# Prognostics for Wiring: Managing the Health of Aging Wiring Systems

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## Abstract

Faulty wiring has been identified as a major safety hazard in aging aircraft. This paper describes the scope and progress of ongoing work to develop "smart wiring" that measures and monitors the degradation in aircraft wiring over time. The smart wiring measurement system is made with embedded processors and microsensors. The embedded processor uses model based reasoning techniques to model the wiring system performance stored in a memory chip. Model based reasoning provides software prognostics and services to assist in pro-actively managing the health of aging aircraft wiring systems. This paper describes work that has been on-going for ten years in the Air Force Research Lab in an attempt to integrate wiring as a part of an overall diagnostic approach that will yield system level diagnostic coverage. This paper describes the current status and explores planned research for future Aircraft Wiring Health Management.

## Introduction

Wiring is found in nearly every part of an aircraft (40 miles of wiring in an F-16). Wiring ages and causes safety problems by flexing, chafing, corrosion, stress and fatigue. In 1998, the FAA added wiring to its list of aging aircraft focus items. Most Air Force aircraft fall into the aging category. Over half of aircraft in commercial service in the United States are also older than 18 years. The wiring aging phenomena is not confined to just aircraft, consideration must also be given to the aging characteristics for naval and space vehicles.

Aging wiring in military aircraft has been a problem for a number of years. The philosophy of wiring design for many in service aircraft today is that it would never wear out, would not need to be replaced, and therefore not designed in modular fashion or for ease of maintenance. As wiring accumulates increased operational time, increased stresses due to environmental and/or aging effects, the rate of failure gradually increases the need for maintenance. Old wire breaks more often than new wire, and one way to solve the problem is to rewire older aircraft. This is obviously a straightforward (but drastic) approach and is generally too costly to consider, and a more cost-effective solution is needed to solve this problem.

Wiring system maintenance is an organizational level task due to the relative permanence of wiring harness and cable installations. A significant portion of total aircraft maintenance man-hours is expended in the troubleshooting of wiring to affect repairs of avionics and weapon systems. Wiring troubleshooting is still a "hands on" art, with very little having changed in the last 40 years. In fact, advances in avionics systems, such as Built-In-Test (BIT) have hampered or even misled technicians if the fault turns out to be in the system wiring. Wiring repair is so costly that some aircraft wiring is not being repaired unless it actually causes a system failure or is a safety hazard.

The development of an automated or semi-automated system for managing the health of the wiring system is needed to bring about change in this important but neglected area of aircraft ownership and operations. A troubleshooting tool is needed to detect, isolate and locate wiring faults quickly and expedite repairs on the flight line. This diagnostic tool will be used to document and store for future comparison the current status or condition of an aircraft wiring system's "health" on a tail number basis. This adds the additional capability of detecting trends with the intent of fixing wiring failures before they occur, during a time for planned maintenance versus trying to fix a fault during the sortie generation cycle. What is needed is a cost-effective means to manage wiring health as well as the ability to look at safety implications of degrading wiring. For the first time, wiring systems can be "managed" in the same manner as Line Replaceable Units (LRU's) and engines, targeting specific tail numbers for wiring maintenance or upgrade based on concrete, measurable data.

**"O" Level Wiring Maintenance**

Operational Level ("O Level") maintenance is performed at the flight line. Most aircraft systems have two types of tests, operational and fault isolation tests. Operational tests run on an aircraft without modifying the basic operational configuration. Fault isolation tests alter the aircraft configuration to provide more observability into the system. The symptoms of a failure for an aircraft can be classified into three categories: 1) The symptoms can be reproduced at the flight line, 2) the failure symptoms can only be observed in flight, 3) the failure symptoms were a result of some transient external interference and the vehicle system is functioning properly. If the failure is a type two or type three category, the only way to verify the repair with absolute certainty is fly the aircraft and recreate the conditions that caused the failure to occur. The third class is important because any removal action will result in a ReTest OK (RTOK) because it is impossible to distinguish between the second and third classes when the failure is reported.

