference is intended for researchers, R&D engineers, and managers working in this emerging interdisciplinary field. The primary objectives of the conference are to:

- Deliberate and establish the scientific methodologies for PHM research
- Foster collaboration and communication between academic, government, and industry PHM communities across the globe
- Identify innovative business approaches that utilize PHM methods and findings.

The RS PHM Conference will create a sociable and professional environment for the participants to connect with researchers in the field, forge new relationships, and deepen existing ones. This conference covers a broad range of research and application topics:

- **Principles:**
  - Physics of failure
  - Software failures
  - Sensors
  - Structural sensing
  - Health management system design and engineering
  - Modeling and Simulation

- **Methods:**
  - Data-driven methods for anomaly detection, diagnosis, and prognosis
  - Model-based methods for fault detection, diagnostics, and prognosis
  - Standards and methodologies
  - Automated reconfiguration
  - Verification, validation, and maturation
  - Component-level PHM
  - Software health management
  - PHM for electronics
  - Structural health management

- **Results:**
  - Innovative applications
  - Industrial applications
  - Informed logistics
  - Lessons Learned from PHM systems design and integration
  - Systems and platform applications
  - Component-level prognostic results

The RS PHM Conference features keynote presentations by senior leaders in the field, panel discussions, and a full day of tutorials free to all registrants. Leading companies and research institutions exhibit their products and demonstrate their technologies during the event. A unique feature of the RS' first PHM conference is the PHM Challenge, featuring cash prizes and open to everyone in the field. Winners of the PHM Challenge will be invited to present their methods and results in a special session. Author submitted papers are refereed by experts in the field based on the criteria of originality, significance, quality, and clarity and the conference proceedings will be published on CD for conference attendees, and in IEEE *Xplore*®.

European Conference with Special Session on PHM

FLINS 2008, Madrid, Spain, September 21-24, 2008, Special session on soft computing methods for diagnostics and prognostics: Many efforts have been devoted in recent years to the development of techniques for system health monitoring, fault diagnosis, and prognosis in a joint intent to rationally improve the safety and economic performance of existing and future plants and processes. To these purposes, innovative computational techniques are being used with increasing frequency due to their ability of capturing the complex nonlinear relationships of systems and processes from possibly uncertain and ambiguous information contained in the available real-world data. This session aims at gathering experts and collecting their contributions with regards to the innovative computational techniques for 'on line' monitoring and real time fault diagnosis and prognosis.

Other PHM Conferences

- Reliability And Maintainability Sysmposium (RAMS) – 3 PHM Sessions (partial day)
- IEEE AESS Aerospace Conference – PHM Track
- Symposium on Prognostics and Health Management, MIRCE Akademy, UK (2 days)
- SPIE (International Society for Optical Engineering) Component and Systems Diagnostics, Prognosis, and Health Management Track (2 days)
- Japan Electronics and Information Technology Industries Association (JEITA), CALCE – Prognostics and Health Management Consortium, and Yokohama National University's Conference on Prognostics and Reliability (1 day)
- AFRL Integrated Systems Health Management Conference
- NDIA (National Defense Industrial Association), Systems Engineering Division Annual Conference – Sessions on Integrated Diagnostics / PHM, R&M, Logistics
- IEEE AutoTestcon

PHM Research Centers

- U of MD CALCE specific "PHM Center"
- Georgia Tech, University of Minnesota, and Northwestern University's Multi-University Center for Integrated Diagnostics
- Penn State Applied Research Laboratory
- Sandia PHM Center of Excellence
- Government Labs: AFRL, NAVAIR, NASA