

Predicting and Preventing Machine Failures

FEATURE

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The military and industry look to prognostics and health-management systems to increase safety and cut costs

New advances in sensor technology and failure analysis are instigating a revolution in the way large electromechanical systems such as aircraft, helicopters, ships, power plants, and many industrial operations will be maintained in the future. For industry and the armed

services, the 21st century will bring the age of PHM—prognostics and health-management systems.

In times past, one spoke of fault diagnostics, the detection of an existing problem or failure in a system in order to correct it. Today's advances are raising the bar toward machine prognostics, where failure modes and the remaining life of a system can be predicted. This breakthrough promises not only more efficient operations and reduced maintenance costs, but also the saving of lives. Both industry and the military have shown an interest in this emerging technology. In fact, the U.S. Department of Defense plans to incorporate a full-scale PHM system into its newest tactical aircraft, the Joint Strike Fighter (JSF) (background figure).

The JSF program will develop a family of multirole strike fighters for the Navy, Air Force, Marine Corps, and U.S. allies. According to William Scheuren, who heads both the JSF's PHM program and corresponding

efforts at the Defense Advanced Research Projects Agency, constructing this aircraft will reduce costs of engineering, manufacturing, maintenance, and repair, and costs for procurement, operations, and support.

A multiyear, \$2.2 billion JSF concept demonstration program began in November 1996 with the award of contracts to Boeing and Lockheed Martin. In a competition for the final contract, each will build and fly a prototype JSF, an aircraft on which a sizeable effort is under way to reduce risk and life-cycle costs. The emphasis is on technologies with high potential payoff in affordability, maintenance, survival, and offensive power. Prognostics is one of these technologies.

What is PHM?

Machine prognostics essentially involves taking data from sensors and probes that are placed on various system components to record specific parameters, and feeding these data into a computer program so that potential system faults and failures can be identified, tracked, and predicted. The aim of prognostics is to stop disabling or fatal failures before they happen. Before such a program can be devised, however, the data associated with various system parameters—recorded as failure occurs—must be thoroughly analyzed to understand the physics of each failure (Figure 1).

Thus, the concept of prognostics goes beyond diagnostics, in which the sensor data are simply monitored for the occurrence of anomalies or failures that are then corrected (Figure 2). The prognostics process is analogous to the way physicians deal with medical problems. First the problem is detected; then a diagnosis is made about the failure mode and its severity. It is also important to predict the evolution of the failure in order to estimate the remaining useful life of the machine (Figure 3).

Sounds wonderful, but can it work? That's what the JSF program will determine by using numerous simulations, tests, and demonstrations, according to Scheuren. However, evidence from industry already supports the benefits of prognostics technology. For example, the Electric Power Research Institute (EPRI) has successfully demonstrated and proved the use of diagnostic technology at its Eddystone Station fossil-fuel power plant outside Philadelphia. Since the 1987 installation of a dual-purpose vibration monitor and rotor-crack detector for bearing wear at the plant, EPRI says it has saved \$250,000 in costs for teardown of machinery.

"Anticipating failures long before they occur is going to be a key part of the electric utility's planning of oper-

