Wiring Integrity Research (WIRe) Pilot Study

Design for Safety Initiative

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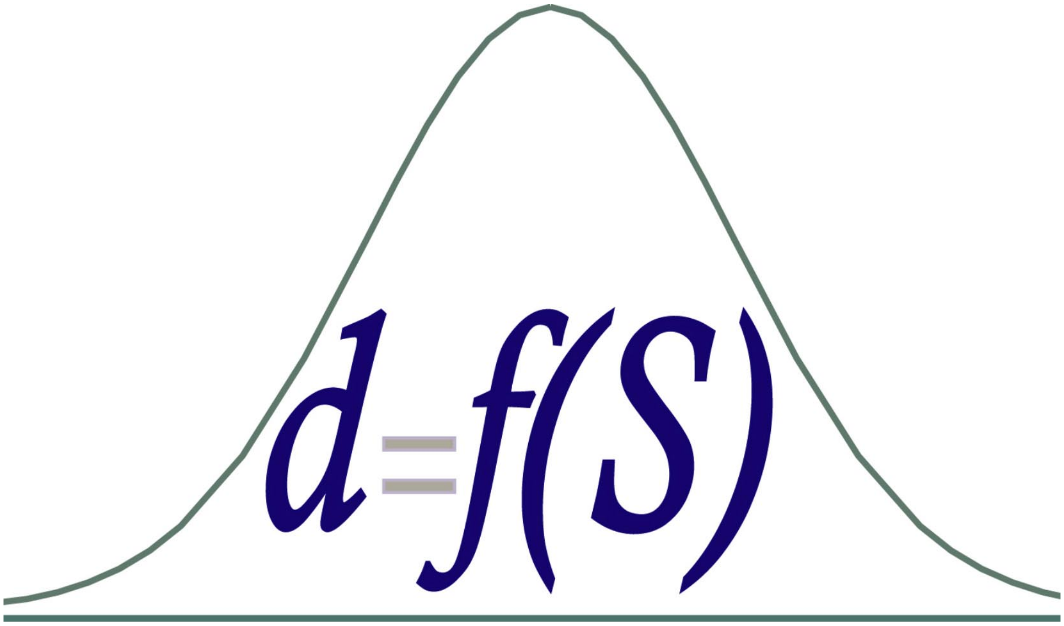

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Approvals

Matthew Blake

Program Manager, Design for Safety Initiative

Henry McDonald

Director, NASA Ames Research Center

Wiring Integrity Research Project Team Members

Julie E Schonfeld

Julie Schonfeld

WIRe Pilot Study

Systems Engineering Division

NASA Ames Research Center

Owen R. Greulich

Owen Greulich

Subteam Lead, Emerging Test Technologies

Systems Engineering Division

Ann Patterson-Hine

Ann Patterson-Hine, PhD

Subteam Lead, Informaton Systems

Computational Sciences Division

NASA Ames Research Center

Leonard Hee

Leonard Hee

Emerging Test Technologies

Systems Engineering Division

NASA Ames Research Center

Jim Cockrell

Jim Cockrell

Subteam Lead, Shuttle Application

Sverdrup Technology

Lynn Hofland

Lynn Hofland

Automated Testing

Sverdrup Technology

John H. Luu

John Luu

Shuttle Application

DMJM, Inc.

Tim Snyder

Automated Testing

Sverdrup Technology

Dana Lynch

Dana Lynch

Emerging Test Technologies

Systems Engineering Division

NASA Ames Research Center

Dwight Sanderfer

Dwight Sanderfer

Subteam Lead, Automated Testing

Computational Sciences Division

NASA Ames Research Center

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Qualtech Systems, Inc.
ECAD Division of CM Technologies Corporation
GRC International, Inc.

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Section 1 – Executive Summary

Overview

Incidents in the Shuttle Program and the aviation community have resulted in a heightened interest in the possible aging of aerospace vehicle wiring and the potential consequences of this aging on safety. A specific wire problem on STS-93 resulted in the commissioning of the Space Shuttle Independent Assessment Team, and the Wire Integrity Research (WIRe) Pilot Study was initiated due to a recommendation by that team.

The Charter of the Design for Safety Initiative (DFS) WIRe Team (detailed in Section 2 of this report) was to address Automated Verification and Validation (AV&V) of vehicle wiring configurations including risk/reliability assessments, Automated Condition Assessment for maintenance, and integrated in-flight wire integrity. Topics for research were also suggested at a later date by the Space Shuttle Program Office (SSPO). There was some overlap. The SSPO topics are listed and briefly discussed in Appendix 2.

During research towards the production of this report, the WIRe team consulted with Shuttle personnel, equipment vendors, industry users, and other experts in wire testing. Several test beds with and without simulated wire defects were constructed. These were tested by outside vendors to demonstrate currently available technologies. Various studies on the capabilities of test management software were performed, and a prototype software tool was developed to translate Orbiter wiring data for analysis of the wire architecture.

While researching this study, the team reached a variety of general conclusions.

Current Orbiter test methods are effective in the detection and localization of wiring faults (shorts and opens), but there is no reliable technology for detecting wiring defects (anomalies that have not yet become faults). Current inspection techniques for defects are laborious and are less than 100 percent effective.

Certain technologies, including Time Domain Reflectometry (TDR) and Standing Wave Ratio (SWR), have been shown to detect some wire defects, but they are not yet practical for the Shuttle Program. They need improvement in sensitivity and automation for field use. Once practical, they could become important tools for wire testing.

However, application of new test techniques introduces programmatic problems. All test techniques to some extent increase risk of collateral damage, and the most promising techniques require accessing test points at connectors. Accessing the needed test points exposes wire components to additional risk of collateral damage, costs schedule time, and requires performing functional retest after connections are re-established.

To minimize these problems, a set of test management software tools has been envisioned. These tools would perform the function of optimizing test point selection and scheduling to minimize the effect on the remaining workflow. They would archive quantitative test data beginning perhaps with resistance and capacitance values, which are easy to obtain with test equipment that the Centers already have on hand so changing values could be identified and used to alert engineers to possible wire problems before they manifest themselves as faults. As emerging test techniques are introduced, data from these could be incorporated also. Wiring interconnection models, built using test management software tools for test point selection, have other benefits. They can be used for computer assisted wire risk analysis and can track test coverage. Tracking of test coverage is useful to maximize coverage at minimum cost, and so that fault statistics and other data can be incorporated into wire-specific hazards analyses. Ultimately such tools might be extended for use in automated in-flight wire integrity assessment, using deductive reasoning about system interconnections based on functional models.

Together, emerging wire integrity test technologies, managed using new test management software tools, will form an integrated wire test management system. The test management system will save labor from manual inspection and reduce risks associated with wire. It could be integrated within schedule constraints of the Shuttle Program. Wire integrity test technologies validated in the Shuttle Program could benefit other space vehicles and the entire aviation community.

The follow-on work to this pilot study should be to take a systems engineering approach to wire integrity testing, including a trade study, cost-benefit analysis, and risk analysis of the emerging test technologies and test management tool alternatives. Specific recommendations for a development program are given in this report in Section 4.

Conclusions/Recommendations

1. NASA should establish an integrated agency-wide program to address advanced techniques for ensuring the integrity of electrical systems in the Space Shuttle Program.

A number of independent wire integrity efforts are underway within NASA, other government agencies, and the private sector. An agency-wide program will ensure a coordinated development approach to wire integrity technologies, and will serve as a focal point for collaboration and technology exchange among these various entities. The kinds of development efforts that may be part of an integrated program could include not only test technologies, but also advanced wire repair technologies and mechanical wire protection technologies.

The Federal Aeronautics Administration (FAA) and the Department of Defense (DOD) are currently pursuing development of several technologies for defect detection, wire protection, and, for new designs, advanced techniques for monitoring of wire health. NASA should actively participate and collaborate in these efforts.

2. NASA should pursue development of automated integrity testing technologies.

a. Develop Integrity Testing Technologies

The program should foster development of a means of performing automated wire integrity testing capable of detecting wire defects. Such a system would encompass automated testing, emerging integrity test technologies, automated signal processing, and finally, integration of all of these into a system appropriate for the operational environment of the vehicle.

Current testing practices for the Shuttle Orbiter find faults in the wiring, but it is the currently unrecognized defects in the wiring, damaged insulation, or exposed conductors, that are a safety concern. As the number of defects in wiring increases through normal wear and tear during maintenance, the probability of failures increases. Development of technologies to find these defects is needed before the probability of failure due to wiring defects exceeds acceptable risk levels.

Various test technologies have been demonstrated to be sensitive to defects in wiring. None of them is yet ready for implementation in an operational environment, but several have shown promise that, with further development of the technology and the addition of signal processing capability, could be used effectively in Orbiter operations. Development of these technologies will result in reduced labor, reduced Orbiter processing time and reduced schedule and safety risks.

Time Domain Reflectometry, Standing Wave Reflectometry, and Impedance Spectroscopy are some of the more mature techniques that show promise for wire defect detection. Development of these techniques should be pursued through the use of theoretical modeling, laboratory validation, and operational testing.

Discussion about results of AV&V and integrity test technologies is found in Section 3A.

b. Develop Automated Signal Processing Techniques

Automated signal processing methods should be developed for use with defect testing techniques since the resulting data is complex and difficult to interpret.

