Dynamic Autonomous Test Systems for Prognostic Health Management

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Track:

Abstract

This paper presents the state of the art in real time reactive supervision using micro-module sensors. The paper will show how automatic test equipment is becoming more and more an anachronism as the Joint Strike Fighter Prognostic Health Management (PHM) team forges new links that connect on-board, event based diagnostics and prognostics to ground-based support. The paper will discuss how on-aircraft PHM combines micro electro-mechanical systems (MEMS) and micro-electro-optical systems (MEOS) with prognostic microprocessors to sense, detect, consider, prognose, message and perhaps correct problems. The paper will explain how miniature electronic technology (E.T.) will use web based JAVA technology to receive rules for PHM and send results of PHM via downlink to the Joint Distributed Information System. (JDIS) The paper will show how E.T. is embedded in the wiring, cables and connectors that are the life lines of the electronic systems, and how E.T. will be fused into mechanical structures to detect aging and battle damage. Finally, the paper will describe the cost benefits that result from radically changing the current way defense systems are supported.

1.0 The Problem with Test Equipment

Test equipment and test software program sets have come a long way in the past fifty years. In the 1950's test procedures often were done with a voltmeter and eight weeks of training in basic electronics. The transistor changed the picture. In the 60's and 70's test sets were developed to check the combination of analog signals and digital "1's and O's" used in avionics and other systems. In the 80's computer programs entered the picture, adding complexity. "Can Not Duplicate" and "Tests-OK" now represent about 50% of test results. Maintenance personnel spend about ten times longer trying to "fix" these problems and often introduce a fault just to reduce the trouble. "Cannot Duplicate" (CND) and "Tests OK" (TOK) situations represent about 50% of today's repair results. CND and TOK are frustrating, and many operators just ignore the fault indications and hope its another "false alarm". Test equipment from the days of TTL logic and circuit boards just cant cope with emerging massively parallel architectures used in defense systems. The complexity is just too great, such as testing the stealth characteristics of a fighter which must be done during flight.

History has shown that "false alarms" can make systems appear to be very unreliable, and can take several maintenance hours per flying hour. The F-15 electronic systems have a average "mean time between failure" of under 100 hours. The F-15 logs about 25 maintenance man hours per flying hour. Sortie rates are affected as the equipment is taken off line to be tested and repaired. The high altitude, high speed missions of other fighter aircraft like the F-16, F-14, and F-18 aircraft cause similar headaches. Other aircraft have similar situations, albeit of a lesser degree, as their roles are usually subsonic, and their environment for use is more benign. However, their test equipment problems are very similar. Developing and supporting test program sets is a big business dominated by a select few suppliers. Test sets come with their own problems, such as required use of ADA to assure software upgrades, and failure rates that are often as bad as the equipment being tested. The problem is getting worse as software begins to dominate the functionality of new systems. Testers designed to check voltage levels are not suitable for testing 400mhz computers used in digital signal processors and avionics today.

1.1 Cost Aspects

The cost of maintenance and support of current generation weapon systems usually exceeds the delivered cost. Test equipment costs are sky rocketing. It's not unusual for the cost of the ATE to exceed the half the cost of the product it is built to test. Spares, parts, TPS and ATE are very big business. The US Department of Defense spends about $8 billion on test related hardware each year.[1] Solving the problem of external test equipment is not a simple matter of spending more money.

1.2 The Added Trouble of Commercial Off the Shelf (COTS) Systems

The problem of cost and availability is not limited to the DoD. Commercial firms and businesses have many of the same problems. Commercial producers often produce only a few years of spares. Automotive firms have a three to five year spares policy. Many firms find that it is cheaper to scrap a failed computer or system than to try to find replacement parts. The DoD hopes to replace expensive custom systems with systems built from commercial off the shelf (COTS) components. But, most commercial off the shelf (COTS) components are not designed to be testable, and COTS products are usually not durable enough for harsh military environments. Also, COTS products are constantly upgraded and revised to add new technology. New systems will be increasingly complex.

