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Ground Based Vehicle Health Monitoring for Lifecycle Cost Reduction

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ABSTRACT

Unprecedented rates of change in the economic equations of air transport infrastructure are impacting military, NASA and civilian fleets. Military aero-asset operational lifespans are being continually assessed for extension, and younger assets are tasked to higher levels of mission dispatch reliability. NASA, post Columbia will now undergo a new round of safety and reliability assessments of structures and wiring on the space shuttle fleet to ensure a safe return to flight. New FAA regulations to improve aging airplane structural and wiring safety motivate comprehensive change in the approach to aviation maintenance. There are concerns that these challenges of improved reliability and life extension will further strain the resources of DOD/NASA and economic health of the civilian aviation industry. However it can be shown that the knowledge developed through implementation of these recommendations through a comprehensive vehicle health monitoring system can be used to actually reduce operating costs.

This paper will review and discuss traditional maintenance and deterministic inspection practices that must now be updated and improved to meet these regulatory and cost challenges. A solution is proposed to optimize vehicle health monitoring based on developments by Honeywell International Inc. on an integrated, ground based vehicle health monitoring system. This comprehensive vehicle health monitoring system consists of two major elements. The NOVA Wire Integrity Program™ provides cradle to grave monitoring and management of the wiring system. The SAM™ Structural Anomaly Mapping system monitors and manages the lifecycle structural condition of the airframe. This collection of fully automated scalable sensor modules and robotic systems allows complete inspections of wiring and airframes using non-invasive sensing techniques, whether in a fully crewed hangar maintenance bay, in the aircraft interior, or on-wing on the carrier deck. The total vehicle health monitoring and management system can provide a quick comparison of results across a fleet of aircraft to detect early indications of fleet-wide problems. This can reduce the manpower dedicated to these activities while improving early detection of wiring and airframe defects. The system can be customized for any aircraft/space vehicle, and offers inspection and analysis in hours without requiring removal of the aircraft from flight status. By providing repeatability and consistency of measurement, NOVA/SAM™ provides optimal reliability for the detection of critical vehicle wiring and structural anomalies. This knowledge will enable a transformation of traditional maintenance practices, extending maintenance intervals, and therefore reducing cost, while improving safety and aircraft availability.

THE CHALLENGE FOR WIRING

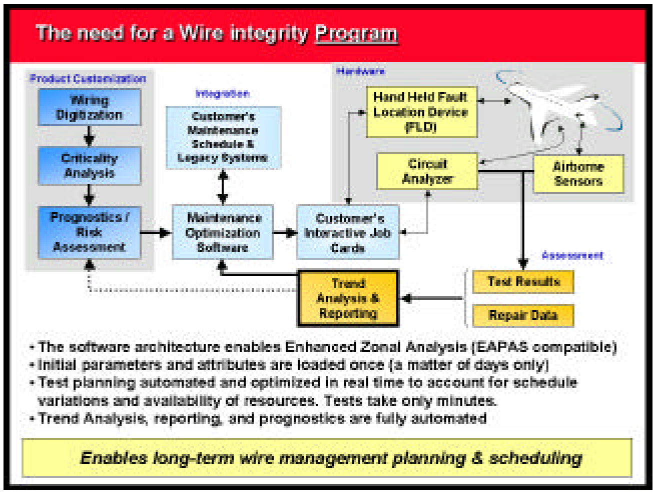
WIRING AGES FROM THE DAY THE AIRCRAFT ENTERS SERVICE

Recent accidents, such as TWA 800 and SR 111, have increased awareness that proper wiring maintenance is important to the safe operation of aircraft. The associated investigations, hearings and industry research have pointed out that the way that the industry currently maintains aircraft wiring appears inadequate. How significant the problem is and the actual risks associated with it, are currently a subject for debate. However, it does appear that the number of wiring related incidents is increasing, as is the average age of the aircraft in the airline fleets.