Current evidence suggests that the more simple potential defect detection technologies will not be able to detect a majority of the defects that are of concern. Therefore, more sophisticated techniques will need to be employed to fully assess wire integrity. These more sophisticated techniques generally produce data that are difficult to interpret and require correlation with other types and the wiring architecture to provide useful information about wire defects. For example, TDR signatures must be correlated with complex impedance data and the cable harness schematics. Automated signal processing would simplify interpretation of the data, making it more suitable for the operational environment, and reduce the high level of expertise currently required. This could make implementation of these testing techniques in an operational scenario practical for routine use.

Advanced signal processing techniques could likely be employed for signal classification, feature extraction, and pattern recognition, resulting in signal processing algorithms which provide definitive results about the integrity of the wire for a testing technician in an operational environment. This would reduce the high level of expertise currently required for interpretation of test results and would make feasible the automated testing of large numbers of conductors for defects. Wavelet Analysis, Neural Networks, and Automated Reasoning have been successfully employed for similar signal processing requirements and should be explored for use in defect detection testing.

Discussion of advanced signal processing techniques is found in Section 3A.

3. NASA should pursue development of an integrated test management system for the Orbiter.

Test management tools are needed for analysis of test coverage, test configurations, and sequencing during Orbiter processing. These tools could optimize test point selection during Orbiter processing flows and archive fault and wire test coverage information that would feed into later trend analyses and risk analyses for Orbiter wiring. The need for time-consuming end-to-end visual inspection would be greatly reduced, while maintaining an acceptable level of risk, or lowering risk. These tools would maximize the value of the information obtained through the wire integrity testing described above.

An Orbiter wiring architecture model should be developed using test management tools, for the purpose of conducting test analysis and management for the Orbiter. The model database would be used to optimize test point selection and to track test coverage. Overall, it would be used to minimize the impact of testing on Orbiter processing. This model could be generated directly from current wire architecture databases.

The model, in addition to providing a path for implementing automated testing to reduce Orbiter processing timelines, could be augmented with functional dependency information to evaluate test sequencing, significantly reduce the effort for risk assessment, and eventually lead to automated diagnostics and wire health maintenance. These capabilities would allow condition-based maintenance for wire. Commercial, off-the-shelf system modeling software could be adapted for this task. A description of how this can be done is expanded in Section 3B, Test Management.

4. NASA should conduct an in-depth cost-benefit analysis on test technologies and test management software development and application strategies in order to optimize the return on investment.

The recommendations summarized here and provided in more detail throughout the report are considered the most expedient course of action to pursue automated wire testing. In nearly every case, however, there are new concepts and emerging technologies that need further development and validation. Some of the recommendations will require long-term development programs. For each recommendation there are a number of alternatives to consider. For example, while it is recommended that NASA develop and validate wire test technologies for use in the operational environment, there are many choices of technologies to consider (e.g., Time Domain Reflectometry, Standing Wave Ratio, Microwave Impulse Radar), the operational requirements for their potential use will require further research.

The cost-benefit analysis should include risk analysis. Each technology comes with an associated cost to schedule and its own added risk of collateral damage. These must be balanced against the schedule improvements and the risk reduction provided by the automated process (over the previous techniques) and better defect detection.

NASA should do a risk assessment of Orbiter wiring to determine functional models developed to determine whether risk is at an acceptable level with or without integrity testing. Functional models developed for test management tools will aid in this. A probabilistic risk assessment specific to wire could be developed using functional dependency models described in the Test Management section of this document.

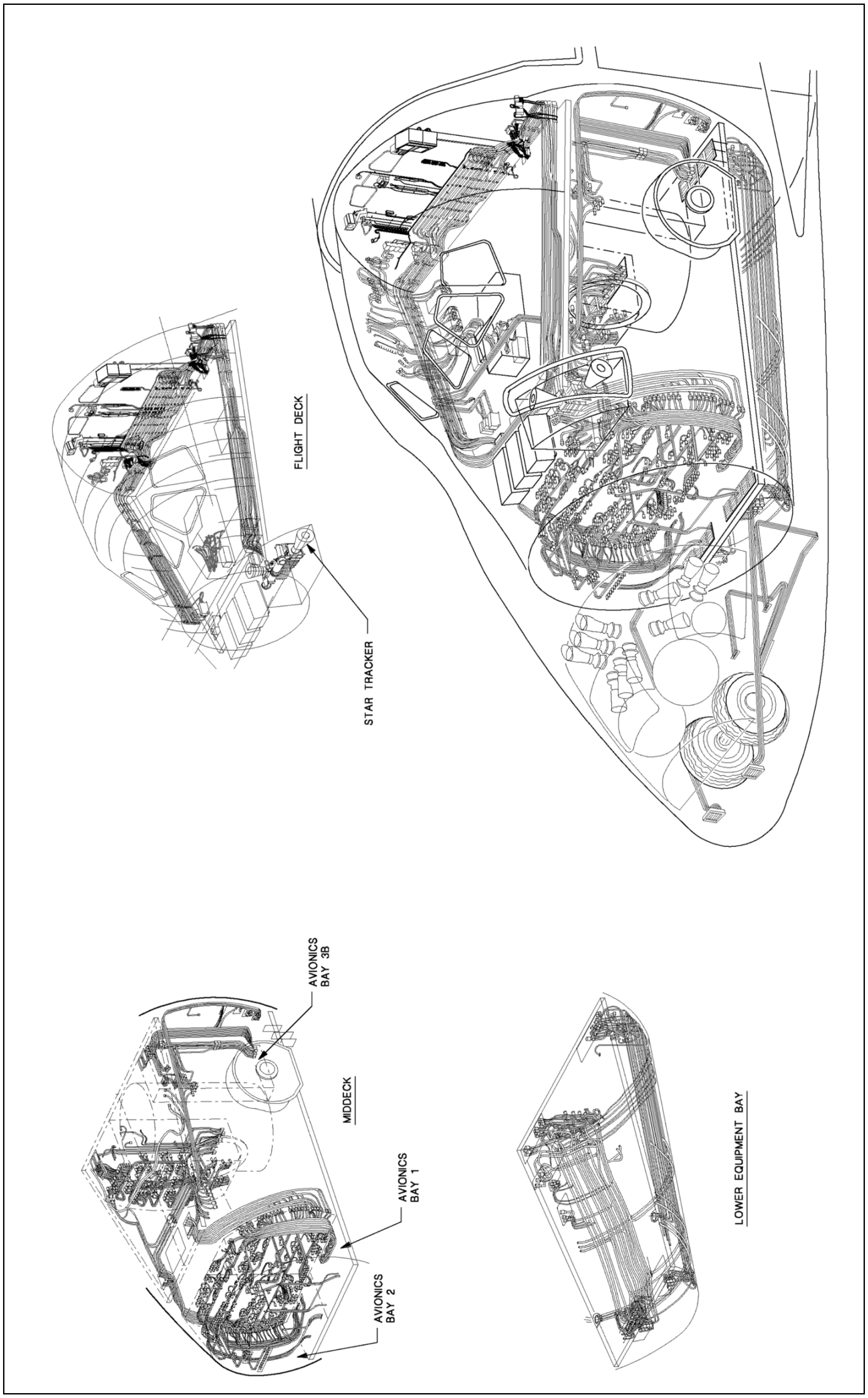


Figure 1. Some of the 200 Miles of Wire and 5,000 Connectors Found in Each Orbiter.

Section 2 – Introduction to the WIRe Pilot Study

Background

Following anomalies that occurred in the STS-93 flight, an independent assessment team (Space Shuttle Independent Assessment Team, SIAT) was convened to review Space Shuttle systems and maintenance practices. One of the anomalies that occurred was due to a latent defect in a wire that had apparently existed for some time.

As the Space Shuttle approaches its third decade of service, wire and cable harness integrity will become a critical issue that will require more scrutiny. Wires, cables, and connectors have lifetime limitations due to normal material degradation, the vibrations and stresses that they come under during launch and re-entry, and the collateral damage that occurs during normal Shuttle maintenance. New and better methods for testing and assessing wire are essential, first and foremost to insure the safety of the crew, as well as to maintain the functionality of all Shuttle systems.

Maintenance and assurance of the integrity of the wiring in the Space Shuttle Orbiter is very challenging, for many reasons. The magnitude of the wiring in the Orbiter is immense (over 200 miles, over 100,000 connections, over 5,000 connectors. Wiring (illustrated in Figures 1 and 2) is an extremely complex, yet relatively unsophisticated component of the Orbiter. Because of that, the technicians, engineers, and managers in the Space Shuttle Program (SSP) at Johnson Space Center (JSC), Kennedy Space Center (KSC), and their supporting contractors must do a painstaking job of tracking, testing, and maintaining the wiring architecture. Moreover, the SSP has been continually evolving the set of tools used for maintenance of the wiring architecture.

One of the outcomes of the SIAT investigation has been that visual inspection of the wire is dramatically increased, at least in the near term, for each of the Orbiters. Aside from the subjectiveness involved with inspections of wire, the high labor cost and the fact that much of the wire is visually inaccessible, a major concern with visual inspections is the risk of introducing additional damage in the course of gaining access to inspect the wire. Also, the rate at which defects accrue is unknown. The extent to which periodic visual inspection can maintain risks from latent defects is unknown. Ideally, a test technology would exist that is automated, non-invasive, and will detect even defects in the wire.

This Pilot Study was initiated to provide an assessment of this critical area. The Design for Safety Initiative (DFS) Wire Integrity Research (WIRe) Team conducted a systems engineering research pilot study to investigate the technological options for identifying and/or developing an intelligent, integrated wiring integrity assessment system for application to the Space Shuttle Orbiter.

