A Low Cost Embedded Instrumentation (EI) Framework for Vehicle Health Management Systems (VHMS)

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Abstract—This paper presents an overview of emerging technology components that in combination form a low cost embedded computing infrastructure and framework for embedded instrumentation (EI) for VHMS. The paper will present how the EI technology adds Real Time - VHMS with very low weight (or even weight savings) in legacy and new air, ground and sea platforms.

First the authors will describe the need, customer requirements, and benefits for adding EI for VHMS to old and new platforms. Next the authors will describe the barriers often encountered by developers of current EI VHMS concepts. i.e., safety issues, software development, installation and use certification, data analysis, support centers and life cycle cost.

Next the authors will present how these barriers are being overcome with an initial application for ground vehicles using the new EI architecture to provide real-time VHMS.

Next the authors will present how a well constructed general purpose EI framework can be defined that reduces development time and minimizes installed weight as well addressing other issues. The authors will explain its open architecture with features such as user defined real-time data collection, data storage, custom analyses, and publish/ subscribe environment that accommodates updates, messages, alerts and offloading.

Finally, the paper will end with examples of snap-in connectors and designed in "smart wiring" based approaches that have been developed with MDA Airborne Laser, Army, and Navy funding. This technology is being advanced to field testing on Army ground vehicles to pave the way for application to military and commercial aircraft. [1][2]

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1. INTRODUCTION

Embedded Instrumentation (EI) has been around for a considerable time, but has recently emerged with a new emphasis on extended functionality and life cycle support of the embedding system. This paper describes a new class of EI being developed for addition to existing systems, as well as for design into new systems, to implement advanced Vehicle Health Management Systems.

The largest and most pervasive subsystem within any vehicle or other system is the wiring subsystem. The wiring subsystem typically "gets no respect," yet is critical to the functioning of the total system. Wiring faults can account for almost half of the system faults in an aging system. Additionally, these wiring faults can increase the ambiguity associated with other potential faults making troubleshooting difficult and increasing the likelihood of false failures. By accessing information available on the vehicle wiring system, the overall health and status of the vehicle components, as well as the wiring system itself, can be assessed.

Additionally, if other sensors (e.g., fiber optic based sensors) can be embedded into the wiring harness, then additional status and health information about the vehicle can be obtained. For example, a simple fiber woven into the overbraid of a cable can be pulsed periodically. Assuming the wiring integrity has not been breached, then the return pulse will be normal. Should a chaffing situation be occurring, the fiber will be broken or severely degraded so that the chaffing actions can be identified and corrected. Similarly, a wiring bundle that is routed through a sump area can include a graded index fiber that becomes highly lossy when in the presence of liquids. Such a sensor would identify a leak or contamination.

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[1] 1-4244-1488-1/08/$25.00 ©2008 IEEE.
[2] IEEEAC paper #1494, Version 1, Updated 2007:12:19

2. BACKGROUND

Embedded instrumentation (EI) for real time monitoring, diagnostics and prognostics is becoming ever more important to network centric operations as a means for enabling commanders to query the current health and operational capability of equipment. The need is multiplied for unmanned vehicles and lightly manned ships. EI is not a new concept, it has been around for thousands of years. Egyptian hieroglyphics tell that one of the earliest examples of EI was the use of caged myna birds in underground water channels along the Nile to announce the annual flood.

Diagnostics and Prognostics

Diagnostics and prognostics have a different meaning to different people and are often confused. Diagnostics for troops operating Army vehicles means warning or "idiot lights" that tell when an event has happened. The definition of "prognostic" varies. For most, a prognostic is a warning that something probably will happen, for example that a water pump is wearing out and likely to fail soon. The automobile industry considers a low fuel light a prognostic. Historically the diagnoses are based on changes in measurements of operational capability and significant changes in signatures such as shaft vibration or rate of cooling which exceed a threshold value.

