An Innovative Approach for Affordable Prognostics Health Management in Aircraft

Sonia Vohnout, Kenneth Blemel, and James Hofmeister

***Abstract*—Prognostics-enablement of electronic systems, subsystems, and components involves acquisition and processing of multiple data and sensor inputs. Data collection and fusion creates an accurate prognostic prediction. To that end, Ridgetop Group and Management Sciences, Inc. (MSI) propose an innovative and affordable approach using "smart connectors" and an intermittency detection sensor. A framework for real-time health monitoring without the need for additional "black box" instrumentation, special software, or costly data collection is proposed. The authors describe how using inexpensive wireless micro-instruments packaged into aerospace connectors can be used to monitor the health of aircraft components.**

This paper also describes an extensible architecture for a Prognostics Health Management (PHM) system providing State of Health (SoH) and Remaining Useful Life (RUL) metrics. The key enabler is the Ridgetop Sentinel Network™, which collects SoH information wirelessly from distributed "smart connectors" in the aircraft.

***Index Terms*—Condition-Based Maintenance, Health Management, Prognostics, Sensors**

I. Introduction

EMBEDDED Instrumentation (EI) is needed to monitor the health status of structures, avionics, fuel, wiring, landing, and other systems in aging aircraft. In this paper we describe how a set of connectors, each made with a microprocessor, forms a new class of EI for addition to aircraft.

The most pervasive subsystem within any aircraft is the wiring subsystem. The wiring reaches into almost every deep corner. Wiring typically "gets no respect," yet it is critical to the functioning of the total system. By gathering and processing information flowing on the vehicle wiring system, the overall health and status of the vehicle components, including the wiring system itself, can be assessed.

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Furthermore, by connecting sensors to the wiring harness, additional status and health information can be obtained about both structural and electronic components.

Traditionally, prognostics or predictive diagnostics have used observations of measurements to develop a prediction of impending failure of the observed system. In some cases, a precursor or "signature" event is directly measured. In other cases, multivariate inputs are necessary to determine the precursor event, along with the fault-to-failure progression model.

This form of prognostics is "passive," somewhat like watching a cigarette smoker develop a cough and loss of lung capacity, which is the signature of emphysema. Once the diagnosis is made, a prediction (prognostic) is that the smoker has a few years to live. It is intuitive that detecting the causal factor (smoking) with cessation of smoking would lead to a dramatically improved prognostic.

Prognostics methodologies embedded in "smart connectors" can extract stressor signatures and other precursor information from sensors located in prognostics-enabled printed circuit boards (PCBs) across the aircraft. These methodologies detect evidence of causal factors (poor input voltage) that, left unattended, will result in (predicted) failures. The prognostics methodologies also provide support to Condition-Based Maintenance (CBM) and Autonomic Logistics Systems (ALS).

Embedded instrumentation (EI) for real-time flight operations is becoming ever more important to identify the stressors, current health, and operational capability of aging aircraft equipment. Over the past few years there has been increasing interest in extending the traditional statistical analyses used for diagnostics in the traditional sense to using sensor data for detecting stressors in real time. However, there will still be a place for statistical analysis because not all important health parameters can be obtained directly from sensors. Many "state of health" parameters can only be inferred indirectly from other evidence such as operating hours, temperature, vibration signatures, and other pertinent stress data [1].

The need for timely diagnostics and prognostics is continuing, but the cost to implement on-aircraft data collection keeps growing as third-party developers propose the use of hardware and software to implement solutions that invariably include installing on-board sensors as data sources, as well as adding wiring, digitizers, and memory for data collection, plus radios or data ports for offloading collected data, and data analysis centers.

The value proposition of an EI system is to provide early detection that enables a lower-cost corrective action by preempting a higher-cost situation. To be cost-effective, any diagnostic system must itself be affordable as well as worthwhile. The affordability of data offload and analysis is a major factor in determining return on investment. The cost of a data center and support staff is one reason a simplistic sensor-based approach with offload of data to data centers for statistical analysis has not gained favor, as these programs suffer from high personnel infrastructure costs, resulting in a poor return on investment.

II. Sensor-Focused Approaches

The adoption of electronic prognostics requires monitoring the stressors and the behavior of key components in a system. Stressors can be measured with commercial off-the-shelf (COTS) sensors. Behavior can be monitored with sensors such as Ridgetop's SJ BIST™, which detects faults in Field Programmable Gate Arrays (FPGAs) housed in Ball Grid Array packages [2]; or with Ridgetop's RingDown™, a non-intrusive sensor to monitor degradation on power systems [3]. An example board is shown in Figure 1. After prognostic-enabling the PCB, data can be extracted and linked to a central node where it is collected and processed.