Fundamental to addressing the subject of wire integrity in aircraft is the understanding of the origin of wiring anomalies. Wiring anomalies take many forms. They can be obvious broken or shorted wires, bent pins in connectors, or wires routed to the wrong termination points. Less obvious are subtle changes that occur over months or years. In fact, anomalies can be considered as coming from four general sources:

- Contamination (from metal shavings from repairs, exposure to fluids…)
- Physical abuse (from stepping on wires, improper restraint…)
- Aging (from flexing, bending, environmental effects…)
- Environmental factors (such as humidity, vibration, temperature, light…)

These problems take a toll on wire systems that result in aircraft downtime, unnecessary component removals, and safety hazards. It is important to note that these



factors affect wiring integrity from the very day the platform enters service. One of the manufacturers interviewed quoted that there are more faults in the first 100 hours of operations than there are in the next 900. The ultimate goal is to mitigate anomalies prior to an aircraft leaving ground.

PROACTIVE VERSUS REACTIVE MAINTENANCE

A cultural change relative to wiring is required. Maintenance on wiring is currently performed using visual inspection methods and is very reactive by nature. Notably the FAA data proves that only 25% of the faults can be discovered through a visual inspection. A wire in a large bundle or within a conduit will only be inspected when the encompassing system has incurred a failure. Failures can be benign to severe. We need to find a way to predict when this failure will likely happen, and design a more proactive maintenance plan with sophisticated diagnostic and prognostic tools that go far beyond and complement human interpretation.

First and foremost, we must consider wiring as a stand-alone system that gathers performance data accurately and then isolates failure modes and effects, and their criticality to mission readiness. In most applications, wiring does not have a built-in-test or a suite of sensors to monitor its health. As a result, little actual data is available today to effectively predict rates of degradation and probability of failure from troubleshooting reports. Most of the failures are usually tagged against components in the aircraft; misleading the operators in isolating the true root causes of the failures and the actual cost of wiring related issues.

THE NOVA APPROACH

OVERVIEW OF A WIRE INTEGRITY PROGRAM

The prime objective of a wire integrity program is to enable the collection and management of data to effectively monitor wiring health while the aircraft is in active service. A wire integrity program has several components that are interdependent. As per figure 1, four main activities can be outlined: 1) Modeling, criticality analysis and initial prognostics; 2) Maintenance planning and integration with existing systems and practices; 3) Actual monitoring and testing on aircraft; and 4) Real time data capture, analysis and update of prognostics and maintenance planning based on performance trending against established safety thresholds.

Figure 1: An overview of a wire integrity program

Initially, a comprehensive wire integrity program will use existing operational data, focus group knowledge (manufacturer, maintainers…) and industry averaged aging parameters, which is most notably on insulation material. Failure modes and effects will then have to be modeled to provide accurate initial maintenance forecasts based on criticality.

Once implemented, the wire integrity program data management features will be used until aircraft retirement to recommend zonal inspection intervals that are the least intrusive (avoiding unnecessary interconnects de-coupling) and the most labor efficient, while minimizing risks of failure. It will adapt its prognostics automatically based upon data analysis, and regular laboratory analysis of removed samples during modifications, repairs or upgrades.

To be effective and usable, a wire integrity program must be fully integrated within existing maintenance programs to minimize interruptions, training and associated costs. To minimize training and actual time for inspections and associated costs, its features must be simple to use by the operator with integrated, easy to use graphical interfaces and seamless operation. It must be agile to adapt instantly to changes in aircraft schedules, availability of trained operators or availability of test equipment in the field.

A wire integrity program will have different requirements from different users across the community. A line maintenance user will need fast fault isolation support in a portable format. A depot level user will want more troubleshooting features and system level testing capability. A maintenance engineer or manager will need compiled data across aircraft.

An operator with multiple locations would need a client-server architecture enabling:

- Centralized data management and configuration control
- Remote diagnostic and on-line support
- Simplified publications, policies, training
- Standardization of practices