Charter

The DFS was asked to address the following three primary capabilities:

1. Automated Verification and Validation (AV&V) of vehicle wiring configurations

- Auto-checking of CAD design files against as-built configurations
- Design Verifications
- Risk/Reliability Assessments

Approximate Technology Readiness Level: 6

Percent effort in this study: 60%

2. Automated Condition Assessment for maintenance

- Noninvasive fault detection technologies
- Condition based maintenance intelligent systems

Approximate Technology Readiness Level: 4

Percent effort in this study: 30%

3. Integrated in-flight wire integrity health management

- Sensor technologies
- Health management intelligent systems

Approximate Technology Readiness Level: 3

Percent effort in this study: 10%

WIRe Team Approach

The WIRe team spent a significant amount of time conversing with Shuttle Program engineers at KSC and Boeing Reusable Space Systems (BRSS), Huntington Beach and Palmdale facilities, talking with test equipment vendors, other government and industry experts, and industry users of automated testing. In order to gain experience with test techniques for defect detection, three cable harness test beds that modeled Orbiter wiring were developed. One was designed for wire configuration verification, and two in which defects and faults in the wire were induced were designed for integrity validation. Specific vendors that represented the range of features offered in commercial test equipment were chosen. They were invited to provide test demonstrations of their capabilities for configuration and wire integrity assessment.

A model of the configuration test bed was transcribed into a commercial systems integration tool, which then generated the test scripts for a commercial automated cable harness tester. A prototype software translator was developed over the course of the study. It was used to translate a part of Orbiter wiring into a tool that could then perform analysis for testing on the resulting wire architecture model. The results and conclusions of these efforts are presented in this report.

Organization of this Report

Over the course of addressing each of the areas in the WIRe team Charter, three areas of technology stood out as being crucial to the objectives: automated testing, software tools/models for test management, and wire health maintenance. These areas are detailed in Section 3 of this report with a discussion of technological options as well as findings and recommendations for each area.

The plan and scope of recommended follow-on work is given in Section 4.

Specific information on test equipment, test demonstrations, software tools explored, and vendor reports are documented in Appendices 2 through 9. An acronym and definition list is provided in Appendix 1.

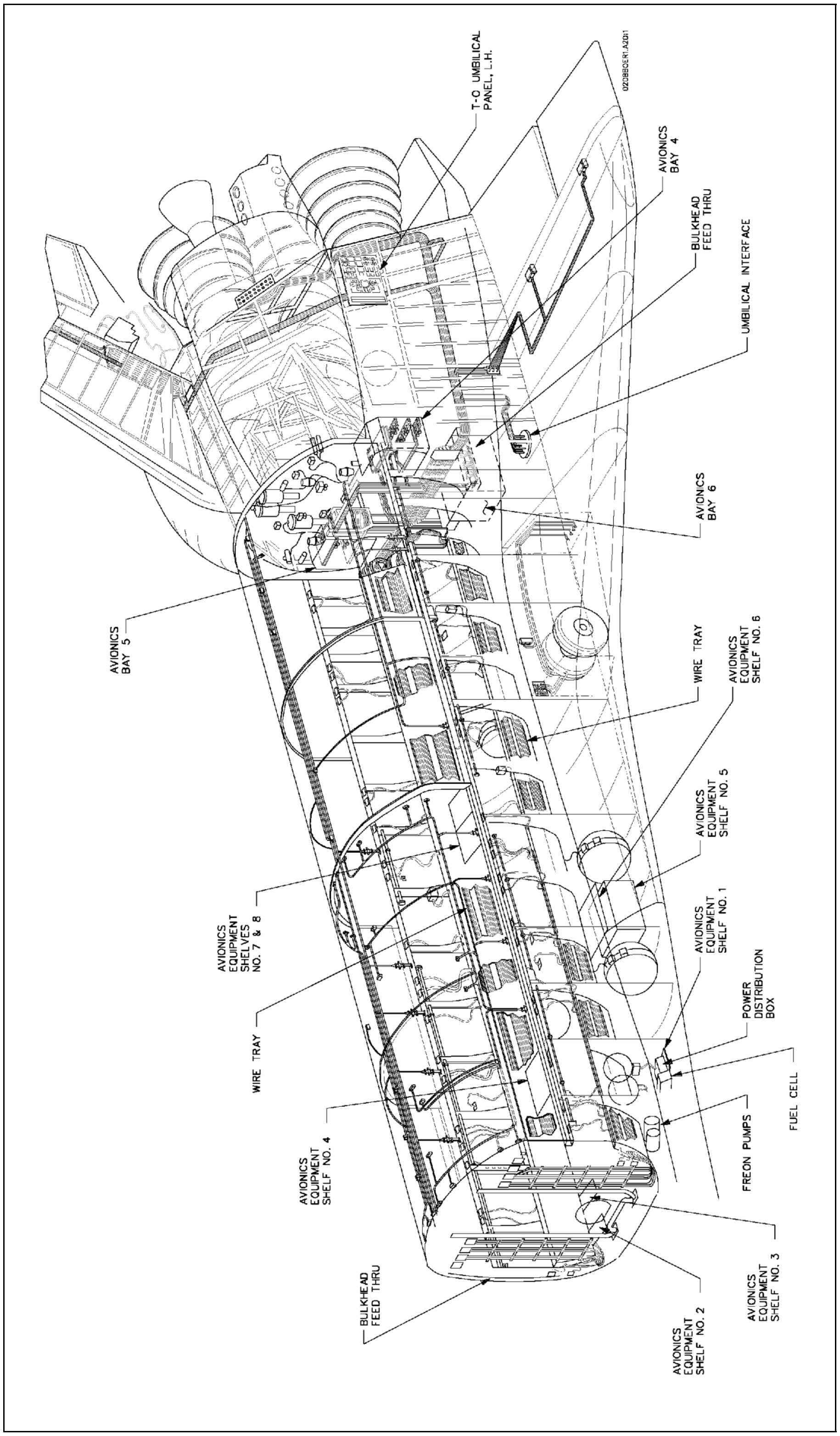


Figure 2. There Sure Is a Lot of Wire on the Space Shuttle. Orbiter Mid-Body Wire Layout.

Section 3 – Test Technologies

3A – Automated Testing

Introduction

For the purposes of this report, automated testing is defined to include the following: automated switching and sequencing, automated test generation, the test technology employed in defect or fault detection, and automated feature extraction and analysis used to differentiate defects from normal wiring system structure (wire, fuses, terminal blocks, connectors, etc.).

For various reasons, automated wire testing is currently employed in a widespread fashion only during the manufacturing phase for aircraft and Shuttle wiring. During the operational phase, it is typical to test wiring mostly as a means of identifying faults that are affecting the operation of flight systems. Until recently wiring was considered a passive system, which, once put into service, did not require inspection, testing, or maintenance. The incidents on STS-93, TWA Flight 800, and Swissair Flight 111, and other less publicized events have provided compelling evidence that regular testing of the wiring infrastructure of the Orbiter should be considered.

Automated Verification and Validation testing reduces processing time from that required for manual testing, reduce or eliminate human error in testing, and through vehicle wiring end-to-end testing, reduce the risk of collateral damage from more piecemeal testing. This is being done to some extent in the Orbiter. Automated integrity testing would be less subjective, take less time and labor, and provide greater coverage than visual wire inspections.

Implementing wire testing on a regular basis at this point in the operational phase of the Orbiter is not easy and represents a tremendous challenge, as well as a major change in philosophy and processes. Limited physical access, potential collateral damage, and tight flight and maintenance schedules are and will continue to be obstacles to the implementation of regular wiring system inspections.

Most efficient testing in many cases requires that the testing capability be included in the initial system design. Access and wire test coverage both require this design inclusion, but this capability is not a part of the current Shuttle wiring system design.

Current wire test technology provides the ability to identify and locate faults (short and open circuits). There is no currently available test technology for reliable detection of wiring defects, but there are emerging technologies that merit investment and development. The only way of making an informed choice as to where to invest is through a follow-up trade study that would include a cost-benefit analysis. This cost-benefit analysis must include consideration of the reduction in schedule and in risk attained by early identification of wiring defects, balanced against the costs of the inspection in time and money, and the probabilities of collateral damage associated with the inspection or test.

The WIRe team performed an extensive survey of test technologies available on the market and in various development programs. Both Automated Verification and Validation (AV&V) and integrity test techniques were surveyed. Details are provided in Appendix 4.

Evaluations reveal that the most promising wire integrity testing technologies TDR and SWR, combined with complex impedance spectroscopy can detect wire defects, although they will require development and automation before they are ready for deployment on the Orbiter. Also, unfortunately these techniques are intrusive, that is, require access to electrical contacts on one or more de-mated connectors. Non-intrusive techniques were also evaluated. Some of these, such as thermal imaging, have the same drawbacks as visual inspection. They require line-of-sight access to entire harnesses. Even passive tests do not entirely avoid risk of damage to wire, since they require access to the wiring and the presence of an inspector or technician.

Current Technology – Fault Detection

Automated testing, as currently employed, on the Space Shuttle Program consists of continuity, isolation, and Dielectric Withstand Voltage (DWV), commonly referred to as high pot (for high potential , with various spellings) and the capability to automatically switch for rapid testing. TDR is used in a limited fashion at Palmdale for fault location. These test techniques expose faults within the cable harnesses, i.e., a shorted or broken wire or connection. For operational environments, these tests are frequently performed with handheld equipment connected to breakout boxes for de-mated connectors.