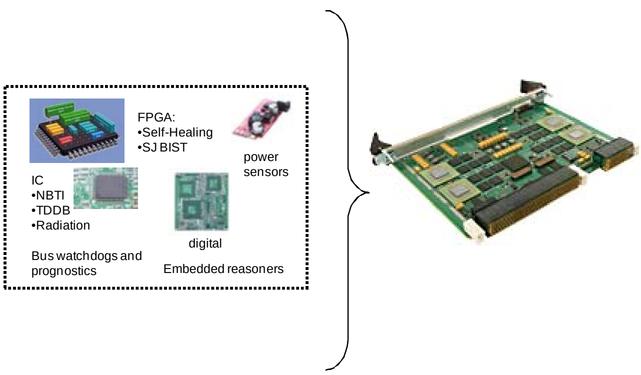

Figure 1. Printed circuit boards (PCBs) or modules can be "prognostic-enabled" by using sensors that employ physics-of-failure methods.

Another approach is to use prognostic-enabled PCBs in addition to EI in "smart connectors", where the sensors and the prognostic capabilities are part of the circuitry of the connector, as depicted in Figure 2.

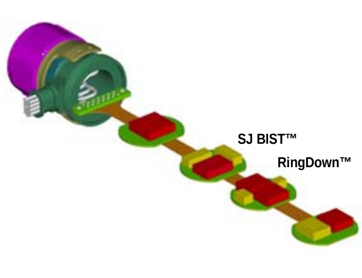

Figure 2. Circuitry added to the back shell of a wiring connector.

A properly configured, on-board, prognostic-enabled system [4]:

- Continuously monitors State-of-Health (SoH) during operation.
- Extracts prognostic information from modules to provide remaining useful life (RUL) indication.
- Reduces overall test costs with improved observability of faults.
- Improves fault coverage through dedicated prognostic circuitry added to "smart connectors".
- Supports invocation of remote diagnostics.
- Collects data and manages geographically dispersed assets with full information on the SoH and RUL from a central collection point linked to the on-board prognostics sensor.

With prognostics capabilities now extended to both stressors and embedded electronic modules, the acquisition of system information must be assembled in a hierarchical manner, assessing the effects of stressors as well as the failure rates for subassemblies within the modules – and determining the modules' SoH and RUL from a wide range of observations, prognostic sensors, and algorithms.

This information fits into a taxonomy consisting of diagnostics, prognostics, and system-level Integrated Vehicle Health Management (IVHM). In order to provide a versatile analysis platform, the system architecture should be intuitive, easy to use, and simple to interface to other applications. Unlike systems developed for the mechanical world of turbines and engines, this architecture is optimized for electronic systems. This includes short time constants, non-monotonic component degradation, and intermittencies.

Using Electronic Prognostics with Embedded Instrumentation and Health Management offers the following benefits:

- Instant determination of the electronic module's SoH.
- Prediction of the electronic module's RUL.
- Advance notice of impending failures.
- Integration with the supply chain through ALS.

III. Smart Connectors and Intermittency Detection

The Embeddable Programmable Instrumentation Circuit (EPIC) - A "Smart Connector"

As with any complex, highly automated machinery, wiring harnesses reach into all (or nearly all) compartments of an aircraft. The ubiquitous nature of wiring makes it an ideal source for placing some of the data collection and processing infrastructure. With weight on wheels, the distilled information can be offloaded from various sectors in the aircraft to an on-board or off-board Internet web site for transfer to a central computer such as an ALS.

The Embeddable Programmable Instrumentation Circuit (EPIC™, Figure 3) is a 32-bit processor that includes 64 megabits of local memory and also USB and Ethernet ports, wireless communication, and support for gigabits of memory.

Figure 3. The one-ounce Embeddable Programmable Instrumentation Circuit (EPIC).

The tiny EPIC has been architected to be a low-power hybrid computer with analog inputs, digital processor, analog outputs, and digital outputs. MSI has demonstrated that the minuscule EPIC is a viable solution that can be placed inside a specially constructed mil-spec connector forming a conduit for proactive diagnostics and prognostics. Being embedded, the EPIC can collect and process the stressors and the behavior of the electronics and send the results to the pilot or to maintainers, as well as to a data center.