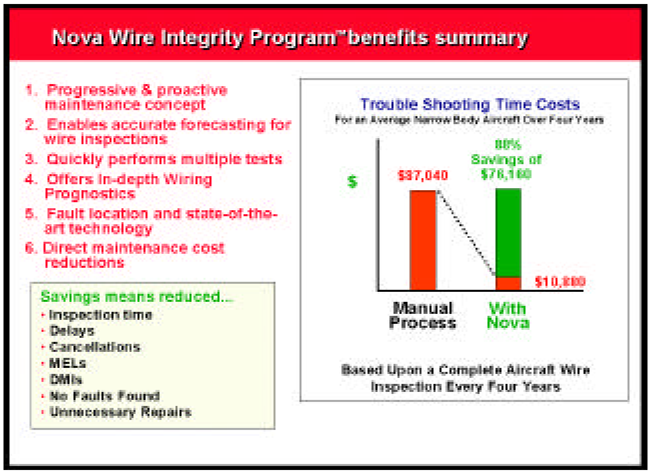


Figure 2: A Wire Integrity Program Savings Potential

THE BENEFITS OF A WIRE INTEGRITY PROGRAM

As demonstrated on engines and airframe structures, it is anticipated that a progressive and proactive maintenance concept where probability of wire failures can be determined will enhance safety levels while reducing costs. Preventative maintenance minimizes on-condition failures and improves dispatch reliability.

Accurate forecasting for wire inspections minimizes the unknown element of inspection time. Multiple tests and real time health monitoring across aircraft zones and multiple wire bundles are performed accurately providing efficient and comprehensive testing. It is anticipated that labor-intensive visual inspection requirements might be reduced as a result of the use of advanced Non Destructive Testing (NDT).

Based on Honeywell survey material, between 3 and 10 percent of total maintenance hours are spent on wiring issues, mainly on reactive troubleshooting. A state of the art wiring integrity program will enable maintenance personnel of all experience levels, from novice to expert, to identify the location of electrical faults within inches minimizing troubleshooting time, delays and flight cancellations.

Currently, the data surrounding wire defects is immersed into component removals and troubleshooting reports. A new ATA sub-chapter 97 has been recommended by the industry, to treat wiring as a system. A wire integrity program has the potential to reduce, notably, the rate of unconfirmed removals. As a result, a reduction in spares level and its associated logistics is anticipated. An estimated 40% of the removals are unconfirmed or No Fault Found. A large majority of these could be mitigated if the root cause of the problem was diagnosed in the first place: Wiring.

As exampled in figure 2, Honeywell has evaluated that a visual inspection program on a commercial widebody cost $87,040 every 4 years (direct labor cost only), and returns only 25% of the possible findings. This leaves the operator with a potential risk of failure and the need for troubleshooting labor, spare LRUs, delays, flight cancellations and other variable costs not accounted for.

The use of a wire integrity program to perform the same inspection over the same period of time could only cost 1/8th of the above, or $10,880 in direct maintenance costs and probably a lot less in troubleshooting and associated costs.

Honeywell based on its findings to date estimates that implementing a comprehensive wire integrity program will save no less than a conservative 20% on direct maintenance costs associated with wiring. Assuming an averaged $270 maintenance cost per hour (B767 & B777 form 41 data Q1/01 – Airframe Labor), and that a conservative 10% of that is wiring related (inclusive of labor, spares, No Fault Founds (NFF), AOGs, Delays & Cancellations…), current costs are in average of $27 per hour. Savings 20% of this by implementing a wire integrity program would reduce costs to operators by a significant $5 per flight hour.

CONCEPTUAL OVERVIEW OF HONEYWELL'S APPROACH

Honeywell has taken the challenge to assemble a team of specialists to supplement or replace existing techniques in effect today in the industry, primarily based on visual inspection and the use of multi-meters. These techniques are reputed inefficient, even by the FAA, and are primarily reactive to a known failure.

The goal of Honeywell's Nova Wire Integrity Program™ (Nova) is to provide the aerospace industry with a comprehensive suite of technologies that are integrated into an effective and usable format. The intent of this program is to support aircraft operators and maintainers on the flight line, overnight performing routine maintenance, at fixed base operations, and in major maintenance. The Nova program includes services, software, laboratory support, computers and servers, and testing equipment to address this challenge.

The Nova program capitalizes on enhanced zonal analysis processes and prognostication of risk based on complexity and population of the zone. The available state of the art suite of test equipment can take sample tests at a rate close to 5,000 tests a minute and pin point the location of the failure within inches.

The prime objective of Nova is to enable and ease the collection and management of data to effectively monitor wiring health during the aircraft in service time. Nova has several components that are interdependent.