2.0 The Joint Strike Fighter (JSF)

The JSF is a good case in point. Like the F-15, the JSF is a multi-role strike fighter aircraft. In the past, this meant that the JSF would contain about one hundred analog and digital "black boxes" performing dedicated functions. However, the JSF will be mainly "flying software" with numerous distributed computer systems that will share and participate in function. The JSF will be a "fly by light" supersonic aircraft with electronic "black boxes" running complex software. Having distributed processing provides redundancy and flexibility which mean increased survivability and inherent reliability. But inherent reliability only lasts until the first failure. Many failures will be software "glitches" that appear to be failures of hardware. Operational availability depends on the repairability and testability of the hardware and software. Unavailability will result if the test equipment designed for flying hardware is unable to cope with the new design architectures that replace prior generation

[1] Proceedings of the DoD Joint Test Conference, Orlando, FL, 1995

electronics with systems based on software signal processing. Untestability at the flight line will result in sending the equipment to repair depots and the manufacturers, inflating the pipeline and turn around time.

At the 1996 testability meeting for the JSF, test system and test software manufacturers said that the solution to having better testability only requires more time and more money, because better test sets will require better computer programs. But this means that the test modules are usually delivered long after the system enters service. Test equipment also fail, in two ways. They often fail to test the equipment they were designed for. And, the TPS/ATE components fail, requiring test sets for repairing the test sets. The Pentagon budgets for TPS and ATE represent a major part of new system acquisition costs and will rise dramatically if something is not done.

3.0 Solutions

Many system managers wait years to receive test program sets (TPS) and automatic test equipment (ATE) that simply do not perform as required because the test set programmers and developers can't cope with the complexity and changes. Faulty equipment gets recycled into the system to return again with great consistency. There are several feasible solutions to the problem: 1) allocate much more time and much more money to develop test program sets and ATE that will be able to cope with the complexity, or 2) increase the amount of self test and bit within the electronic systems. The advantages of spending more money on test equipment and test programmers are entirely in the pockets of conventional test equipment manufacturers and dedicated repair facilities.

There may not be enough time, or enough money to produce adequate test equipment and software. It is far easier to take advantage of the built in processing power and software diagnostics aboard the system. Real time diagnostics and tests performed aboard the system makes it possible to use prognostic health management. PHM diagnostic and prognostic procedures will provide detection and isolation services to make sure that only true hardware failures result in maintenance. The data generated by PHM will be delivered to the maintainers along with recommended procedures to assure a quick turn around. Figure 1 shows the principle elements of autonomous logistics support. Incidents aboard mission aircraft cause messages to flow to command and control centers of forward logistics support centers. Aircraft can be serviced at any facility having the skills and parts on hand, or the resources can be expressed to the selected support center.

3.1 JSF Prognostic Health Management (PHM) Office

The JSF program for PHM is managed by Dr. William Scheuren. The purpose of the project is to dramatically change the way aircraft and systems are designed, operated, maintained and supported. The JSF PHM office is promoting research and development of pro-active, built-in, on-board diagnostic and prognostic systems that will increase the safety, availability, performance, and affordability through innovations including use of advanced "smart systems" using sensor technology. The JSF PHM project wants real timely "Reactive Supervision" to observe, detect, reason, understand and react to ongoing events during missions, during maintenance, and throughout the life of the aircraft. The PHM will result in autonomous logistics support achieved through watching for symptoms, detecting problems, isolating faults, and performing real time repair/restarts. The PHM system will report to cockpit displays, hand held maintenance aids. Data links will transmit health and status information to support sites.

3.2 Short and Long Term Goals

The long term DoD/JSF goal is to eliminate ground support test equipment and test program software wherever possible by moving test and diagnostics on-board, using aircraft computer systems to detect, diagnose, and isolate failures. Another goal is to have the aircraft systems order parts and maintenance during the course of the mission to achieve "autonomous logistics support". Autonomous logistics would be like breathing is to humans, eliminating much of the delays that choke and limit operational availability. The DoD would like to eliminate scheduled maintenance by shifting to "on condition" maintenance as needed. The JSF program wants to use methods similar to those used by commercial aircraft systems developed for Lockheed Martin, Boeing and Airbus Industries. New commercial aircraft designs like use on-board diagnostic systems to notify ground crews of maintenance needed to restore airworthiness. If the parts are in a city other than the destination, the airline has time to get the parts delivered "just in time" to cut the time otherwise required to wait for parts.

4.0 Embedded Self Prognosis and Dynamic Resource Management

Achieving autonomous supportability will require innovations that use fuzzy logic and expert systems to "feel" events, detect failures, and prognose the need for parts and maintenance during flight. The self prognosing system will use the test data built into the software systems. The system will determine recurring patterns during mission operations that are impossible to find after the system has returned to base. The diagnostic software will assess the probable root causes for faults and failures relaying the information to ground crews along with work instructions.