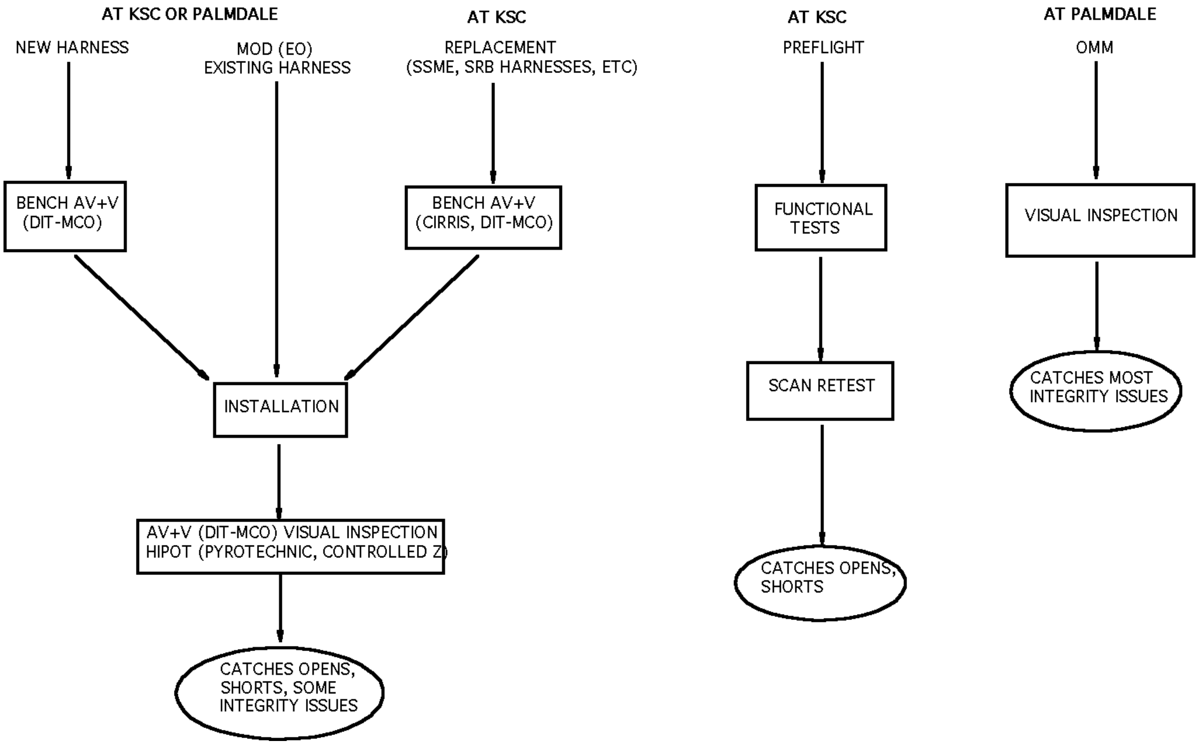


Figure 3. Present Shuttle Wire Assessment Test Activities at Kennedy Space Center and Palmdale.

Boeing Engineering, Huntington Beach is researching additional techniques which a number of vendors have implemented, including highly sensitive capacitance and resistance measurements. Ratios of capacitance and resistance measurements can be used to determine an approximate location of a fault.

Commercial Automated Test Equipment (ATE) capabilities are relatively similar from company to company, and they tend to focus on the switching capability required for rapidly stepping through all conductors of a wire harness. The differences show up in the scalability of the products, the software interface, and the support capabilities of the company. Test program inputs include connector-pin/connector-pin in a spreadsheet format, and test parameters (voltage/current, pass/fail condition). Test outputs (usually in the form of a text file saved to disk) include connector- pin/connector-pin, pass/fail result, and/or actual result value. An Auto-learn feature is available in most products. It is intended to generate a test program from a known-good harness. This feature is intended for a manufacturing environment in which many multiples of a single harness configuration are fabricated. It is likely not to provide a significant benefit for a vehicle such as the Shuttle Orbiter.

BRSS Palmdale facility is experimenting with importing CDF&TDS Automated Wire Lists (AWL) tables directly to automatically program new DIT-MCO equipment for bench testing new harnesses.

Since most of the test software is MS Windows-based, test programs and results can be manipulated using standard desktop applications such as MS Excel or Access. With these tools, the data is readily manipulated into reports or trended data.

Emerging Technologies – Defect Detection

Most wire testing, with minor exceptions, is only beginning to be extended to defects in wiring, i.e., small nicks or abrasions to insulation, shields, or conductors. Techniques to find some defects in characteristic impedance-type cables such as coaxial cable are relatively mature, using either Standing Wave Ratio (SWR) or Time Domain Reflectometry (TDR). While there have been efforts over the last 20 years to extend these techniques to non-characteristic impedance wire and cabling, there has not been an industry-wide compelling reason to do so. However, with the recent concern about aging aircraft, more attention is being devoted to defect detection for those additional types of wiring and cabling which constitute the majority of aircraft electrical interconnectivity systems.

Capacitance and DWV measurements are the most readily available test techniques being considered for defect detection. Capacitance measurements are the most simple technique that could be employed for defect detection. Capacitance techniques depend on the presence of a second conductor, conductive surface or structure, and measure the capacitance between the two. BRSS has recently been experimenting with capacitance measurements for wiring defects and trend detection.

DWV detects current leakage through a break in the insulation to another conductor or ground. Conventional DWV requires that the conducting elements be located extremely close to one another, on the order of 0.01 inches, in order for the test to be effective. Experiments have been done to enhance the effectiveness of these techniques by purging the wiring harness in a medium other than air to either reduce the dielectric constant or increase conductivity. Use of tap water, a 20-ppm concentration of salt in water, or an ionized or inert gas to alter the dielectric constant can make it possible to detect very small insulation defects within a wire bundle using either a direct capacitance measurement or DWV. Wire impedance will change, albeit slightly, due to the change in dielectric constant when a substance other than air fills the pocket created by a defect in a wire. Since the dielectric change is subtle, the thrust of the research should be in improving the sensitivity and selectivity to defects. Obviously, there are practical constraints to applying some of these techniques, especially with respect to exposing Kapton wiring to water contamination. Some, however, such as purging with inert gas seem more promising than the others do, and these should be pursued. Use of the correct gas and/or higher voltage with strict energy limitations can increase the sensitivity of DWV such that the distance to an exposed conductive surface can be as much as an inch, and the technique has been experimentally demonstrated to be effective for wires inside a wire bundle.

TDR and SWR make use of the fact that a change in the impedance of a wire causes reflection of a portion of a pulse sent down that conductor. TDR calculates distance to the fault as a function of the time required for the signal to return to the source based on the velocity of propagation of the signal in the wire. As the rise rate and duration of the pulse become shorter (referred to as higher frequency), the minimum detectable defect decreases in size. An increase in frequency for a Standing Wave Reflectometry (referred to as SWReflectometry to avoid confusion with Standing Wave Ratio) measurement has the same effect. SWReflectometry uses a swept frequency and standing waves as a means of calculating the distance to a defect. Increased frequency also has the effect of reducing the distance over which defects can be detected. In the tera-hertz range it is estimated that effectiveness will be limited to approximately 60 feet. This distance, however, is still adequate for testing a very large number of wiring harnesses, and the detectable defect becomes much closer to a typical defect size.

Use of these techniques in conjunction with other measurements, such as the characteristic impedance of a conductor, improve the ability to identify defects in the wiring. These combinations of techniques require a significant amount of validation and development before they are ready for the operational environment. The range of potential defects on different types of wiring needs to be characterized. The excitation signal needs to be optimized for wire and defect type and ideally the test techniques will to be automated. This requires the development of impedance-matched switching relays.

Another area which requires development is signal processing. It has been demonstrated on the NASA wire integrity test bed, a typical wire harness fabricated with known induced defects, that TDR and complex impedance measurements are sensitive to defects of concern. Currently, the interpretation of the data requires a high level of expertise and experience. Significant features in the time domain signature would require differentiation and signal classification, and then that information should be compared with other types of data, such as complex impedance data, for pattern recognition. This is discussed further in Test Management Software Tools in this section. Further development of these technologies has the potential to make them extremely valuable on a much broader scale.

Research on theoretical TDR and SWR response of wire and defects would also further the application of these technologies. Ames Research Center has initiated one such theoretical study, due to be complete in September, 2000.

Other techniques are currently being researched include enhanced visual and thermal imaging. Various means have been developed for the enhancement of visual inspections. These include magnification, reflective or other devices permitting viewing all sides of a conductor of bundle at the same time, and video recording techniques. In some cases infrared imaging in conjunction with resistive or external heating is used. By using real time processing it is possible to look at such characteristics as thermal inertia, allowing imaging of subsurface defects. All of these techniques are limited by visual access to a wire bundle, and subsurface imaging is limited in its ability to locate small defects by the complexity of the structure of the wire bundle. Therefore, their utility in the Shuttle workflow, even during an Orbiter Maintenance Down Period (OMDP), is limited to areas that are visually accessible.