SJ BIST™ - Solder Joint Intermittency Fault Detection

SJ BIST (Solder Joint Built-in Self-Test™) is an innovative sensing method for detecting cracking or faults in solder balls used in Ball Grid Array (BGA) packages that are part of Field Programmable Gate Arrays (FPGAs). FPGAs, such as the XILINX® FG1156, are widely used as controllers in aerospace applications. The ability to detect faults in solder-joint networks increases fault coverage and health management capabilities and support for condition-based and reliability-centered maintenance. As both the pitch between the solder balls of the solder joints in these BGA packages and the diameter of the solder balls decrease, the importance a real-time solder-joint fault sensor for FPGAs increases. As an embedded IP softcore programmed into the FPGA, SJ BIST is the first known solution for detecting high-resistance faults in solder joint networks of operational FPGAs [5].

SJ BIST correctly detects and reports instances of high-resistance with no false alarms. Test results are shown in this paper. The program for the test boards contains temporary data collection routines for statistical analysis and uses less than 250 cells out of more than 78,000 cells for a 5-million gate, 1156-pin FPGA, to test 8 pins.

Rigorous testing indicates SJ BIST is capable of detecting high-resistance faults of 100 or lower and which last one-half of a clock period or longer. In addition to producing no false alarms in the current period of testing, no additional failure mechanisms are introduced to an assembly because, with the exception of fault reporting and handling, SJ BIST is (1) not invasive to an application program; (2) is not computer-intensive, so timing problems are not anticipated; and (3) any failure in SJ BIST itself is a failure in the FPGA or the board. Therefore, either a real failure is reported or no failure is reported, and neither is a false alarm.

SJ BIST is a useful sensor for mitigating troublesome intermittencies and can be combined with a smart connector such as the EPIC to provide a comprehensive solution for interconnects. Early detection of problems allows the user to replace modules or connectors before subsequent fatigue damage causes an application to fail, and therefore intermittent operational anomalies are avoided.

IV. An Electronic Prognostic Analysis System Platform

Ridgetop's Sentinel Network™ architecture [4], as illustrated in Figure 4, supports the prognostics-enablement of a network of distributed assets using wireless transmission technology (through a network of smart connectors such as the EPIC shown in the red-dashed box in Figure 4) and a centralized collection point for examining the individual assets' State of Health and Remaining Useful Life. This approach supports CBM strategies, reducing the cost of maintaining these systems across a widely dispersed area, improving the overall "up-time" of these assets, and equipping service personnel with correct sets of replacement parts and diagnostic tools to rapidly repair or maintain the systems.

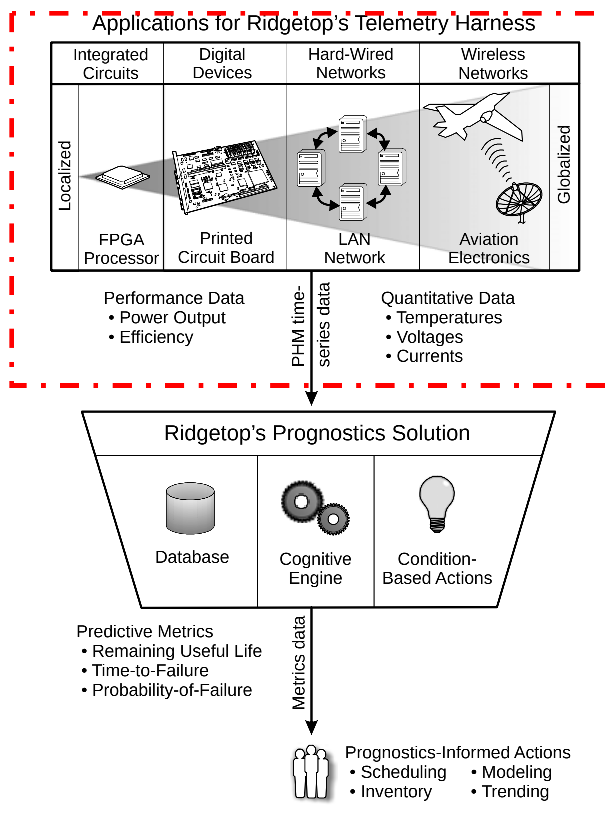

Figure 4. Application, scalability, and process flow of Ridgetop's telemetry harness and Sentinel Network™.