In 1996, DARPA awarded a contract to explore in-flight embedded self prognosis (ESP) using new software and sensor techniques to identify problems and select the maintenance and repair methods. The research demonstrated that ESP is not only feasible, but demonstrated using ESP handling "sledgehammer" failures in distributed computing systems. The contract identified other innovations such as moving ESP on computers in "smart wiring" to create an aircraft neural backbone. MSI demonstrated that smart wiring can be used to detect, isolate, and perform other reasoning to perform dynamic resource management (DRM) autonomously.

5.0 Smart Technology for Autonomous Logistics Support

Smart technologies are emerging "just in time" to enable autonomous logistics support. "Smart" sensors will provide the data, information and knowledge required for "on condition" maintenance. The use of intelligent wiring will also eliminate many of the problems caused by frequent technology upgrades. Technology upgrades are a fact of life caused by technology advances every few years. For example, many JSF electronic systems will be digital signal processors (DSP) that replace prior generation radars and analog systems for navigation and control. Most DSP use numerous dedicated COTS computer processor systems. According to Moore's Law, computing technology changes every 18 months. (Many claim it is closer to nine months today.) This means that JSF systems will be constantly upgraded with new technology to fend off obsolescence.

6.0 Virtual Prototype Co-Design

To be really effective, "smart systems" for PHM need to be designed in, with "open system" techniques that allow room for planned technology upgrades. The Defense Advanced Research Project Agency (DARPA) has teamed with NASA to fund development of hardware and software concurrent design using virtual prototyping. Three dimension (3-D) computer aided design (CAD) programs already have the necessary power needed to create a virtual hardware prototype of the mechanical design. Chrysler Corporation has been advertising how they virtually prototype new car designs. The new car design is driven over virtual highways to identify areas for improvement that improve functionality, reliability, safety and maintainability. The Rapid Prototyping of Application Specific Signal Processors (RASSP) project started in 1993 to develop computer programs automatically from behavioral specifications. As a result, co-design is being used to identify how and where to place sensors that will provide the data for on-board real time diagnostics, and to automatically produce the diagnostic and prognostic software needed to eliminate off board test program sets.

7.0 Neural Circuits and Smart Test Modules

To be cost effective, the designers of reactive supervision must dramatically reduce the time and costs associated with writing software programs. This paper presents the state of the art in real time reactive supervision using neural circuits comprise of micro-computer modules equipped with micro-sensors. Neural circuits are not neural networks. Rather, neural circuits are collaborating computers that work together to optimize reliability, supportability, maintainability and safety as part of the on-board computer systems

Smart neural sensor test modules can be designed autonomously test the health status of not only electronic systems, but also the mechanical and structural systems. Sensors can be built with microcontrollers and diverse micro machined electro mechanical systems (MEMS) and micro optical sensors. The smart sensor will process the data using rules stored in a knowledge base. When the rules indicate, the smart sensors take appropriate actions in the form of messages or using D/A converters to make controlled changes. Smart test modules connect to higher level smart processors which diagnose and prognose, sending condensed information to ground based support.

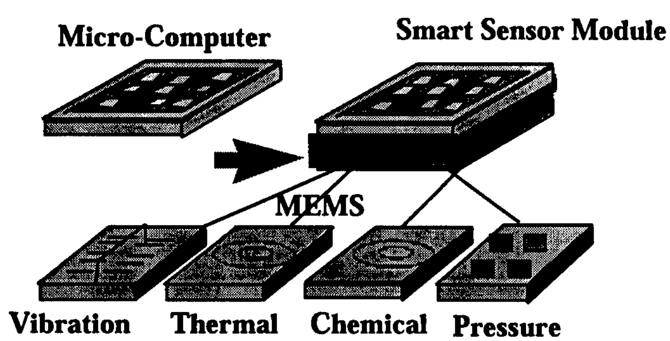

Figure 1. Smart Sensor Modules

8.0 Reactive Supervision

Rule bases used by sensory neural circuit modules can be used to detect when system elements need inspection, based on time since last failure, symptoms, exposure to ultra violet rays, temperature, vibration and corrosion. Rules can be established enabling autonomous activity to discover and correct problems. The nature of the reactive measures is defined in "fuzzy rules" loaded into memory. Smart sensors can take reactive supervisory measures defined in a supervisory program. The measures could be as simple as generating a message, or as complex as taking collaborative action in concert with several other smart sensor devices to regain control of situations.