Over the past few years there has been increasing interest in extending the traditional statistical analyses for diagnostics using sensor data. One reason for this interest is that not all important health parameters can be obtained directly from sensors. Many "state of health" parameters can only be inferred indirectly from other evidence. Inference models can incorporate data such as operating hours, temperature, vibration signatures, and other pertinent data. [1]

For prognostics, modeling and simulation techniques can make a probabilistic estimate of the remaining life of components such as thrust bearings and other rotating components. However the remaining useful life of such components is also a function of applied stresses. There is a new interest in mission prognostics which apply the historical and expected stress factors of an upcoming mission into the prognostic model. For example, mission prognostics for components in the engine and power train would rely on probabilistic models based on prior mission experience information plus an assessment of expected mission stresses based upon the mission planning. With this approach, the current state of degradation can be modeled with the stresses expected during upcoming mission operating conditions to determine the probability of mission success.

Barriers

The need for timely diagnostics and prognostics is continuing, but the costs to implement D&P keeps growing as agencies and contractors begin to understand the costs of software. Early programs included the Navy Helicopter Usage Monitoring System program and the USMC Advanced Logistics System for ground vehicles. The solutions invariably include installing on-board sensors as data sources; wiring, digitizers and recorders memory for data collection; radios or data ports for offloading collected data, and off-vehicle statistical data analysis.

The value proposition of a diagnostic system is to provide early detection that enables a lower cost corrective action by preempting a higher cost situation. Cost can be in any metric such as safety, productivity, maintenance, operational downtime and replacement costs. To be cost effective, any diagnostic system must itself be worthwhile. The simplistic sensor based approach with offload of data to data centers for analyses has not gained favor because these programs suffer from high infrastructure costs, long procurement cycles, and a poor return on investment.

Getting EI into service is a function of cost, technology readiness, weight, and reliability as well as gaining approvals or certification for the installation. Weight is a concern because increased weight implies increased fuel consumption, reduced operating range, and additional system stresses. Reliability is a concern because unreliable EI would need more maintenance and spare parts, driving up life cycle costs. Approvals are needed because of safety requirements and other factors such as meeting electrical magnetic interference (EMI) limits. It is intuitive that adding EI to an aircraft requires extensive testing and certification. However, the path to adding EI to ground vehicles lacks the "gravity effect", and cost and weight become the limiting constraints.

Recent efforts

The Joint Strike Fighter (JSF) program was one of the first with requirements for a systemic Air Vehicle Instrumentation System (AVIS). The JSF AVIS was initially proposed as a flight data recorder with offload to a data center for analysis. However, JSF wanted more than flight data collection of built in test and mission parameters. A Broad Agency Announcement (BAA) solicited concepts that would cut life cycle costs.

3. THE "SMART WIRING" CONCEPT

As with any aircraft or complex highly automated machinery, the JSF wiring harnesses reach into all (or nearly all) compartments. The ubiquitous nature of wiring makes it an ideal source for providing the infrastructure for adding sensors, processors and data bus communications for various sectors in the aircraft to the AVIS central computer. If the weight of new components for EI did not adversely affect the system, then considerable gains in system performance could be made.

About the same time, miniature Micro-Electro Mechanical Systems (MEMS) like the automobile air-bag chip came on the scene. The DARPA MEMS research project was exploring ways to use MEMS to advantage as sensors in defense systems. At that same time James Lyke of the US Air Force Space Systems Division had developed the "Advanced Instrumentation Controller" (AIC). The AIC was architected to be a radiation hardened electronic hybrid computer with analog inputs, digital processing, and analog outputs for closed loop control in "Star Wars" space equipment. The package of the AIC was about the size of a half stick of chewing gum, made possible by using high density interconnect (HDI) packaging developed in another DARPA project. The AIC offered a path to bring real time processing in distributed processors placed in a wiring harness. The processors could be in any "safe location" such as under the wiring harness overbraid or inside a specially constructed mil-spec connector.

The JSF program VHMS team liked the "smart wiring" concept for several reasons. First, the processors would be very small, adding less than an ounce of weight each. Low cost for the electronics package was another attribute as the AIC could be made with HDI for less than twenty dollars each in quantities needed for the JSF fleet. Being in the wiring would eliminate otherwise expensive cost for changing the design of hundreds of avionic units. A major plus would be that the health state of flight critical wiring harness could be assessed to identify the location of shorts and open circuits caused by operational factors or battle damage. See Figure 1 for an example of Smart Wiring Construction using Ribbionized, Organized, Integrated (ROI) wiring.