Figure 5 illustrates a multilevel architecture of subsystems and components. Health monitoring occurs at several levels, from IC die-level to system-level. For example, an actuator system might consist of power sources, characterized actuator (at various levels of model abstraction), and loads. Each element has its own hierarchically modeled subsystems using an underlying, structured, XML approach.

Data Acquisition and Storage

Ridgetop's electronic prognostics solution provides the ability to store sensor data and applies algorithms to make RUL predictions for on-board electronic systems, subsystems, and components. Through the collection and analysis of time series data, the system monitors quantitative metrics associated with physical variables, performance variables, and various quality-of-service metrics.

In the deployed system, it is advantageous to obtain information as quickly as possible, so a real-time link with the deployed system is a powerful benefit. This link can be via satellite, land-line, or wireless connection to the central collection point. With the system SoH data, ground support personnel will know exactly what spare parts are needed to maintain a high level of operational readiness. Through the use of "smart connectors" like the EPIC, we can download the information that is being strategically collected through our network of connectors in the aircraft wiring harnesses.

EPIC processors distributed in wiring harness connectors form an adaptive cognitive proactive network. In a new aircraft, the set of EPIC processors can be connected via the aircraft data bus. In a legacy aircraft, the EPIC can be connected with a wireless transceiver like Zigbee or Bluetooth.

As shown in Figure 4, field data is statistically analyzed at the data center by a cognitive engine to make assessments for condition-based actions. By its nature, the central data center uses "on the average" statistical models. It is intuitive that "on the average" methods with a fixed ontology lack the ability to include all parameters. Further, some parameters can be extremely important, such as lightning strikes and high thermal conditions experienced by aircraft during equatorial flight operations.

The EPIC uses standard Internet protocols to publish stressor data, behavior signatures, and updated parameters and structure to the central repository. When new models are developed at the central data center, the EPIC receives the updated models using Internet protocols.

When used to the ultimate, the EPIC, with its Sentient Reasoning engine, is proactive. When abnormal stressors such as high heat, loss of a hermetic seal, or low supply voltages happen, the Sentient Reasoner can be programmed to publish a warning to the operators and maintainers as well as the data center.

At the data center, data is stored in a hierarchical structure (see Figure 5). An XML-type (Extensible Markup Language) software architecture offers these levels of abstraction as well as compliance with MIMOSA standards. A simple example for an avionics actuator can be represented as a system with subsystems and individual components with XML that is imported into a database platform and used for further diagnostics and prognostics support.

Cognitive Layer or Engine

The cognitive layer (see Figure 4) at the data center provides the necessary fault trend analysis and recommends maintenance actions to the scheduler. An easy-to-use interface with domain experts in the field provides support for engineering changes and equipment recommendations. The primary functions include performing fault isolation via more enhanced diagnostics, prognostic assessments, health management, false alarm mitigation, and data trending. The interface supports optimized maintenance planning and better class-wide management capabilities. Overall, PHM and fault trending analysis reduces total maintenance costs and increases the reliability of in-service actuators.

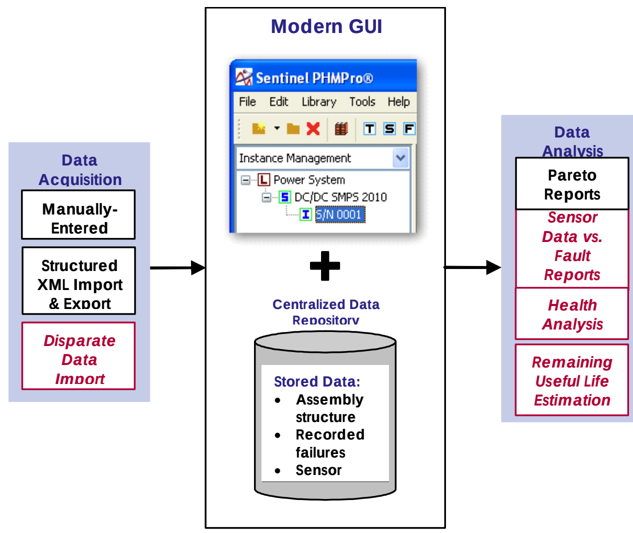

Figure 5. Architectural view showing a power system at the top level.

A key benefit of Ridgetop's Sentinel Network™ is the use of collected information to calculate system RUL. There are several techniques employed for such estimates including: analysis of actual operands and measurands; existing diagnostic output vectors; prognostic sensors; and "canaries." Data from this constellation of inputs are collected and fused. Algorithms yield composite estimates of system health at a particular level within the system hierarchy. The algorithms available include adaptive model-based reasoners, Bayesian network reasoners, and others. With a platform available for quick analysis, various options can be explored.