9.0 Rule Based Autonomous Testability

Autonomous reactive supervision and dynamic resource management requires data inputs, rules, rule processing, recognition with discrimination, decision processes and taking actions. The rules define the sampling rate for the input signals. Rules also define the guidelines for reasoning processes. Java rules define the nature of any messages, commands or other actions using analog drivers. The smart sensors can attempt to take corrective measures, such as releasing chemicals to stop corrosion. Messages can be used to notify other Smart sensors or to notify maintenance personnel of problems such as loose connections or vibrations that cause chafing. If wiring is damaged due to fires or collateral damage, the smart sensors can switch to a better wiring configuration using cross bar switches. The rules used to detect the problems also provide the internet URL to receive the report of taking preventive actions. If desired, the receiving URL can request additional information, or request another configuration.

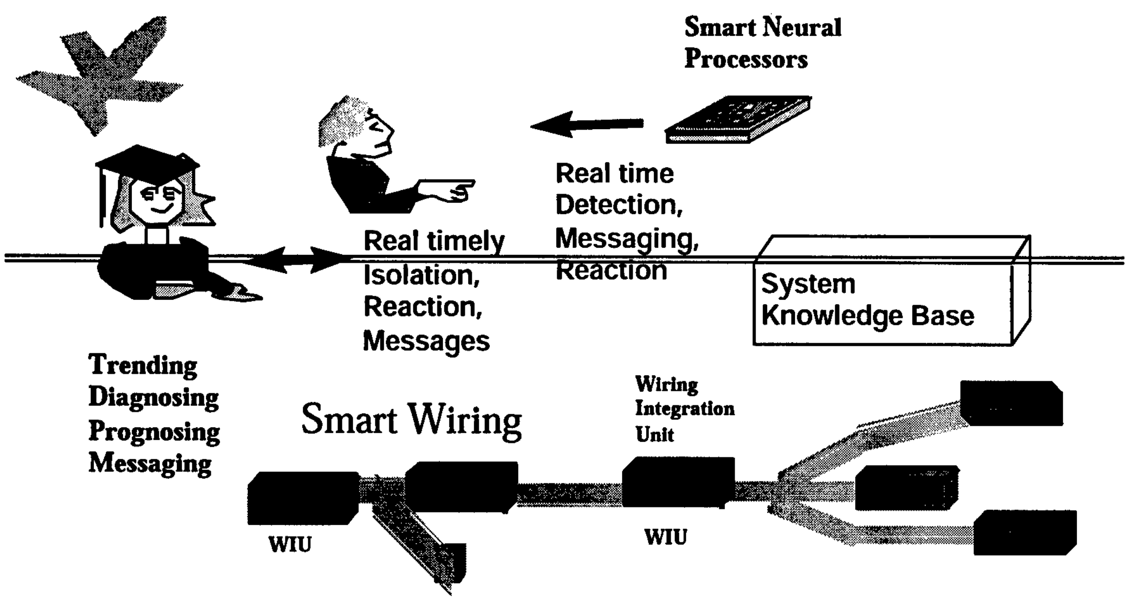

Figure 2. Autonomous Diagnostics and Test

10.0 Autonomous Logistics

On system failure isolation and verification also provides "autonomous logistics" which automatically order the parts and procedures from the support facilities where they are located. Autonomous logistics functions react immediately to gather the resources dynamically, unless overridden by human commands. Built in test information often can identify the root cause of the problem, such as a failure in the power supply. Economic decisions will identify the best way to restore operation of the system, and operation of the failed units.

11.0 "Smart" Wiring

Built in test information is too valuable to use only for maintenance. The data can be used by on-board processors to facilitate reassignment of assets to maintain functionality of mission critical systems. The wiring system that carries the test data information is an obvious choice for siting of PHM sensors and dynamic resource managers. By embedding computers and microcontrollers in the wiring, the electronics and software will be tested before, during use.

ESP in smart wiring can eliminate much of the ATE and TPS that would otherwise become expensive baggage. Demonstrations of the concepts were held in late May 1998. The JSF PHM program office has funded research projects to prove that smart wiring using COTS sensors embedded in COTS electronics and wiring is cost effective. Demonstrations are scheduled for late summer and early fall of 1998. On aircraft demonstrations are being scheduled for the summer of 1999. The latter demonstrations will show autonomous reactive supervision by on-board diagnostic and test systems embedded in the wiring system.