Troubleshooting faults using technical manuals or electronic technical data assumes that all failures are category one failures, and immediately jumps into a fault isolation procedure without verification of the actual presence of the failure. There may be a Fault Reporting Code (FRC), but this is an indication that a fault (or possible anomaly) was observed by the BIT system and may have momentarily exceeded an established threshold. Diagnosing a system with no failure present will result in removing and replacing a functioning LRU. This LRU will then RTOK at the intermediate or depot level. Because fault isolation procedures do not handle the second and third class failures, no mechanism other than pilot observation is established to track possible class two and three failures over multiple flights. Pilots are not always capable of detecting and tracking wiring fault phenomena.

Experiments conducted during the Self-Repairing Flight Control System (SRFCS)[a] included six fault scenarios that were exercised during flight test. In scenario 1, a dynamic pressure sensor connector separates when a certain G level is exceeded. The connector then reconnects when straight and level flight is resumed. This is a type two failure and is nearly impossible to reproduce on the ground. However, real time diagnostic data was acquired to make the repair possible. This is one of the first instances of realization that aircraft wiring needs to be integrated with the rest of the subsystem for diagnostic purposes in order to eliminate the Cannot

Duplicates (CND) and RTOK phenomena. Generally for wiring fault isolation there is no Fault Isolation Manual (FIM) or fault tree. The technician is on their own to develop a strategy to diagnose the wiring. At the end of the fault tree the technician gets a "refer to schematic" to fault isolate the wiring if the problem is not corrected.

Troubleshooting wiring in the field is more of an art than a science. Probably the most important factor in troubleshooting wiring in the field is to have the correct configuration data available. Field testing of the Flight Control Maintenance Diagnostic System (FCMDS)[b] had proven the importance of the accurate configuration data for the aircraft wiring segment being diagnosed. The FCMDS program included wiring as part of the diagnostic strategy to get total flight control system coverage. Using automated techniques inside the FCMDS software, a single wire was displayed from end to end. (See Fig 1.) The wire in question was part of the diagnostic process along with the signal that might cause the possible fault. The ability to trace the wire from end-to-end gave the technician attributes of the length and type of wire, the interfaces (connectors and bulkheads) and the pin locations at each interface. This made manual measurement of the wire electrical characteristics easy in a simple graphical display. A test of the system measured the human performance using a paper schematic for a technician to trace a wire from end-to-end and then accomplished the same by a computer. The technician using the paper manual took about 20 minutes to trace the wire from end-to-end. Some of the time was spent going down the wrong path for a configuration that was not correct for the tail number being diagnosed. The developed wiring database was able to sort to the correct configuration and display the configuration in thirty seconds. Therefore having a wiring database that will take into account the configuration of the aircraft is a critical attribute in modeling the behavior of the wiring. During development in the late 1980's and early 1990, the measurement of the electrical parameters was performed manually. In 1992 when the program was completed, it was envisioned that the wiring could be embedded with sensors and this would take most of the