TECHNICAL DESCRIPTION OF NOVA

Honeywell Nova System Architecture

The Honeywell Nova Wire Integrity Program is an integrated solution for maintaining wire integrity. The tool suite can stand alone or work in a networked environment. The Nova system is comprised of ground based hardware and software components that aid the user in testing, managing, and analyzing aircraft wiring health.

The Nova system is implemented in an open architecture that provides flexibility in test equipment selection and integration. The current Nova hardware configuration includes two pieces of test equipment: a FLD-1000 Fault Location Device (FLD) and a circuit analyzer model HIT-1000. The 3rd element of the system is a computer to host the suite of software applications.

The HIT-1000 is a compact and portable wiring analyzer that supports up to 300 test points of switching. This system tests cables, wire harnesses, chassis and electrical racks, relays and control panels. The FLD measures the distance to a fault from one end of the harness, thus saving time in locating a fault after the circuit analyzer detects an anomaly.

The Nova system is operated through a data driven integrated suite of software applications that capture models of the harnesses, generate test sequences and operational instructions, execute the tests, record and analyze the test results, and produce reports to identify trends within an aircraft or across entire fleets. This combination provides a state of the art suite of test equipment that can take sample tests at a rate of 5000 tests per minute, automatically classify failures and pinpoint their location to within inches.

At the heart of the Nova system is a relational database called RDS that stores information about the aircraft in a given fleet, the configuration of their wiring systems, and the results of wiring tests that are performed throughout the life of the aircraft. The RDS, built upon relational database technology, interfaces with commercial off-the-shelf software products that provide Nova functions.

For each piece of test equipment or sensor, the Nova system provides a software bridge that allows information collected during a test to be stored in the database as it associates with a specific aircraft or wiring component. As this data builds, Nova employs a knowledge base application with analysis and reporting features that provide information about unfavorable trends and recommended maintenance and test intervals. With all of this capability, the user simply works with a single browser based graphical user interface. The Nova interface allows the user to enter aircraft and wiring system data, to initiate testing with any of the integrated hardware, to view trend data, and to generate reports. Some examples of Nova reporting capabilities include failures per aircraft type, harness number, tail number or subsystem; failure types per part number, component or zone; number of part failures versus age; and testing and repair hours over time.

The client-server architecture of Nova provides deployment flexibility while insuring data security and integrity. The client component includes the graphical user interface, the test equipment operating software, and the bridge software that provides the interface between the test equipment software, the user interface, and the RDS.

Testing Capabilities

Figure 4 shows the types of tests that can be performed with Nova and compares the capabilities to those of existing techniques. With the existing visual inspection techniques, technicians can detect some wiring anomalies. Unfortunately, many wiring bundles cannot be inspected visually without extensive labor hours to provide the appropriate access. Nova can aid in detecting many anomalies – shorts, opens, damaged insulation, damaged conductor, damaged shields, corroded connector, fault location/interpretation, life limit, and components/configuration check – without the need for visual inspection and access along the entire length of the bundle. With the Nova Wire Integrity Program, technicians can perform a variety of tests that can detect anomalies in wiring and the degradation of wiring and insulation caused by contamination, physical abuse and aging. These tests include the following: TDR, Continuity, Isolation, Capacitance Measurement, Resistance Measurement, Conductive Fluid Scanning, and WIDAS Test.

		Existing Visual Inspection	Nova Test Capabilities: TDR	Continuity	Isolation	Capacitance Measurement	Resistance Measurement	Conductive Fluid Scanning	WIDAS Test
Anomaly Detection	Shorts		X		X		X		
	Opens		X	X		X			
	Damaged Insulation	S	S		X	X		X	
	Damaged Conductor	S	S	X		X	X		
Advanced Capabilities	Damaged Shields	S	S	X	X	X			
	Corroded Connector			S	S	S			
Additional Capabilities	Fault Location/Interpretation	S	X			X	X	X	
	Remaining Useful Life								X
	Components/Configuration Check			S	S	S	S		

Figure 4: Nova Test Capabilities

Nova Methodology

The aircraft industry is currently employing a test-centric approach to address wiring problems. A wire health management solution, such as Nova, overcomes the limitations of a test-centric approach by providing continuous assessment of health of the managed wires, thereby predicting the probability of wire failure over time. At its heart is a continuous risk assessment process, shown in Figure 5, that combines data from a variety of sources to predict what to test, when to test it, what testing technique to employ, and how to utilize the test results to improve the condition of the individual aircraft as well as the entire fleet.