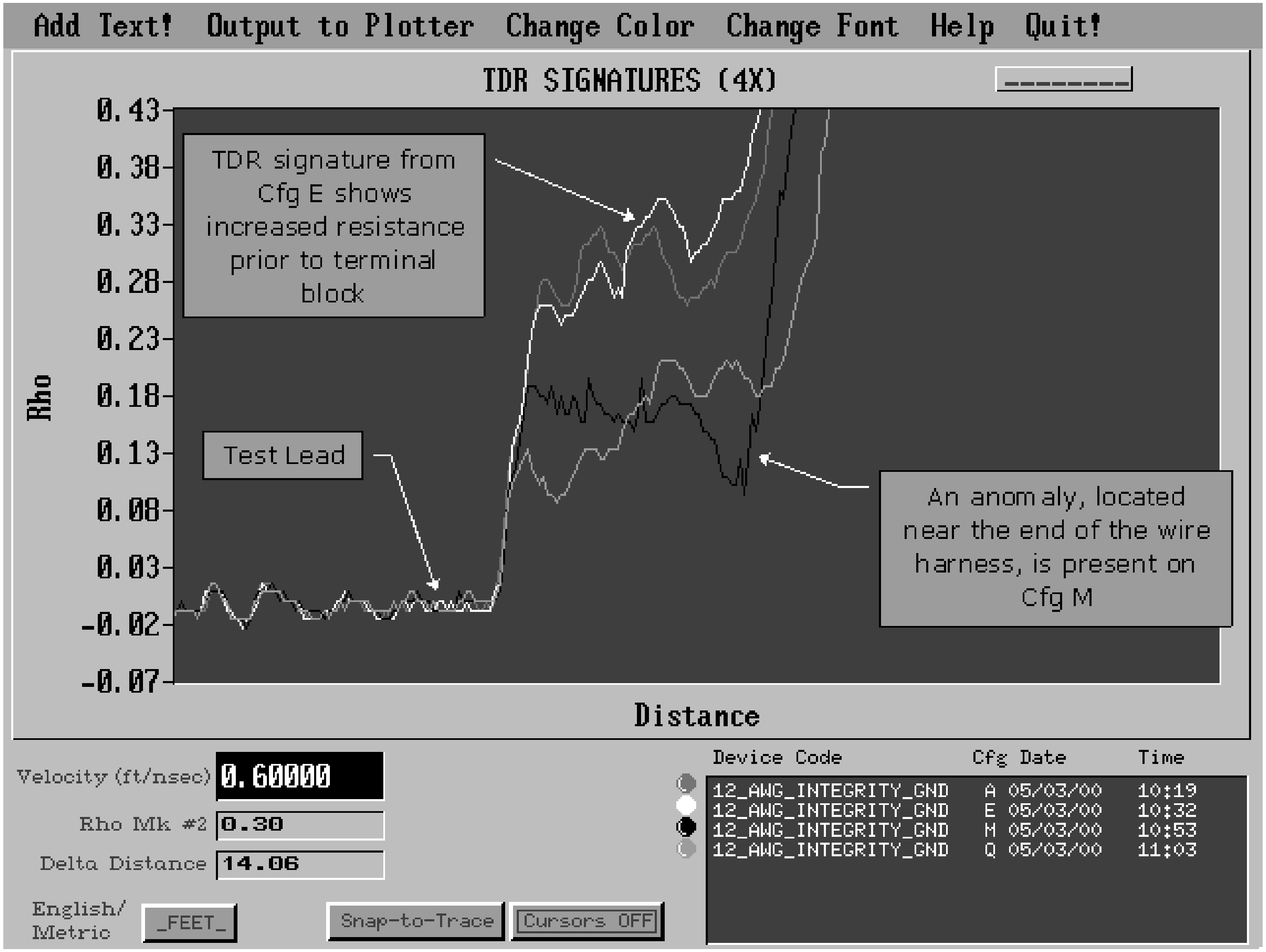
Ultrasonic, radiographic, and radio signal techniques appear, for the time being, to show less potential, although radio signals can be used to detect defects in cable shields.

Test Signal Processing and Analysis

State-of-the-art of wire testing, continuity, isolation, and DWV, are essentially pass/fail tests. Though they may yield more information about the health of a wire than whether the wire passes or fails, they don t require any significant or sophisticated signal processing.

It is for the use of emerging wire test technologies for defect detection that signal processing techniques for measurements on wire will be needed. Current test techniques do not find defects in wiring; there are enough defects being found during visual inspections to warrant new test techniques; and the most promising techniques are complex to interpret. TDR and SWR, combined with complex impedance measurements, demonstrate the ability to detect and locate defects. For measurements like these, which yield hundreds or thousands of multiple types of numbers rather than a single value, processing is required. Figure 4 shows a sample TDR trace indicating various wire features.

Time-domain reflectometry and frequency-domain reflectometry methods have been used for years without significant use of signal processing, but only because their use has been restricted to finding opens and shorts in controlled-impedance cables where interpretation is relatively straightforward. The techniques were primarily used on characteristic impedance-type wire. Now that wires have become more of a concern due to the longevity of the Space Shuttle, there is impetus to apply more sophisticated techniques like TDR and to learn how to extract the information that is contained in these measurements. Moreover, if these measurements are to be automated, it will be necessary to break away from the practice of training engineers in the art of TDR analysis and, instead develop algorithms to allow our instruments to interpret the response of the wire to the applied test signal.



TDR signature from Cfg E shows increased resistance prior to terminal block

Test Lead

An anomaly, located near the end of the wire harness, is present on Cfg M

```
Velocity (ft/nsec) 0.60000
      Rho Mk #2    0.30
 Delta Distance    14.06
English/
Metric
```

```
Device Code            Cfg Date       Time
12_AWG_INTEGRITY_GND    A 05/03/00    10:19
12_AWG_INTEGRITY_GND    E 05/03/00    10:32
12_AWG_INTEGRITY_GND    M 05/03/00    10:53
12_AWG_INTEGRITY_GND    Q 05/03/00    11:03
```

Figure 4. Expert Interpretation of TDR Traces to Distinguish Wire Features from Flaws.

The way to understand wires is to begin to model different wires and simulate their response to various test signals that will be used on them. There is an industry of modeling and simulating signals in printed circuits, and this industry has spawned at least one commercial computer program that cables. This includes insulation and shielding, and simulates TDR response based on Maxwell s equations. Another approach has been developed based on equivalent circuit models. This has successfully simulated the response of motor rotor windings to swept sinusoidal voltages such as applied by gain-phase analyzers. Once wires (including terminal blocks, fuses, connectors and various components that make up wires) can be modeled, and once it is possible simulate wire responses to TDR, network analyzer, gain-phase analyzer, and SWR signals, the tools will be in place for recognizing and extracting features in these signals.

NASA can contribute to this by supporting the efforts of researchers to understand signal responses in Shuttle wiring and correlating simulations with experimental data from test beds and actual operational vehicles. One researcher (Smith, Cirrus) proposes doing TDR simulation as a doctoral thesis. Another researcher (Rogovin, Boeing) has modeled motor-stator wiring using transmission line theory and confirmed the models with experiment. A further contribution will be made as these modeling approaches are learned and applied in-house.

Without the understanding of wire response it is only possible to guess how the signals will be processed. Some features will be recognized by simple thresholding techniques. Other features will be recognized by simple edge-detection algorithms. Traditional signal processing leans heavily on Fourier analysis for extracting information, but this is not likely to be the best method since Fourier analysis (even 'windowed' Fourier analysis) works best on stationary signals. Wavelet analysis is better suited for non-stationary signals, particularly with transients. It is likely that wavelets will be more efficient at sorting out structures in TDR signals, once the structures of interest have been identified.

TDR and frequency-domain techniques will not be the entire solution. The holistic approach taken by CM Technologies (see Appendix 8), combining TDR with SWR and other lumped parameters to characterize the state of a wire, is probably a good model to follow when we understand wires well enough to read the information that is held by all of these different signals, particularly when we begin to automate the analysis. Where CM Technologies uses an experienced engineer to interpret all the data, algorithms will be required in the operational environment for routine testing. Neural networks are ideal for taking sets of lumped parameters like those used by CM Technologies, assigning weights to the parameters and learning' their interactions in order to interpret data. Multi-valued measurements like TDR and network analysis will need to be pre-processed as sketched above, and reduced to some discreet set of parameters to be fed to a neural net along with other parameters for interpretation. We have found a number of cases where wavelet analysis was combined with neural networks to successfully interpret signals.

The need for more information from wires under test is clear, since continuity, isolation, and DWV are unable to illuminate defects. That information may be available already, buried in TDR and frequency-domain measurements and needing only the understanding to read it and interpret it.