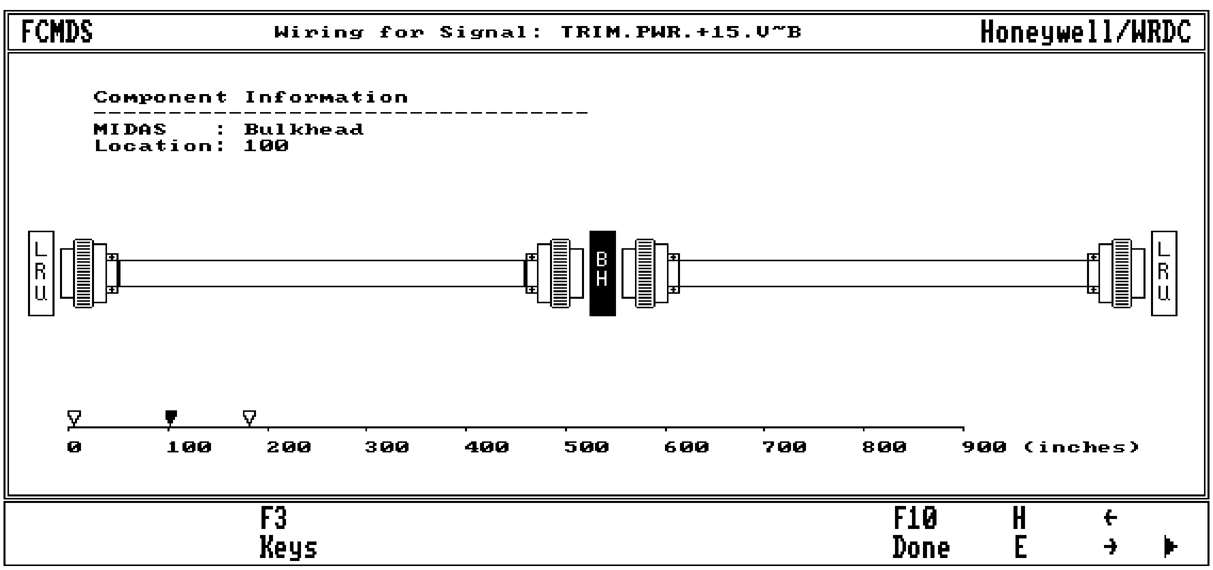


**Figure 1.**

human intervention out of wiring troubleshooting and establish a fault location.

## Wiring as an Integral Part of Diagnostics

Wiring is a fundamental element of an electronic system. As such, wiring must be an integral part of the diagnostic system as well. Wiring has often been neglected in developing fault isolation manuals, because it usually functions perfectly when installed in a new aircraft. Typically, wiring failures do not occur until an aircraft reaches 5 years of age and older. The information necessary to make repairs is contained in paper wiring diagrams that may be out of date. In addition, wiring repairs do not always follow a set procedure, so non-standard repairs may make the wiring sequencing different than in the manuals. It usually requires the technician to spend many hours using many pieces of test equipment to isolate the problem. Over the last twenty years the number of wires needed to interconnect all of the electrical and electronic systems in military and commercial aircraft has grown dramatically. Because of this growth, great efforts have gone into reducing the size and weight of wiring. This means that wiring density has increased and sensitivity of signals has become more critical. Therefore you have more signals per harness and more sensitivity required in that harness than in previous aircraft systems. Several methodologies have been explored to embed sensors to improve sensitivity, keep the harnessing weight to an acceptable level for today's aircraft designs as well as planning for wiring modifications and replacements.

## Embedding Sensors in Wiring

Adding sensors to existing wiring harnesses is not a simple task. Installed wiring is one item that is best to leave alone if possible. Increased manipulation can easily lead to induced failures, especially if a high percentage of the bundles are poked and probed in the process. One way to accomplish the addition of sensors without disturbing much of the installation is to add any sensors directly behind specific selected connectors. By reviewing harness drawings, it would be possible to select key connectors that contain a large percentage, if not all, of the wires in any particular wiring harness.

The nature of conventional wiring methods places an important limit on the ability to add sensors. Since most existing aircraft have shielded twisted cable constructions for addressing electrical crosstalk interference issues, it is not possible to access individual wires in these cables except where and when the shielding is removed, and this is behind the connectors. The shielding is removed to allow for wire termination to take place. Because it is necessary to access circuit wires individually, sensors must reside directly behind the connector. In most cases, the sensors could be housed in what would essentially be a large Electromagnetic Interference (EMI) backshell, and thus become an innocuous part of the wiring harness.

These sensors will be of an inductive nature, so that it would not be necessary to make direct and permanent contact with the wire's copper conductor. The implications to reliability and maintainability are significant. Sensing systems which must be spliced into wires are costly and eventually troublesome. Splices are not only a common failure point of wiring, they are also high on the maintainer's suspect list of where failures may reside. Splices are regularly hunted down, inspected and manipulated in hopes of quickly finding a fault. Inductive sensors eliminate these implications.