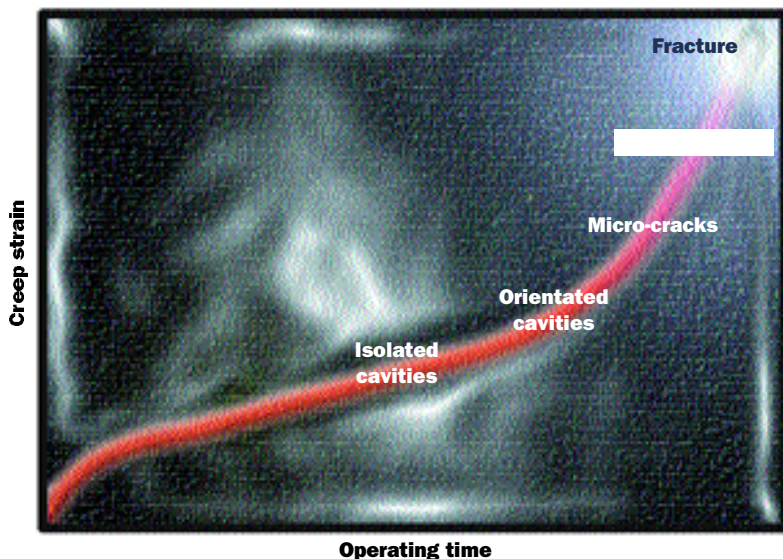


Figure 1. A leading cause of metal cracking is creep—time-dependent deformation at high temperature. This progression can be monitored at the metal's surface to help predict failure.

ating and maintenance (O&M) strategies in the future,” says Vis Viswanathan, EPRI’s senior manager for material applications. Pressure to cut O&M and capital costs in the emerging deregulated market will drive the industry increasingly toward predictive “early warning” systems, he says.

PHM strives to advance monitoring by drawing on maturing diagnostics technologies to develop the power to predict forthcoming failures. PHM may seem to be at odds with today’s consumer mentality of discarding items if they cannot be repaired for less than \$100. However, particularly for large-scale systems, PHM is about predicting and preventing failures so that expensive equipment does not destroy itself or need to be discarded. If one does ultimately decide to junk an item, having more data on the faults found (diagnostics) and life expectancy (prognostics) can only help. The goal of PHM is to reduce the current reliance on diagnostic sensors, which already exist in many industrial systems, in favor of intelligent systems that correlate the data from these sensors and use it to make predictions.

Lower cost, increased efficiency

Among the varied potential applications of prognostics are the prediction of surface fatigue faults in rolling element bearings, cracking in turbine engine blades or in helicopter rotors, and shorts in induction motors. While the initial costs of engineering such PHM systems might be substantial, proponents of prognostics say costs can soon be recovered through increased reliability and fewer unexpected failures. Such gains have been substantiated through the use of diagnostic and simple predictive maintenance practices in nuclear and fossil-fuel power plants.

A 1990 EPRI study cited an estimate that one-third of the money spent on preventive maintenance in the electric power industry (which that year amounted to \$60 billion) was wasted. EPRI lists a nominal power plant maintenance cost of \$17 to \$18 per hp-year for corrective maintenance, \$11 to \$13 for preventive maintenance, and \$7 to \$9 for predictive maintenance. Projected cost savings of 50% are not unreasonable in industry, although this figure may not hold true for military operations.

In 1988, Technology for Energy Corp. surveyed more than 500 power, pulp and paper, metal, food processing, and textile plants worldwide that used condition-based maintenance, an anomaly-detection approach without a prognostics capability. The results of that sur-