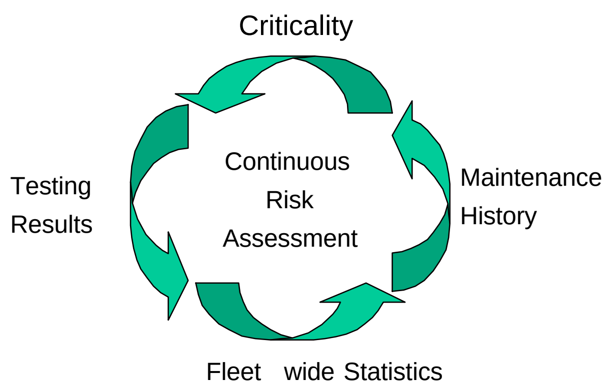


Figure 5: Wire Health Management Solution

Location	Years 1	2	5	10	20
	% Failures				
Bomb Bay	0	0	0	24	33
Wing, Outboard Trailing Edge	0	0	0	28	53
Galley/At Cabin	0	0	0	41	61
Wing,Center Leading Edge	0	0	15	23	30
Forward Electrical Load Center	0	0	24	35	48
Avionics Bay C1	0	0	43	57	68
Wing, Inboard/Root, Leading Edge	15	20	32	46	60
Avionics Bay H1	21	23	40	46	78
Hydraulic Service Center, Under Deck	20	26	39	56	64
Main Wheel Well	38	42	50	72	100
Nose Wheel Well	31	57	89	100	100
Wing, Center, Trailing Edge	0	74	91	100	100

Figure 6: Wiring Failure Statistics for the P-3 Aircraft (Courtesy Lectromec)

The essential elements of this wire health management approach are described below.

Fleet-wide Statistics: Aircraft of similar construction, age and usage will have similar reliability statistics, and the knowledge gained in a comprehensive study of a statistically significant population of aircraft may be extended to its peers. Such statistics are extremely valuable in preliminary risk assessment, and help establish the baseline expectations. Additional data is collected through all phases of the wire health management program and used to continuously refine the statistics. Data mining and/or statistical analysis techniques are utilized to identify additional factors (e.g., number of take-offs) that influence failure rates, and to identify systemic issues (e.g., problem areas like nose wheel well).

One example of this statistical data for polyamide insulated wiring on the P-3 is shown in Figure 6. This data shows the results of wiring analyses conducted in various locations on the aircraft over a period of 20 years. It is evident that wiring in some areas is subject to early failure, whereas, wiring in other areas may fail only as the aircraft ages. For example, the data shows that wiring in the wheel wells tends to experience some problems within the first year of operation. Other areas, like the galley area, do not seem to experience problems until the aircraft has been operational for 10 years. In Nova, this type of information is recorded and analyzed to establish appropriate inspection and testing intervals for specific wiring components in the aircraft.

Aircraft Maintenance History: Much of the trauma damage to wire insulation can be attributed to prior maintenance activity in the vicinity. The maintenance history of individual aircraft is therefore a significant factor in assessing its wiring health. The aircraft repair and replacement records will identify the set of wire harnesses that may have been affected by maintenance activities. In addition, the maintenance history will help identify recurring or intermittent problems caused by wiring. Maintenance records are also used to update the Fleet-wide statistics, including identification of patterns in wiring problems and estimating the costs and times associated with testing and troubleshooting wiring problems.

Criticality: Wires themselves are not critical, but may be carrying signals from line replaceable units (LRUs) that are of critical significance. Criticality and nature of the affected function are two important considerations in the risk assessment process. For example, it may be acceptable to let the wires in non-flight critical systems deteriorate to failure, but wires in the avionics, fly by wire, fuel or power distribution system must be proactively tested and maintained to prevent failures. It is possible, however, that an apparently non-critical wire may be routed through critical zones, such as fuel tanks. When this information is captured in Nova, the system will ensure that such wires are also proactively tested.

Testing Results: No single piece of test equipment can detect all possible faults and damages in wiring. The Nova solution seeks to combine test results across multiple diverse sources including opportunistic inspection during routine non-wire-related repairs, spot checks of insulation at high-risk areas, troubleshooting of wiring problems and heavy testing at hangars.