It is much easier to add sensors to other wiring system types, both existing and new design. The ribbonized wiring system used in the V-22 Osprey known to the industry as both Ribbonized Organized Integrated (ROI) Wiring and Integrated Wiring System (IWS), is inherently friendly to imbedded sensors. The easiest method of incorporating sensors with an ROI system is to make use of an inherent feature of most modular ribbonized designs, and that is the Wiring Integration Unit (WIU). WIUs, a fancy name for a removable junction box, are used to connect the minimally branched ribbon harnesses together. In the V-22, upwards of 97% of all the circuits in the aircraft are routed through at least one WIU. This makes all those circuits accessible for sensor implementation. Incorporating the sensors into the WIUs would not require a system "volume" increase as the WIUs are not densely packed. More importantly, a set of sensor equipped WIUs could be retrofitted into existing aircraft in a matter of hours. ROI systems can be equipped with sensor technology in other ways. Because ROI harnesses do not used shielded twisted cable constructions, individual wires are not electrically "hidden" from inductive sensors by shields, but are accessible along their entire length in the harness. Although placing sensors behind connectors is still the preferred location, it is not necessary to crowd the back of the connector as it is with conventional wiring designs. This gives the designer and installer additional leeway in sensor placement. Furthermore, the flat nature of wire ribbons allows for flat sensor arrays that can be easily designed, built, and installed much easier than what would be appropriate for conventional wiring designs

ROI wiring was developed in the 1980's as a lightweight and more easily repaired alternative to classical bundled wire harnesses. ROI harnesses consist of individually insulated wires woven into flexible flat ribbons, with copper foil shields between the ribbons surrounded with conventional gross shielding and fabric outer coverings. ROI (IWS)[c] is lighter, less fragile, and survives battle damage better than ordinary wiring. ROI wiring terminates into standard circular connectors used in ordinary wiring, boxes, equipment, and airframes. ROI is used in the V-22 Osprey Tiltrotor, which is a "fly-by-wire" aircraft that enters OPEVAL this fall.

**A New Approach To Wiring Health Management**

The FCMDS made wiring part of the overall diagnostic strategy thereby giving system level coverage for the F-16 Flight Control System. It did not however incorporate any sensory or embedded test capability for wiring. With advances in computer systems, development of a wide array of small sensors, embedding this capability is not now a difficult task. Testing has been performed in a lab environment to prove that management of wiring health is possible however, it must be designed and managed as part of the overall diagnostic system. Managing aging wiring should focus on the health and safety of the vehicle and its systems while in operation. It should also focus on the management aspect of wiring, as opposed to the waiting for failures to occur. Application to wiring in aging aircraft presents a slightly different problem. This concept has been explored by the team of AFRL, MSI and Raytheon in putting together a system that can be used to baseline the aircraft wiring at predetermined inspection intervals. The first step in that process will be to baseline the wiring to determine the serviceability of it as installed in the aircraft. Further nondestructive inspection will take place to record any changes since the last inspection. Prognostic algorithms will then make a determination as to when the wiring may need repair, individual, or wholesale replacement. This will allow the aircraft operators to "plan" for the wiring maintenance activity and schedule replacement during aircraft downtime or during scheduled phased maintenance.