Unlike the Cognitive Engine at the central data center, the EPIC processors employ a plastic Sentient Reasoner, a Turing complete cognitive inference calculus for making diagnostics and prognostics.

Unlike traditional fixed models, the Sentient Reasoner is plastic and employs machine learning of parameters and structure that are used to continually improve the accuracy of the inference model. Being cognitive, the calculus learns to understand the effects of such stressors as temperature excursions and electrical load, which shorten the remaining useful life. From the prognostic view, the predictive estimate is specific to the stressors and loads expected to be experienced in upcoming operations.

For example, at the board and module levels, a Built-in Self-Test (BIST) identifies and isolates faults, as well as providing predictive capability of impending failures. This data is immediately interpreted by the Sentient Reasoning in the EPIC. Emphasis is placed on reducing false alarms and identifying prognostic techniques to anticipate system degradation and allow automated recovery. This prognostic approach provides an accurate picture of forthcoming faults and component degradation – the predictive indicators of failure – and is extremely useful to the crew. The solution also allows timely action needed to avoid costly or catastrophic damage to critical Line Replaceable Units (LRUs) and to maintain availability/readiness rates for weapon systems.

The Sentient Reasoner is entering service on the USMC AV-8B Harrier fighter and is within weeks of being ready for flight testing in the F/A-18. In the case of the AV-8B, the Sentient Reasoner issues alerts that warn the pilot not to take off, or to return to base. Should catastrophic damage to flight-critical LRUs occur, the Sentient Reasoner provides an immediate alarm to the pilot. In the case of non-flight-critical damage, the diagnostic is delivered to the flight line.

During maintenance and inspections the network of EPICs provides wireless communication to assist in tests and troubleshooting.

After maintenance or overhauls the wireless feature of the EPIC can send messages regarding assurance of return to baselines.

V. Summary

An innovative method of detecting faults in interconnects has been presented. Data collected by major aerospace and automotive firms confirm the efficacy of the sensors. The combination of Smart Connector from MSI and SJ BIST from Ridgetop offers a unique solution to difficult prognostic applications.

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BIOGRAPHY

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Sonia Vohnout is Systems Engineer at Ridgetop Group, Inc. She earned her B.S. degree in Computer Science from the University of Costa Rica, and B.S. and M.S. degrees in Systems Engineering from the University of Arizona. In the past she has worked for Modular Mining, IBM and AT&T Bell Laboratories. She previously owned and operated a manufacturing facility in Mexico. She is an expert modeler and has extensive expertise in software and computer systems. Ms. Vohnout has more than 20 years of experience in systems engineering, quality systems management, and business development and management.

Kenneth Blemel

Kenneth Blemel is a co-founder and Vice President of R&D for Management Sciences, Inc. Ken has successfully guided MSI research and development in IR&D, BAA, and over fifteen SBIR, and STTR contracts. Ken is recognized for seminal work in developing "Smart Connectors" and "Smart Wiring Systems" for embedded diagnostics and prognostics. Ken holds several patents including electronic hardware and methods for electronic microsystems used for implementing wiring-based tests and diagnostics. Mr. Blemel has published many technical papers and has participated in several panels, most in the area of software and embedded systems for reliability, maintainability, and logistics. In 1987 he was awarded the Best Technical Paper of the 41st Quality Congress of the American Society of Quality Control. He has a B.S. degree in Applied Mathematics (Engineering) from the University of Cincinnati, and an M.S. in Applied Mathematics (Engineering) from the University of Rochester, NY.

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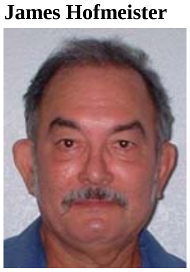

James Hofmeister is a senior principal engineer and engineering manager. He has been a software developer, designer and architect for IBM and represented IBM as a member of the board of directors of the Southern Arizona Center for Software Excellence. At Ridgetop Group, he is a principal investigator and lead design engineer, specializing in analog and digital circuit designs for electronic prognostics. He is a co-author on six patents (5 IBM and 1 Ridgetop) and five other pending Ridgetop patents. He retired from IBM in 1998 after a 30-year career and joined Ridgetop Group in 2003. He received a B.S. degree in electrical engineering from the University of Hawai'i, Manoa Campus, and a M.S. degree in electrical and computer engineering from the University of Arizona.