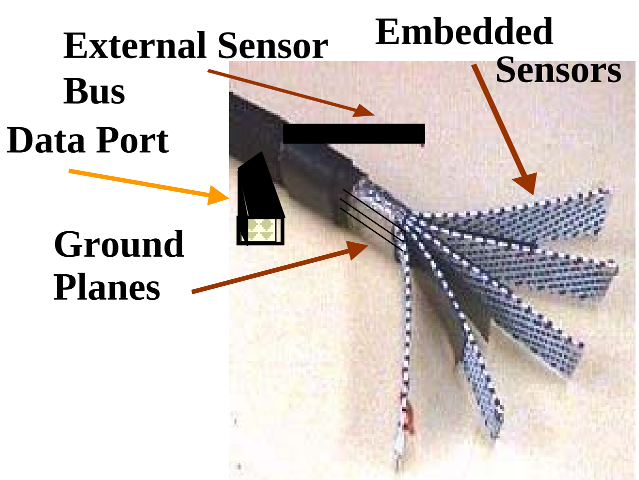

Figure 1. Branches for COTS Sensors.

A particular advantage would be that the processors would be passive, easy to procure, and readily programmable with specific diagnostic – prognostic algorithms for engines, electrical power systems, flight controls or other subsystems.

This wiring system allows the embedding of various fiber and similar sensors directly within the wiring system to detect shorts, chafing, fluid immersion, and other faults. Additionally, other sensors can be bundled into the wiring with branches to various nearby locations for other information sensing. Finally, the AIC processors can be bused together, or otherwise communicate, through the embedded data port.

1997 seems long ago, yet DARPA projects are typically ten years ahead of the time. Fast forward from then to today. The AIC with its HDI construction was redesigned and improved in 2000 emerging as the Sentient Instrumentation Controller (SIC) (US Patent 6,938,177). The SIC is currently being upgraded to a new 32-bit architecture which includes USB and Ethernet ports, wireless communication, and gigabits of memory. This improved design is sponsored by the JSF program office and is called the Embeddable Programmable Instrumentation Circuit (EPIC). From the software side, the AIC software has also been upgraded to take advantage of the increased size of memory and field programmable gate arrays (FPGA) to host the application specific health monitoring algorithms.

4. The Role of Software with Modeling and Simulation for Embedded EI

There has been a flurry of papers about use of modeling and simulation which compares known "good" signatures to incoming signatures from sensors and performance measurements. Writing a simple statistical algorithm for diagnosing the health of a non-complex device like a lead-acid battery usually requires several man-months. Writing the individual subsystem specific software for diagnostics and prognostics needed for complex system health monitoring (e.g., aircraft power train) is a challenging task. Writing the health monitoring for all of the possible operating domains multiplies the problem several fold. Historically such efforts have consumed tens of man-years and cost running into several millions of dollars.

In the late 1990's DARPA launched a project to develop a new method for programming applications like those used for VHM called automatic coding or "autocoding" which builds software "on the fly". The project name was the Rapid Acquisition of Application Specific Signal Processors project (RASSP). The RASSP project goal was that system engineering tools and autocoding tools could reduce development time by a factor of four or more. The RASSP project established a benchmark led by MIT's Lincoln Labs that proved autocoding could reduce cycle time by six in the case of a synthetic aperture radar. Today autocoding methods are becoming more common.

Beginning in 2003 several DoD programs sponsored by the Office of Naval Research and the US Air Force funded development of auto-coding for generating diagnostic and prognostic subsystems. The auto-coding process feeds a set of rules called “metadata”. The metadata are a stored set of rules for constructing a model. The metadata is processed with a generic application called a “Rules Engine”, which as its name implies, produces the application and situation specific model from a set of rules which replace hard coded software.

The capabilities of processing with a “Rules Engine” for VHMS was demonstrated in 2004 for monitoring flight parameters on an F/A-18. This demonstration included all phases of flight.

EI framework

Once the need and feasibility of an EI system are determined, the time and cost to deployment divided into system engineering, prototyping of the EI hardware and software, testing and technology maturation. The System Engineering effort that defines the architecture is most important as the architecture directly impacts weight and costs.