The advantages of using "smart wiring" are numerous:

- On-board restoration of many problems by rebooting, cold starts, or resets
- Accurate run time detection, diagnosis and isolation with on board computers
- Dramatic reductions in NFF and RTOK
- Significant reductions in maintenance
- Dramatic reductions in life cycle support costs
- Dramatic reductions in costs for TPS and ATE
- Substantial increases in operational availability and supportability
- Dynamic verification and validation of technology upgrades.

11.1 Applications for "Smart Wiring"

Wiring carry signals, power and data to and from processes attached to the wires. The wiring is very much like the veins and arteries of the human body. Current wiring systems are passive. Sensors can be added to the data network that are analogous to neurons that provide "feelings". The wiring is an ideal place to place the detection, reasoning, and reacting processors. Inventing a new generation of "smart wiring" starts with destroying most of the rules for conventional "dumb" wiring. Research to develop the "first generation of smart wiring" is being funded by the JSF PHM office. The project is getting enthusiastic support from DoD agencies who bear the cost and frustration associated with the current generation of wiring and test equipment.

11.2 Advantages and Benefits of Smart Wiring

Currently, most wiring is simply connections of wires from point to point. Wiring tends to work quite well until it is subjected to environmental and electrical forces that cause minute problems. Many problems take ten to fifty years to develop. The problems are usually related to chemical deterioration due to chemical reactions. When wiring begins to show signs of wear and tear, the problems that are generated can be very troublesome. In fact, most maintenance personnel would rather dig ditches than attempt to isolate problems in wiring harnesses. Current wiring systems are simply not designed for trouble shooting. In fact they seem to be designed to confound attempts to isolate problems.

12.0 Real Time Logistics Information Systems

In its long term vision, the DoD wants the ground support system and aircraft to autonomously reconfigure assets in order to complete missions. The DoD has initiated the Joint Distributed Information System (JDIS) network will be used to send information to the maintainers on exactly what is failed, identifying the maintenance procedure and parts that will be needed. In this way the support staff will have time to assemble the tools and parts needed to make quick repairs. On arrival, the maintainers will be better prepared to make repairs and quickly turn the system to fighting status. In peacetime, the failed units can be returned to the manufacturer for warranty support.

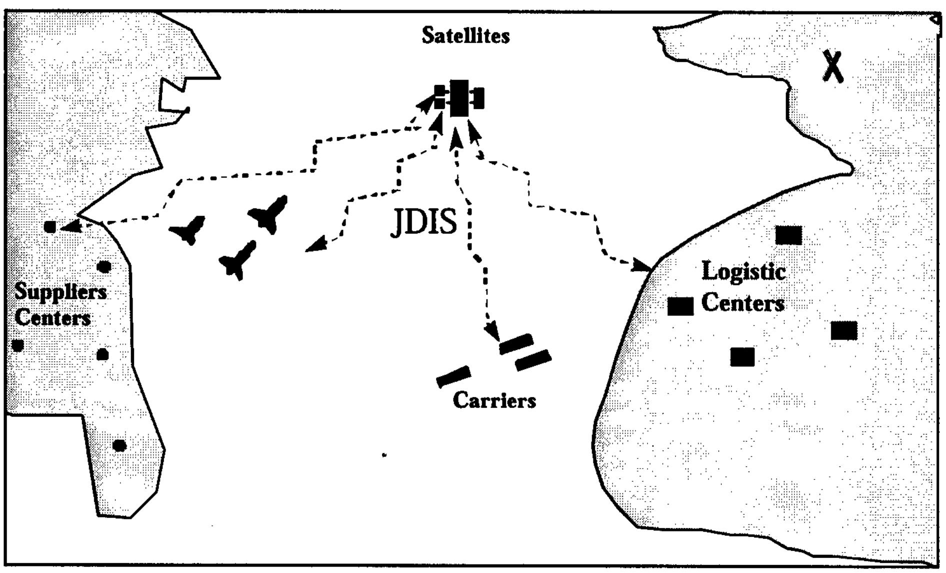

Figure 3. Autonomous Logistics using JDIS

13.0 Summary

The realities of shrinking defense budgets require massive changes in the way systems are designed, tested, maintained and supported. As a result of new initiatives, testability, availability, and supportability are changing. System managers, like Dr. William Scheuren of the Joint Strike Fighter PHM office are making significant efforts to reduce the cost and problems associated with test equipment, maintenance, and logistics support. Defense, automotive, and aerospace companies are designing new technology to bring diagnostic and test systems on board to enable having autonomous logistics support, higher mission availability, and dramatic reductions in external test equipment.

Using autocoding to develop test software will cut the time to develop test software by several orders of magnitude.

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