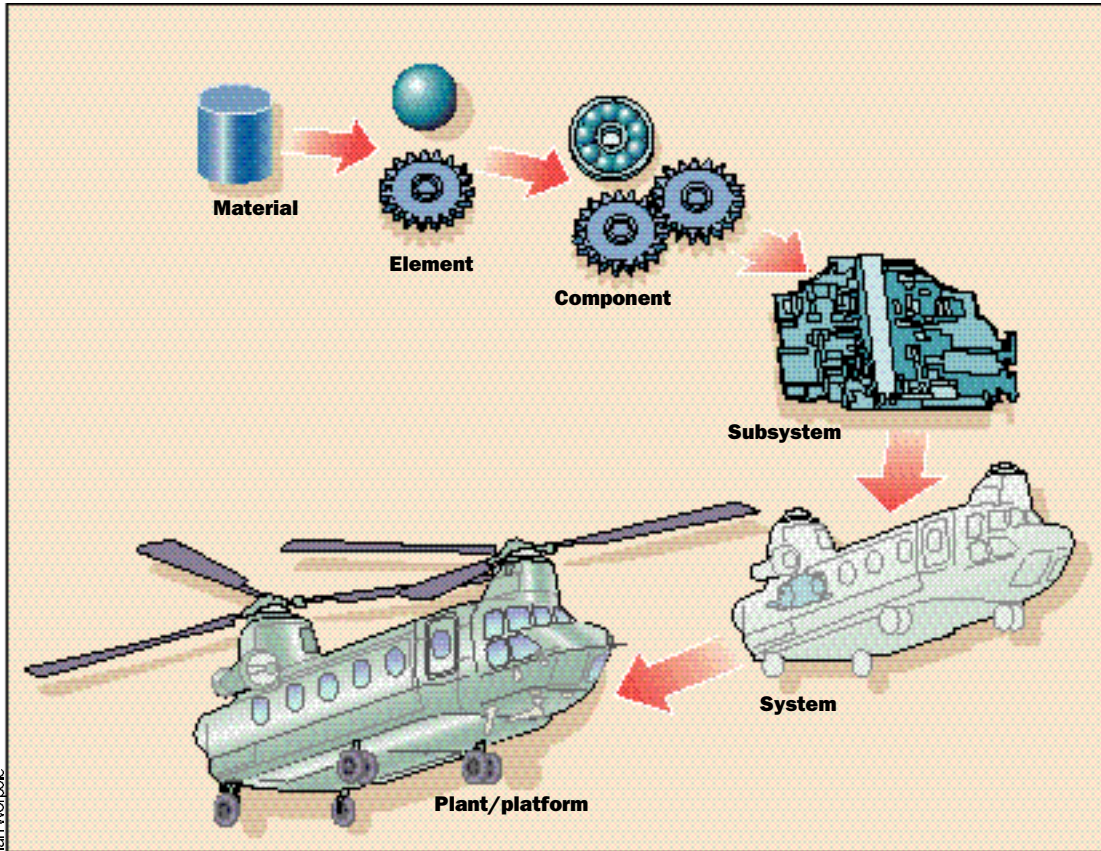
vey showed a 50% to 80% reduction in repair costs, a 50% to 80% reduction in maintenance costs, a greater than 30% reduction in spare parts inventory, and a 20% to 60% increase in overall plant profitability over a three-year period. Such evidence strongly supports the argument that PHM is going to prove cost-effective and pay for itself with an acceptable rate of return on the capital invested.

Improvements in PHM through the development of better sensors and more effective algorithms will provide more lead time to respond to evolving failures. In addition, PHM will bring the benefits of increased safety and operational efficiency, reduction in lost operational hours, lower maintenance costs, decreased likelihood of secondary damage from failing system components, reduced inventory requirements, extended subcomponent life, and improved product quality.

A more fully developed PHM capability will enable one to better gauge when an impending system failure is acceptable, and when it isn’t. From a pilot’s viewpoint, Scheuren suggests, such decisions are critical, as living with failure often equates to ending up under a tombstone, especially in a single-engine aircraft like the JSF. The same holds true for industry, where some failures may take lives and cost millions of dollars.

In addition, better developed PHM systems will help us judge when redundancy is needed in a system, by determining which mission-critical or flight-critical systems need backup. PHM systems will also help us more reliably decide when to switch to a redundant system, if one exists, by providing more accurate mechanisms for detecting and predicting impending failures.

Both the fundamental science and overall operational or economic issues underlying PHM are being studied in research centers such as the Condition-Based Maintenance Department at Pennsylvania State University’s Applied Research Laboratory, the University of Tennessee’s Maintenance and Reliability Center, and NASA’s Jet Propulsion Laboratory (JPL). “In order to reduce operations and manpower requirements and increase overall system reliability, our focus at JPL has been on extremely compact, on-board health and status summarization systems for our vehicles, to increase our ability to predict failure,” says Sandeep Gulati of JPL’s Ultracomputing Group. “We’re interested in fully autonomous and compact diagnostic and prognostic systems—because of our resource-constrained environments onboard spacecraft—yet in systems that can handle a great deal of complexity.”



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Figure 2. Six-layer hierarchy for integrated predictive diagnostics gives a systems perspective on how machines fail. Although mission demands are made at the top level, failure is initiated at the lowest level.