The Systems Engineering activities include the determination of mix of smart connectors vs. smart wiring, the use and integration of sensors in the cabling, and the processing algorithms to be implemented in the “Rules Engine.”

Additional Capabilities

After the EI framework is in place with IVHM, additional capabilities can be readily added. Given the prognosis of faults occurring that can interfere with mission success, the actions can be taken to reduce the probability of the fault occurring during the performance of the mission. An example of this is a vehicle cooling system that is rising in temperature during a deployment. By reducing the load on the “soon to fail” vehicle, total failure can be avoided. Such stress management can be implemented using goal seeking logic or “Teleo Adaptive” algorithms. [2]

Other fault reporting, connectivity (including network or data centric) reporting capabilities can be readily included in the overall system capabilities and the information is readily accessible within the EI subsystem.

Implementation

The EI approach being used for both vehicles and aircraft is to mount the necessary electronic modules in electrical harness connectors which are located in prioritized locations. In cases where electrical harnesses do not exist, a similar package can be used which has a wireless transmitter to deliver the data to and among other processors.

For the AV-8B CSEMS, the concept is to build on a traditional avionics box through the addition of additional sensors. But the embedded processing architecture in the CSEMS is a variant of the processing architecture of the distributed EPIC functionality. This approach is currently a risk reduction effort to add capability while EPIC is initially deployed in ground vehicles to develop an experience base to allow future airborne flight certification.

The “Rules Engine” is the basis for the Crash Survivable Engine Monitoring System (CSEMS), an avionic unit that will be going aboard the AV-8B Harrier in 2009. The models run by the “Rules Engine” will be used to monitor health at startup, vertical takeoff, and other engine operating domains. The process includes combining and processing information from the MIL-STD-1553 bus, vibration and other signatures.

The CSEMS “Rules Engine” is being developed to be hosted on the EPIC module for other applications.

For the MDA Airborne Laser Aircraft the concept for adding EI is not for the Boeing 747 aircraft but for the equipment of the laser and control room. Because the 747 has a relatively adequate space, the idea is to place “smart connectors” at strategic locations in the wiring harnesses.

For deployed Army vehicles the AI can be added in two ways. As a minimum it is possible to add a connector insert where connectors already exist. Or, if certain parts of the cabling are being replaced, a “smart wiring” segment with either a “Smart Connector” or with processors in the wiring can be used. Demonstration activities are being planned for the Abrams M-1 tank to validate the Technology Readiness Level and demonstrate the capability to reduce fault ambiguity groups during maintenance activities. Assuming a successful demonstration, the program will lead to the development and installation of “Smart Connectors” on the Abrams.

5. CONCLUSIONS

A system engineered approach is appropriate for adding EI to new vehicle designs or for new variants and upgrades of older vehicles. This EI can perform effective IVHM when integrated carefully with a fully auto-coded “Rules Engine.”

MSI’s new EPIC configuration, when deployed on ground vehicles to gain experience and a performance baseline, is planned for migration to airborne vehicles. Until then, more traditional avionics boxes will be used to host the processing, but the processing architecture and sensor architecture will remain the same as the Smart Wiring/Smart Connectors implementation.

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Biography

Francis E. Peter *is the Manager for Systems and Programs for MSI. Mr. Peter currently manages the development of Safety Recording and Engine Monitoring systems for military aircraft. He has 16 years experience as a Navy civil servant and 21 years in the defense industry specializing in electronic warfare and Systems Engineering of data bus and common avionics/electronics systems. He has extensive experience in the analysis and development of system level requirements and specifications. Mr. Peter is an expert in system development processes and systems integration. He has a BSEE from Ohio Northern University. Mr. Peter is the 2006/07 President of the Enchantment Chapter of the International Council on Systems Engineering.*

Kenneth G. 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 real time diagnostics, troubleshooting, and equipment life extension. Ken has several patents pending. Ken 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 was awarded the Best Technical Paper of the 41st Quality Congress of the American Society of Quality Control. He has a BS in Applied Mathematics (Engineering) from the University of Cincinnati and an MS in Applied Mathematics (Engineering) form the University of Rochester NY.*