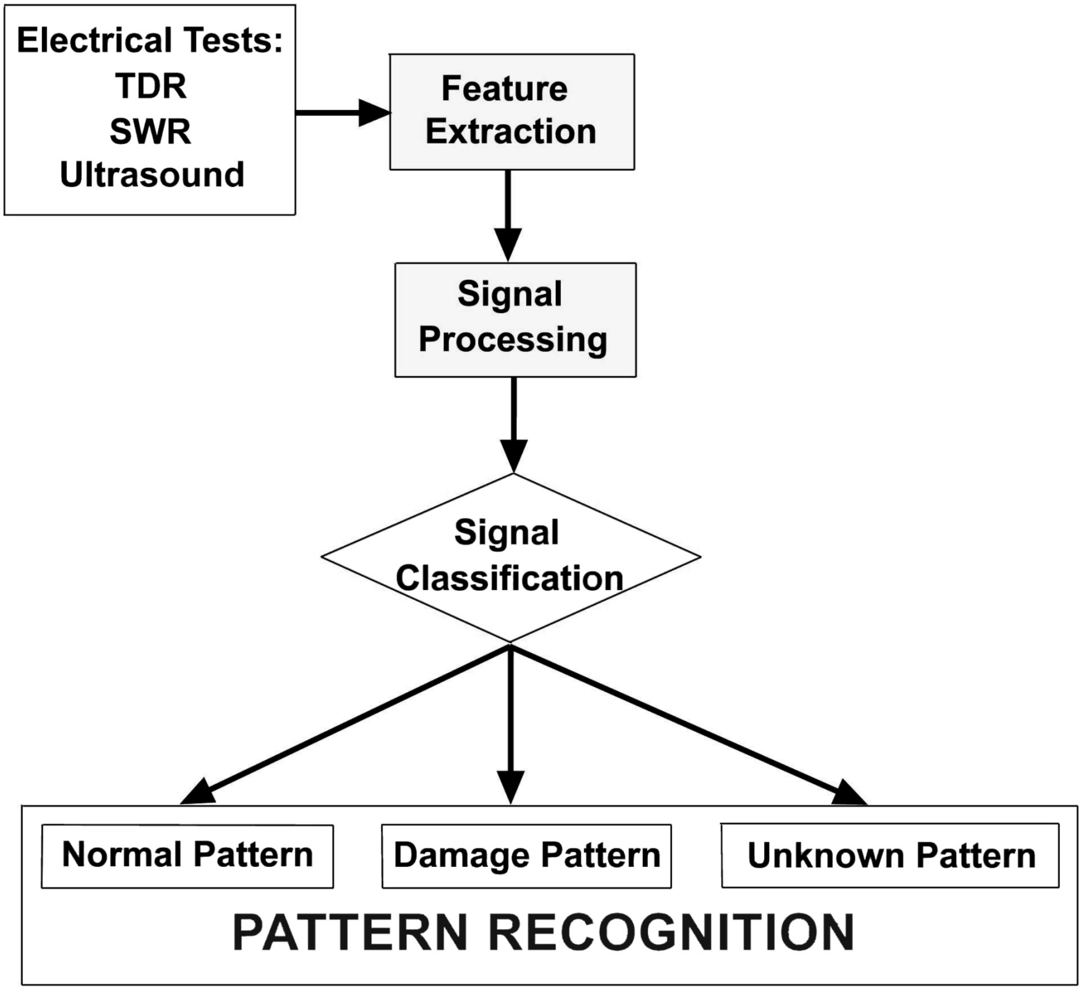


Figure 5. Advanced Signal Processing.

Findings

1. **Wires are currently tested by function and not individually identified.**
   The Shuttle Connector Analysis Network (SCAN) tracks current Orbiter configurations for wiring architecture and flags the need for functional retest during Orbiter processing flows at KSC. The SCAN database presents information in terms of system functions tested, rather than as actual wires that have been tested. Which wires get tested on a regular basis is not assessed. Wire defects and faults, once detected, are not tracked. Wire component test coverage and fault data are needed for wire risk assessments.

2. **Automated testing is done on new and modified wires.**
   After every modification, Orbiter Shuttle wiring configurations impacted by the modification are verified using continuity, isolation, and functional testing (and for controlled impedance cable, DWV). Only new or modified wire gets a full checkout in-between flights. Automated testing is currently being performed at KSC with SRBs and pyrotechnic harnesses and at Palmdale for newly manufactured cables. Palmdale test engineers are beginning to directly generate test

programs directly out of the CDF&TDS wire lists. Automation of some aspects of wire testing is possible.

3. **Visual inspections have shortcomings.**
   Much effort and labor is involved in performing visual inspections. Visual inspections will always be necessary to find potential sources of wire abrasion and for validation of automated integrity techniques, once available. As with any test technique, the access requirements alone introduce risk of damage to wiring. Visual inspections are also somewhat dependent on the individual inspector.
4. **There is a major system complexity and schedule interdependency associated with Orbiter testing.**
   The most promising test technologies for identification of latent defects in wire involve de-mating a connector to apply a test signal, but de-mating additional connectors during Orbiter flow to introduce a test can have a prohibitive impact on schedule.
5. **There are opportunities to apply Automated Test Equipment at routinely de-mated connectors.**
   Approximately ten percent of connectors are routinely de-mated at KSC. During an OMM at Palmdale, there are more opportunities for connector access to Automated Test Equipment.
6. **Analysis of test configurations, test sequencing, and test coverage is challenging.**
   Due to the immense wire architecture of the Orbiter, which is represented in a huge set of conventional hard copy drawings, analysis of automated testing is not straightforward.
7. **SWR and TDR technologies can be used to assess wire integrity.**
   Standing Wave Ratio and Time Domain Reflectometry have been demonstrated to be sensitive to defects in wiring as well as locating defects and faults. They are not currently ready for routine use in the operational environment of the Shuttle Program due to the difficulty in interpreting the resulting data. These techniques are currently most effective with a baseline set of data for comparison.
8. **There are equipment size limitations for test equipment that can be carried into the Orbiter.**
   These limitations somewhat restrict which automated testing equipment can be used.
9. **Dielectric Withstanding Voltage (DWV) tests can cause wire damage.**
   An excessive DWV voltage ramp rate can damage wire. Ramp rate limiting is generally being practiced, but current Shuttle test specifications do not require this.
10. **Turnkey test techniques are needed.**
    Test techniques for defect detection in the Shuttle operational environment need to be turnkey. Application of the test technique must be streamlined, and interpretation of the data must be simplified.
11. **Test technologies require validation.**
    Test technologies for wiring defects have not received rigorous or objective analysis. Validation of these test techniques to characterize sensitivity and limitations of the techniques must be performed before the techniques can utilized in for routine testing. Most techniques require further development to make them useful for the Orbiter operational environment. The WIRe Pilot Study has initiated the development of a model for a preliminary simulation of TDR response for Orbiter wiring.

12. **Signal analysis for wiring defects is hindered by an inability to properly interpret the signals.**
    Time-varying signals such as those from TDR and frequency-varying signals such as SWR will require processing to identify features corresponding to wire defects and faults. No one has applied advanced signal processing techniques to wire defect measurements, but work in other fields suggests that the non-stationary nature of the defect measurements will favor analysis by techniques such as simple edge-detection filters or wavelet analysis rather than Fourier analysis.
13. **Automated reasoning tools can help characterize a wire s health.**
    Automation of signal analysis will require identification of combined parameters such as complex impedance, extracting signals within TDR and SWR data, and then use of the correlated data to characterize the wire's condition. Application of automated reasoning tools like neural networks could provide that integrated solution.

Recommendations

1. **The Shuttle Program should set a goal to automate wire integrity testing, and develop a plan to put it in place.**
   Elements of this should include implementation of automated testing, development of test technologies, for defect detection, and then automation of defect detection.
2. **Evaluation of possible test configurations for automated testing on the Orbiter should be started now.**
   Since automation of currently performed testing could reduce processing time and reduce human error during testing. An assessment should be made of likely systems to test and implementation on a trial basis should begin.
3. **A risk assessment and a cost-benefit analysis should be performed for automated wire integrity testing.**
   The cost of de-mating connectors must be weighed against the benefit of identifying defects in the wiring and the costs of current inspection technologies. An assessment should be made of where automated wire integrity testing should be done because the risk of latent defects exceeds the acceptable level.
4. **In the operational environment, systems engineers would benefit from an interactive electrical connectivity model for the Orbiter.**
5. **Limitations on the DWV test voltage ramp rate should be called out in test specifications.**
6. **NASA should pursue the development of test technologies demonstrated to be effective for detecting wire defects.**
   These technologies include but are not limited to TDR, SWReflectometry, and Impedance Spectroscopy.
7. **Automated integrity testing should be incorporated at Palmdale when test technologies are mature enough to address wire integrity.**
   Processing times will be reduced over other methods of inspection and reliability increased.
8. **Advanced signal processing techniques should be developed to extract features and distinguish defects from TDR and other test data.**

Development should be based on signal responses from both theoretical models and laboratory cable harness test beds. This will simplify test criteria and reduce the need for advanced expertise in the operational environment.

3B – Test Management Software Tools

Introduction

To reduce risk from Orbiter wire defects in a practical and cost-effective way, wire integrity assessments must be managed for least impact to schedule, to have the least physical invasiveness, and cover the most critical electrical circuits. The quantitative and qualitative data obtained from wire integrity assessment, and test coverage statistics should be utilized to continuously update probabilistic risk assessments. This wire integrity diagnostic tool addresses the Space Shuttle Program request for a Risk Assessment Tool (see Appendix 2 for Space Shuttle Program inputs). Feedback from risk assessments can be used to focus test and inspection efforts, save time and labor, further reduce wire risk, and enable condition-based maintenance.

To facilitate this goal, an integrated test management system is needed. The system would be based on a computerized model of the functional dependencies of Orbiter interconnection architecture. Orbiter interconnection architecture includes the network of connected wire harnesses, connectors, terminals, and other wire features. The functional dependency model would be extracted from up-to-date Shuttle wire databases.

The integrated test management system consists of a set of software-based test management tools, and procedures for entering, processing, and utilizing results based on test data. The test management tools can be developed from model-based systems analysis software that is commercially available.

The WIRe team demonstrated two different systems analysis and test management tools and evaluated their applicability to Orbiter wire testing. The results are presented in this study.