PHM takes to the air

Companies such as General Dynamics Advanced Technology Systems, General Electric, Lockheed, and Boeing are already incorporating some machine prognostic technology into their programs. Of these, the largest program aimed at using a fully integrated prognostic and health-management system is the JSF. The Department of Defense envisions production of 2,400 to 3,000 aircraft. The JSF's PHM program is predicated on technological advances in several areas, including sensing, modeling that predicts the behavior of systems, the ability to fuse data gathered by many sensors, and development of the automated-reasoning algorithms necessary to make meaningful predictions.

Sensors, for example, are becoming increasingly self-calibrating, and their sensing capabilities have been augmented by microelectromechanical systems (MEMS), which enable better detection and diagnosis of faults. MEMS, which have brought about the development of miniaturized versions of almost every kind of working device in the macroworld, are used in many of the sensors used in JSF's prognostics system. Only a few micrometers in size, MEMS devices can serve as motors, pumps, resonators, actuators, and sensors. They are already used to align optical components; in wireless communications; and as pressure sensors, fluid-flow sensors, magnetic sensors, and accelerometers (see *The Industrial Physicist*, 9/98, pp. 39-43; pp. 46-47). MEMS

are typically built with the same materials and lithographic techniques used in making integrated circuits, and they are sensitive to such minute changes as about 10 Å for displacements and 5 piconewtons for force. MEMS can function with higher frequencies and bandwidths than larger devices, and can be placed in environmentally stressed locations, such as jet engines, for example.

At General Dynamics Advanced Technology Systems (GDATS), formerly a division of Lucent Technologies, researchers have developed a sensor system for detecting unwanted deflections and vibrations in gas-turbine engine

blades using an eddy current sensor. "This sensor, about the same diameter as a pencil, is placed in the turbine casing, and generates a balanced magnetic field that is disturbed as the metal blade tip passes through it," reports GDATS' Jerry Mulholland, program manager for active structural control. "The change in magnetic flux indicates blade tip time-of-arrival and clearance. Blade tip motion provides insight into blade vibration, which in turn allows for detection and avoidance of resonant response, foreign-object damage detection, blade damage identification, and assessment of the structural life of the blade."

Another key prognostics component is the acquisition of data over time so that the sensed signals can be associated with the corresponding failure modes. Gathering this data often involves using seeded or inserted faults, such as cutting a notch in a gear tooth to simulate a crack, for example. In addition, a thorough understanding of transitional data—that is, the patterns of events that occur in various systems components from their initial state through failure—will enable computer tracking and prediction of the evolution of failure modes. Such understanding will lead to more robust diagnosis and prediction of machinery failures.

The JSF PHM technology maturation program will also make use of intelligent computer algorithms, such as artificial neural networks (ANNs), wavelets, and fuzzy logic. These algorithms can be trained to recognize and predict system anomalies and trends.