**Work Performed**

Management Sciences, Inc. has been developing smart wiring in conjunction with Utah State University, Management Communications and Controls, Inc., Raytheon Systems Division in Indianapolis and AFRL to develop the components for smart wiring. The MSI team has addressed the following issues commonly encountered by maintainers:

· Identification of electronic and mechanical LRU malfunction with sensors
· Detection of corrosion of metal wiring elements
· Detection of degradation of optical wiring
· Detection of degradation of non-conductor parts
· Detection of degradation and failure of EMI Shielding
· Identification of degradation and failure of in line passive components
· Detection of degradation or cocked or misfit of connectors
· Identification of loss of waterproof integrity and/or moisture intrusion
· Detection of compromise or degradation of integration units

During 1997 and 1998, the MSI made a detailed study of problems and potential sensory solutions. The team developed ways to use Commercial off the Shelf (COTS) sensors to detect and measure physical variables using active and passive techniques. The team held three live demonstrations that showed "Smart Wiring" could be cost effectively implemented with COTS sensors in a network of smart processing modules reporting to higher level sector and area software for system level prognostic and health management.

**Findings**

Because MSI has developed the advanced instrument controller, making "smart wiring" for new aircraft is relatively straightforward. However, adding devices to make old wiring harnesses into smart wiring is not an easy task. Further, performing sensing at the flight line must comply with the goal of "do no harm". This means that sensors must remain passive until requested by the cockpit to perform any active tasks. With respect to cost and weight, it was found that weight for implementing Smart Wiring could be minimized to a few ounces by using Micro Machined Electro-mechanical Systems (MEMS) and Application Specific Integrated Circuits (ASIC) that weigh just a few milligrams each. To retrieve wiring data there are two ways that the information can be downloaded. One might be to use an Infrared (IR) link at the connector interface to retrieve the data. In a more advanced application it is envisioned that two or three wires in the harness could be used as an intranet to send data to an on-board recording system and the data retrieved after flight. The information obtained from the added sensing capabilities would be available for either on-board or off-board analysis and be used by prognostic algorithms to determine the health of the wiring. An information system needs to be developed or tailored to track wiring information, similar to the system used for aircraft engines. The Comprehensive Engine Management System (CEMS) used by the Air Force could be a model for a wiring management system. Additional cost would be recovered with reduced maintenance throughout the operational life.

It was found that there are several very interesting high return benefits to use of Smart Wiring. Maintainers will be directed to exact locations of shorts and open conditions rather than using current labor intensive cable test methods. Formerly difficult tasks, such as testing for protection from Electro Magnetic Interference (EMI) will be performed from within the wiring, without removing or disconnecting components. Another benefit relates to the problem the military experiences a large percentage of "Cannot Duplicates" conditions in maintaining electronics. The Smart Wiring technology will reduce the need for Test Program Sets (TPS) as the wiring will be able to test units for behavior and connectivity before removal. This will go a long way to assure that only failed units are removed for repair. Also, the Smart Wiring will be able to monitor performance after reinsertion to assure return to original condition.

**Prototype Smart Wiring**

The MSI is being actively supported by the new Joint Services Aging Aircraft Project. Plans are for the development of the first generation of smart wiring by late 1999. This prototype wiring will have form, fit, and function with a harness from a service aircraft. The prototype wiring will be subjected to various tests and used to detect salient conditions that worry aircraft owners and maintainers. Other work is progressing to develop a hand held rule and task programmer under sponsorship of the Office of Naval Research.

**Flight Testing**

The FY2000 federal budget contains appropriation of funds to build and flight test use of smart wiring sensory systems aboard aircraft. The money will fund the first production versions of smart wiring for aging aircraft, as well as smart ribbonized wiring for new aircraft. The process will take about one year. Introduction into Navy and Air Force aircraft could begin once successful demonstration of smart wiring concept is completed. (See fig 2.)

**Conclusion**

Wiring in aircraft or any other vehicle is the neural system that carries the information needed to make systems function properly. Wiring needs to be included as part of the overall diagnostic strategy. As the wiring system ages, the failure characteristics changes and it will require more frequent maintenance, and at some point it might require replacement. It makes sense from a Life-Cycle-Cost (LCC) perspective to have the ability to mange the wiring health and schedule repair, and in the case of replacement, schedule time at the Depot. It also makes sense to manage aircraft wiring on a “tail number” basis. Wiring will age differently depending on flight hours, stresses, geographic location, physical abuse, current overload, hydrolytic stability and vibration. Wiring must be included as part of the diagnostic process.