After a trade study is performed, one of the system analysis tools could be used as a basis for a follow-on development program. This program would consist of Shuttle requirements definition, systems engineering and industry partnership, as outlined in Section 4, Plan and Scope for Follow-on Work.

Test Management Functions

An integrated test management system would consist of the following functions:

1. Sequence tests, to minimize schedule impact and collateral damage risks
2. Automatically generate test programs and instructions, to reduce labor and human error
3. Archive test results and track test coverage, to enable wire risk analysis and management
4. Report discrepancies and automatically generate dispositions, providing statistical data needed while saving time currently required by avoiding manually generating of dispositions
5. Enable condition-based maintenance, to reduce risk and costs of reactive maintenance

The flow diagram in Figure 6 illustrates the relationship between elements of the wire test management process. The purpose and benefits of the functional elements are individually described in the diagram.

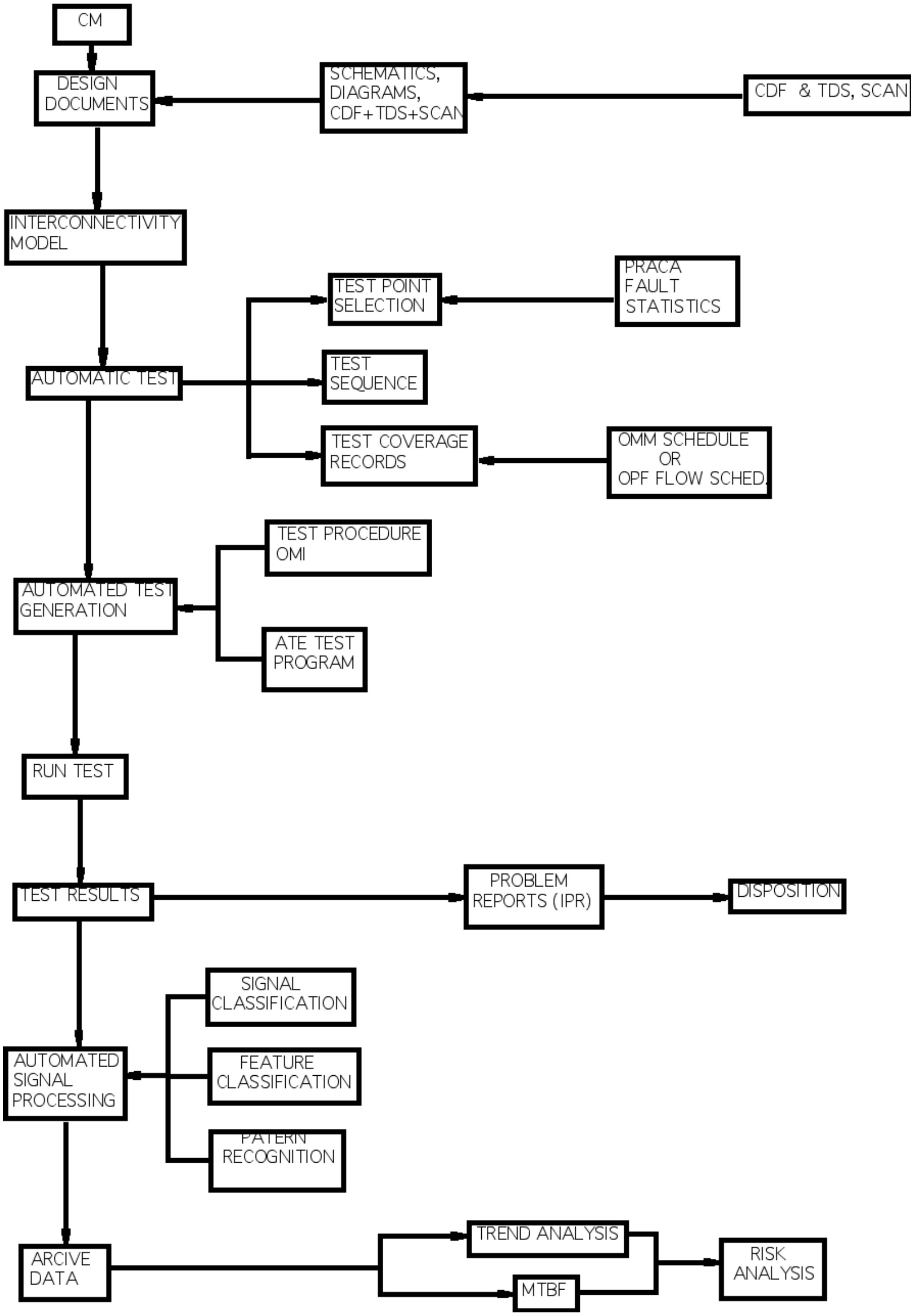


Figure 6. Flow of the Integrated Automated Test System.

Sequence Tests

After consulting Orbiter operations, engineering, and test personnel about wire testing options, certain practical issues became clear: There are fundamental schedule and access constraints to wire integrity assessment in the Orbiter. Since all wire assessment methods even visual inspection involve physical access to wire and/or test points, testing must be done in a way that doesn t expose wire to additional wear, and minimizes impact on work schedules.

Orbiter processing schedule at KSC could make integrity testing of even a limited number of the most critical harnesses impractical. More extensive wire integrity tests could be scheduled during OMM at Palmdale.

An Orbiter Maintenance Procedure (number S00GEN.520) requires that if any connector is disconnected — de-mated —at any time on the ground, all the system functions which depend on wires passing through that connector must be functionally tested once before the next flight. Functional tests take time, and have a ripple effect since they impact work on interconnected systems or affect the need to power on or off other equipment. Because of the impact on the Orbiter workflow, it is essential that unnecessarily de-mating connectors to access electrical test points be minimized or perhaps even eliminated.

One way to minimize unnecessary de-mating is to choose electrical test points at the ends of the longest interconnected runs of cables rather than at intermediate connections. Another method is to sequence integrity tests to take advantage of times when cables are already disconnected, as part of the launch flow or modification schedules, keeping track of the cumulative test coverage over time. Yet another strategy is to prioritize tests for those harnesses containing wires that records show are failing more frequently, are expected to see greater stresses, or are more critical for safety. Lower priority wire runs could be left until OMDP periods (or perhaps the associated harnesses could not be tested at all).

A sophisticated software tool can be developed that recommends, tracks, and issues Work Authorization Documents (WADs) for sequencing wire harness tests. This tool would take into account any or all of the strategies suggested above, as directed by test engineers, to reflect different priorities within the KSC workflow or during OMM in Palmdale. This tool could tailor test sequences in a way that maximizes the test coverage, while minimizing schedule impacts.

Generate Test Programs and Instructions

Once a wire harness is selected for test, the test programs could automatically be generated by test management software. This test program generation is a straightforward process with any database-oriented wire list. One scenario consists of automatically interrogating the CDF&TDS database for wire list data, translating it to the file format required by the ATE, and, perhaps, automatically generating work instructions (a WAD in the form of a standard test procedure or OMI) for test technicians to follow. The WIRe team learned of one incident in which all continuity tests failed, because a test lead breakout box was not connected to the correct connector of a set of connectors. Automated generation of test procedures could help reduce the human errors in test point identification and test set up.

The development of software add-ons to convert existing wire list data into test programs is straightforward. ATE vendors currently supply generator programs to turn ASCII wire list data into simple test programs. BRSS Palmdale is already experimenting with this process using DIT-MCO ATE. Additional information that may need to be included in the test program include pass/fail criteria and current/voltage restrictions. Rules-based algorithms could be developed, so test programs are generated to Orbiter Maintenance Requirements Specification Document (OMRSD) test requirements, automatically incorporating any requirements changes.

Automatically generating test programs and instructions would save time required for engineers to write and test new programs, and reduce some risk of human error in test setup procedures.

Archive Test Results

After test data are acquired, they would automatically be transferred from the ATE and stored in the test data archive. Full configuration data for the test article —part number, revision level, serial number, etc., along with test conditions and pertinent setup information, would be incorporated in the data archive. These data could be extracted and reviewed by test engineers for later analysis, and would also form the basis of the signal processing analysis, test coverage and trend analysis post processing, discussed below.

Archived wire test data could be baselined for a variety of analyses.

For most effective use of TDR, SWR, complex impedance spectroscopy, and other integrity measurement techniques, baseline test records are required. These baselines contain signal data for wire runs of known, intact integrity, and would be compared with newly acquired data. Differences between the baseline data and the new data would flag changes, possibly indicating environmental degradation or recently introduced wire defects.

Further statistical processing of the baseline data might assist in accurately predicting failures before wire problems occur. These predictive data could be used as input for subsequent wire integrity test sequencing, to validate predicted fair wear and tear. Accurate wire failure models could be integrated into a Condition-Based Maintenance program, described in the section below.

Finally, wire defect and fault data, detected using automated methods, will not only automatically be exported as Problem Reports (PRs) to the Problem Reporting and Corrective Action (PRACA) database (see below), but can be processed for probabilistic risk analyses.

Risk management plans can use these test data to detect trends, direct maintenance attention to areas of higher failure rates, and identify areas where design changes should be introduced to reduce risk exposure.