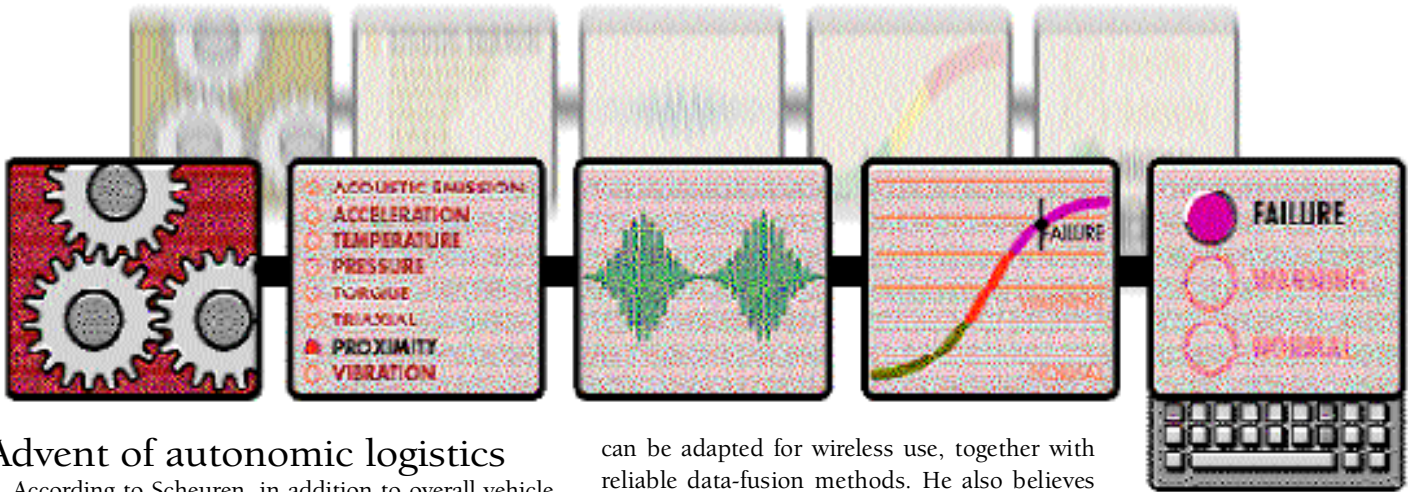


Figure 3. Prognostics and health-management systems involve machinery, advanced sensors, diagnostics, predictive algorithms, and the human interface.

Advent of autonomic logistics

According to Scheuren, in addition to overall vehicle health, a goal of PHM is to enable what the JSF program calls autonomic logistics, which is an intelligent global network that can learn from experience and new data. It is a total knowledge-based logistics system that identifies and communicates appropriate JSF maintenance, supply, engineering, safety, and training actions to support mission execution. It is described as autonomic because it will automatically trigger what it considers appropriate actions within the system unless told otherwise by its human controllers; this process is somewhat akin to the involuntary reactions, such as breathing, brought about by the autonomic nervous system in living organisms.


Because both the individual-aircraft PHM and the fleetwide logistics operations will include intelligent systems, autonomic logistics will eventually predict impending failures accurately and indicate the need to replace parts just before they might fail. During the JSF concept demonstration phase, tests will be conducted on prototype JSF aircraft parts. The test results, where applicable, will be used to train ANNs and help define failure modes. For example, the JSF Program Office has contracted with the primary and alternate engine companies, Pratt & Whitney and General Electric, to conduct forced-fault experiments. In these tests, problems such as compressor blade cracks and actual blade failures will be introduced in order to check the predictive accuracy of the PHM hardware and software. Where funding and scheduling permit, the maturing hardware and software will also be included on the JSF demonstrator aircraft.

In Scheuren's view, the ultimate objective of PHM and its related autonomic logistics system is to reduce maintenance manpower requirements by approximately 20% to 40%, increase combat sorties by 25%, and reduce the complexity of the logistics trail by 50%, compared to current military strike aircraft.

Extensive challenges still exist for machine prognostics, both on the JSF and in general. For Scheuren, the challenge is to obtain small, inexpensive sensors that

can be adapted for wireless use, together with reliable data-fusion methods. He also believes that reasoning algorithms must be made more robust. For example, ANNs for prognostics can often be trained but do not always perform well when tested because, for example, the data used for training is not uniform or mathematically well behaved.

A further challenge for prognostics is to perfect the ability to fully identify and track failure precursors in various system components. This requires a database of continuous transitional data from a fully functioning state to a failed state. To date, this data has not been readily available. For prognostic algorithms to be qualified and validated, such a database of failure progressions under controlled and fully documented conditions is needed. Once the experimental transitional data is obtained, however, there remains the need to validate it in the field and to incorporate a number of external effects, such as varying environmental conditions, into the algorithms.

This sort of failure data, together with ongoing advances in sensors, failure models, and data-fusion and predictive techniques, holds the promise for putting this revolutionary new technology on a sound scientific footing. It will serve as the basis for prognostics and vehicle health management in the JSF and promises widespread use in industry. 

B I O G R A P H Y

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