This approach to overall wire health management provides a robust, yet cost effective methodology for wire maintenance. The program seeks to employ opportunistic maintenance by utilizing occasions when wires are exposed because of other maintenance activity. The Nova system identifies wires that will benefit most from testing, thus eliminating unnecessary tests. The system also identifies the most appropriate test techniques for a given set of circumstances. By accumulating the results, Nova optimizes the benefits for each individual aircraft as well as the entire fleet.

INTRODUCTION SAM™

The concept for structural anomaly mapping is similar to NOVA in certain key characteristics that support a vision of a common knowledge management database. Maintenance and Inspection related service anomaly investigations, as well as economic assessments, have recommended that airframe structural inspections should have quantified reliability, and the records of these activities have a clear audit trail. Adhering to this discipline allows an operator responsible for maintenance and inspection activity to be aware in real time as to the effectiveness of his inspection program. It enables his knowledge of what type and what rate of progression of damage is occurring, and to what degree his inspection program is aware and helps curtail this damage accumulation. This is a central theme in the FAA aging aircraft initiative, where operators will be required to maintain such records as would demonstrate damage tolerance approach to their inspections. In order to provide this level of inspection process transparency, referential integrity to the aging vehicle must be established and maintained with high reliability. A concept for a successful response should include coherent relation of the physical airframe construction, any modifications or repairs, inspection history key events, and integration of inspection reliability data and quantified measures of airframe degradation with the airframe structural model. The process flow for this concept is shown in **figure 7**.

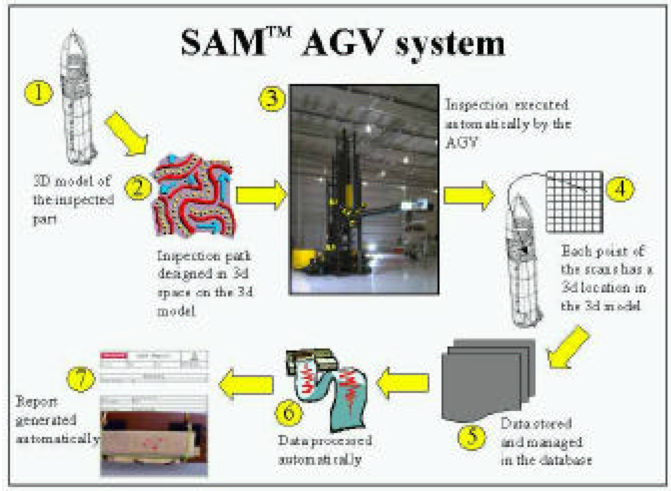


FIGURE 7: SAM process flow

SAM™ PRODUCT DEFINITION – ACQUISITION ENVIRONMENT AND CONTEXT

The SAM™ response to the voice of the customer requesting a new level of lean reliability in their inspection and maintenance program resulted in intensive product development. An offering of improved quantitative awareness and execution of the inspection program is delivered via a sensor suite deployed by the robotic vehicle shown in **figure 8** executing critical external inspections of the airframe in the context of the 3D model of the target vehicle. This means that all inspections carried out are referenced to exact point of execution on the airframe. Acquisition data is related further to the type of construction, repairs, damage history, service bulletins, and, most significantly the inspection reliability performance and acceptance criteria stipulated, for example, in the operators AAIP, or Approved Airframe Inspection Program and its references. This last characteristic imparts a high degree of performance reliability through the reduction of Human Factors in the inspection program.

FIGURE 8: SAM robotic inspection system

SAM™ SENSOR TYPES & SELECTION

While in theory there is not a practical limit on the number of sensors, the product development effort sought to have a minimum number of high bandwidth sensors with known/demonstrated reliability to accomplish a Pareto derived menu of high value inspections in aerospace infrastructure. This concept definition resulted in digital video/image capability for the documentation and analysis of traditional walk around general visual inspections. A laser vibrometer sensor was chosen to cover the inspection of composites, laminates, and general open surface corrosion. During the development of this sensor it was additionally observed that the vibrometer is sensitive to degradation of substructure members, and its effectiveness is being studied for this purpose, and related multi-element, multisite damage. To address the significant real-estate of vehicle bodies constructed of riveted aluminum, including detailed crack and corrosion inspection, an Eddy Current array sensor was chosen. For metal structure above ~.125, sensors including UT, transient/pulsed EC and others are being assessed for key customer applications. Alternate delivery systems imparting greater portability for unique environment, such as an aircraft carrier, or the internal inspection of a vehicle at the major maintenance interval are being developed in close cooperation with customer requirements.