Wiring should be easily repaired in the field. Wiring maintenance using large test systems and test program sets is not the optimal system for field level maintenance. A hand held

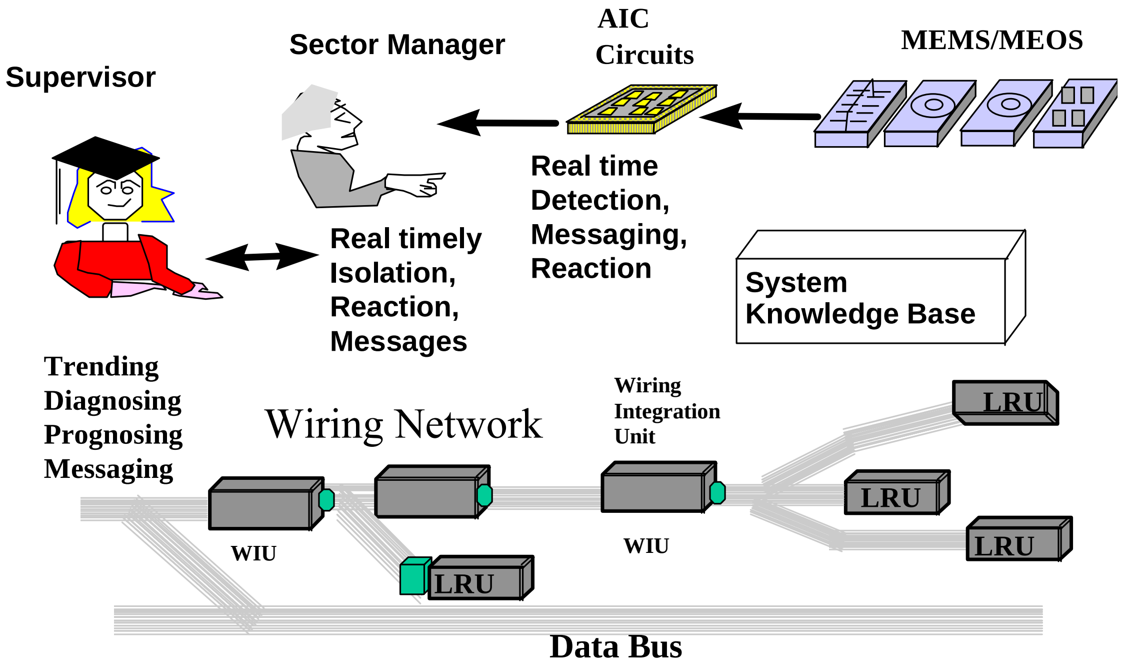


**Figure 2.**

field portable system that tests the wiring in-situ, is user friendly, and integrates with the rest of the diagnostic process is what is needed. In advanced applications, an on-board management system will provide maintainers with the information needed to make informed decisions as to when maintenance needs to be performed and be able to schedule that maintenance during aircraft downtime. As part of this architecture, there needs to be a wiring data system established for the management aspect of this system. No such system exists today.

Wiring should be evolved to new concepts, such as ROI as used in the V-22 Aircraft. The V-22 program has realized savings in weight, manufacturing costs and complexity in the wiring system. ROI can be easily retrofitted to older airframes greatly increasing the wiring reliability and maintainability and give the ability operate aging aircraft in a cost-effective manner.

## References

a. *Self-Repairing Flight Control System Volume 1: Flight Test Evaluation on an F-15 Aircraft*, WL-TR-91-3025, August 1991.

b. *Flight Control Maintenance Diagnostic System*, WL-TR-93-3022, March 1993.

c. Springer, Dale W., Witmire, Owen l. *"Integrated Wiring System Design Saves Weight and Cost for the V-22 Wing and Nacelles"*. Proceedings of American Helicopter Society 52nd Annual Forum, Washington, D.C., June 4-6, 1996