SAM™ DATA ANALYSIS & VALIDATION OF RESULTS

The inspection data acquired must be analyzed in a manner that is consistent with the reliability proof behind the engineer developed & statistically validated inspection protocol. This analysis strategy is executed via an electronic script for each location, inspection type, and is linked to a documented performance reliability database as depicted in **figure 9.** The results of an inspection acquired with any element of the sensor suite can also be compared over time, and against inspection data and history accumulated outside of the SAM™ environment. This trending and analysis takes place in a database, with potential for data fusion on many levels. To ensure the results have quantitative value in a risk based life management context, each deployed inspection is validated at three level; the sensor, the application and the system. First, the sensor physics are validated against the proposed inspection target. Next on the foundation of a robust master gage traceable calibration, gage R&R studies are made to monitor performance of the application in a fully automated execution. Finally, the sensor and application developed are evaluated in the context of the AGV delivery system.

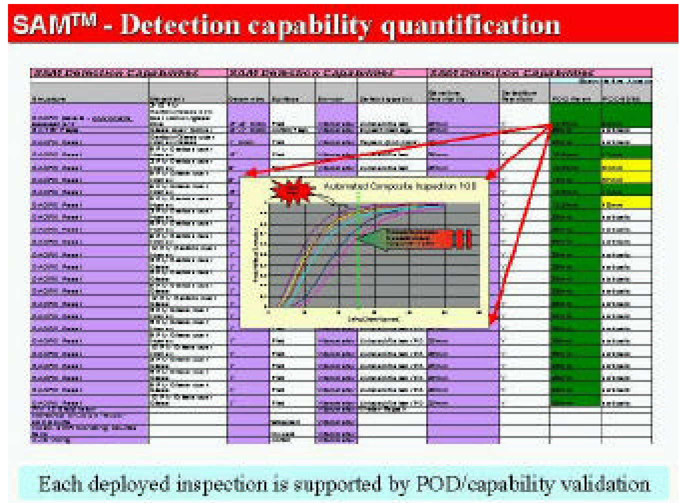


Figure 9: SAM Reliability Assurance

DATABASE COORDINATION SYSTEM

The database coordination system is the heart of the SAM™ system. It is a software system that coordinates the database, Sensor Delivery System, sensors, and processing software packages. The database holds a three-dimensional model of the aircraft. This is used to control the Sensor Delivery System around the aircraft and to steer its sensor arm to place the sensor into proximity with the portion of the aircraft that is to be inspected. The database also holds information pertaining to previous similar inspections of the airframe and any other similar airframes in the same fleet. This allows for quick comparisons to previous measurements so that change detection can be used to monitor changes in the airframe that may occur due to aircraft aging or unusual events such as bird or lightning strikes. Coordination between physical damage to the airframe and wiring events is also enabled through the linking of the SAM and NOVA products.

CONCLUSION

A comprehensive wire and structural integrity program will offer a number of key benefits to operators. First, It can deliver a progressive and proactive maintenance package that helps determining the probability of structural and electrical system failure, enabling a proactive prevention program rather than an on-condition or unscheduled/reactive one. Second, the SAM/NOVA program provides predictability to inspection and repair schedules. By using predictable inspection process and state of the art NDT/NDI equipment, failures are rapidly found and aircraft returned to service quicker. Third, technology is evolving quickly to bring speed and efficiency to the operation. State of the art equipment can test large areas of airframe structure with SAM and thousands of wires a minute across multiple aircraft zones, multiple bundles, and with multiple wires types using NOVA. Data is preserved satisfying upcoming aging aircraft requirements scheduled to be implemented as soon as 2006. Finally, a comprehensive structural and wire integrity program can reduce aircraft operators related maintenance costs by at least 20% and has the potential to improve safety of flight.

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