Report Discrepancies and Automatically Generate Dispositions

Software could be developed to automatically create PRs from wire AV&V and integrity test results, inspection reports and functional tests. After results are analyzed, PRs could be automatically generated in the formats currently in use by the Shuttle Program. Since the test management tools include electrical component reference designators, part numbers and other specific information extracted from CDF&TDS and SCAN databases, repair dispositions could be automatically generated. The dispositions would also be in the currently used formats job cards or WADs and have detailed instructions for technicians. Automatically generated repair dispositions could provide a great timesavings. Orbiter sub-systems engineers spend approximately two-thirds of their time developing repair procedures, which contain a tremendous amount of duplicated procedural information. This addresses one Space Shuttle Program Office input to the WIRe study (SSPO input is detailed in Appendix 2).

A separate study of the PRACA system is being conducted by the Design for Safety Program. An automated discrepancy reporting and disposition system could be developed in conjunction with other recommendations coming out of that study.

Provide Continuous Risk Assessments

Several of the SIAT findings in the area of Shuttle wiring indicate that the increased intensity of maintenance actions and aging effects on wires may result in increased latent wiring anomalies that need to be accounted for when assessing risk. In particular, damage in adjacent systems during hands-on maintenance and reduced redundancy due to single point failure conditions pre-existing in the wire may heighten the vulnerability of systems to additional damage. The sensitivity of critical functions to single- and double-point failures may need to be analyzed with the realization that pre-existing faults could be present in the wiring.

The original Orbiter FMECA does not specifically analyze wire harnesses or conductors. Further, it is in need of updating. Boeing re-evaluated the FMECA for wire criticality and redundancy in the early 1990s. This analysis, contained in several volumes of binders, is not easily digested or updated. Another effort recently reviewed it to recommend where redundant wires of criticality level 1 should be re-routed to reduce probability of multiple failures. Furthermore, although the Shuttle Program is considered to be in an operational phase , the Orbiter is routinely modified to add functionality. A continuously updated probabilistic risk analysis of wire is needed, but if done manually, is cost prohibitive.

Once a functional dependency model is created in a models-based tool for the purpose of wire testing, the model forms the basis for computer-aided risk assessments. Fault Propagation Analyses with multiple failure points can easily be assessed. Test coverage maps, and testability figures of merit (visibility ratio with respect to current test coverage) can be analyzed. Commercial test management tools evaluated in the study, TEAMS and MultiLinx, have this capability. The assessment below describes how the two tools evaluated could be used to study the effects of wire failures by enabling automated failure propagation and analysis.

Enable Condition-Based Maintenance

Condition-Based Maintenance (CBM) is an investment area that holds great promise for providing significant reductions in routine maintenance costs and increased operational safety for many aerospace systems. The basic concepts underlying CBM are that by directly monitoring subsystem components, and reasoning with computer algorithms to make diagnostic inferences, it is possible to calculate reliable estimates of remaining useful life. Depending on the specifics, real-time decisions would then be made to shorten or extend the time between expensive system overhauls, or to modify the real-time use of the system to minimize human or equipment damage.

For both maintenance efficiency and safety reasons, there is continuing interest in the aerospace community for monitoring system health and predicting imminent failures in critical system components. The ability to identify faults near threshold, reason about their effects, and make accurate predictions well in advance of system failure is a key technical challenge.

The test management system described above includes features for archival of quantitative and qualitative data on wire obtained from ATE measurements, Problem Reports and inspection. When automated test is incorporated, this data collection becomes available for the kind of trend analysis from which CBM decisions could be made.

Test Management Software Tool Architecture

To select optimal test points as discussed above, a great deal of information about wire interconnectivity, criticality, and test history, must be taken into account. This test point selection can be done with model-based intelligent software. The model must have elements for every wiring component, be aware of signal functionality and functional dependencies, and of criticality. The model also serves as repository of qualitative and quantitative data —such as length, location, and the value of electrical parameters such as resistance. Data are stamped with dates, so trends can be analyzed, and configuration changes can be tracked. Installation effectivities differences between Orbiters are also noted. To be current, the data must be imported directly from the CDF&TDS and SCAN wire harness databases.

The functional dependency models of Orbiter electrical interconnection architecture, generated as described above for test sequencing can also be used for probabilistic risk assessments. Failure scenarios involving single or multiple-point failures can be analyzed by computer-generated fault propagation, through the functional dependency model. If actual wire failure rates are known as a function of harness location, connector location or frequency of use, for example, these data can be incorporated into probabilistic risk analyses.

Systems analysis tools for creating and analyzing functional dependency models are commercially available.

Test Management Tool Development

The test management tools described would be implemented in intelligent software systems. Commercial systems analysis and test management tools selected through Requests for Proposals can be leveraged as the foundation for an Orbiter test management system. Requirements would be analyzed for all aspects of the test and risk management needs. Trade studies and programmatic risk analyses would be involved in build-vs.-buy decisions for each component. An outline for a test management system development plan is given in Section 4.

Two commercial products were evaluated for applicability to Orbiter testing, as part of the WIRe study.

Evaluation of Commercial Test Management Tools

The WIRe study demonstrated MultiLinx, a system modeling and analysis tool manufactured by GRC International (GRCI). The study also evaluated the Testability Engineering and Maintenance System (TEAMS), a test management tool manufactured by Qualtech Systems, Inc. (QSI).

Evaluation of GRCI MultiLinx

MultiLinx is a system integration and analysis suite of software tools available from GRC International (GRCI). It is currently being used extensively by NASA X-38 and International Space Station system engineers as a design tool. Functional dependency models are created in MulitiLinx. The model is implemented in an underlying database application 4th Dimension, manufactured by ACI US, Inc. MultiLinx includes a set of static and active component templates, including wire harnesses, connectors, relays, diodes, circuit breakers, switches, and terminal junctions that are used to model electrical interconnectivity hardware architecture. MultiLinx can also self-learn a wire harness configuration, by using the DIT-MCO tester self-learn capability. The MultiLinx harness model can then be used to automatically generate test programs for DIT-MCO Automated Test Equipment (ATE).

The MultiLinx database can store any metrics associated with elements of the model. As an example, you could store capacitance values obtained from a DIT-MCO lumped capacitance measurement for every wire pair, or between a wire and ground. This data can be stored for trend analysis to detect changes that might indicate wire degradation.

MultiLinx can also produce a graphical wiring diagram (schematic) based on the model. With additional development, this diagram could provide a graphical user interface to flag faults or AV&V problems to test engineers.

The MultiLinx wire harness functional dependency model can be used for Fault Propagation Analysis (FPA). FPA could be adapted for use by systems engineers to assist with wire risk analyses, failure scenario analyses, test coverage analysis, and perhaps wire health monitoring.

The WIRe team evaluated MultiLinx capabilities with respect to Orbiter wire harness modeling and automatic test generation. The team directed GRCI to create a model of the Configuration Test Bed (described in Appendix 5). The Configuration Test Bed contains fuses, relays, and various shield grounding junctions, challenging for modeling and test program generation. GRCI representatives demonstrated how the model was created, and then used the model to demonstrate the capability of automatically generate a test program for a DIT-MCO model 2115 tester. They also demonstrated the MultiLinx capability for self-learning the Test Bed.

GRCI successfully used MultiLinx to program the DIT-MCO and to run a continuity and isolation test on the test bed. They were able to produce a simple wiring diagram based on the self-learned data. The WIRe team suggested an improvement would be a feature to compare and display differences detected between the model and the self-learned harness-under-test.

The WIRe team did not request GRCI to demonstrate automatically importing Orbiter AWL wire data into the MultiLinx model. This would appear to take substantial development effort. The 4th Dimension database may not be optimal for handling the scope of Orbiter wire architecture and test data metrics. It was noted that external tools are available to link 4D to other ODBC-compliant databases such as MS Access or Oracle, as well as the capability to interface with databases over the Internet using web-browser technology.

Overall, however, it could be seen that the MultiLinx product could potentially be used to build a functional dependency model of Orbiter wiring architecture. This could be the basis for development of test management software tool. A detailed description of the evaluation and review of the product are given in Appendix 7.

Evaluation of Qualtech Systems, Inc. TEAMS

The TEAMS tool suite is a set of software tools for test sequencing and design for testability analysis in complex systems, real-time monitoring and diagnostics, as well as maintenance support through the use of a portable maintenance aid. Qualtech Systems, Inc. (QSI) is the developer of the TEAMS tools, and they began by introducing the basic design support tool, TEAMS, in 1992. TEAMS is being used by projects including the V22, F22, Comanche, and JSF. TEAMS uses a cause-effect modeling strategy called multi-signal flow graphs that relates the fault propagation through a system, failure attributes, system function, and monitoring points in a hierarchical model that can be graphically derived. The model can be analyzed to quantify the testability of a system, which is a measure of the extent to which a system can be tested for the presence of failures. A highly testable system implies a high degree of fault coverage and fault isolation, as well as shorter testing times and lower life-cycle costs. The models also support generation of a FMECA and reliability measures, which in turn can support the assessment of risk for the system. ARC has supported the development of TEAMS-RT, the real-time model-based diagnostic engine that utilizes multi-signal models to isolate failures during operation of a system, through the SBIR program. QSI is currently involved in two Phase 2 SBIRs with ARC to demonstrate various capabilities of TEAMS-RT for in-flight diagnostics on the UH-60 RASCAL helicopter and for 1553 data bus diagnostics for International Space Station.

TEAMATE is a companion tool to TEAMS and supports adaptive field diagnostics and test program set execution for automated testing. Utilizing the information in the multi-signal model that described the monitoring points and defines the tests performed at each monitoring point, TEAMATE can sequence the tests which should be performed to identify failure source(s) in the shortest possible time, subject to constraints on available resources, test setup costs, and operator observations, if available. Data from automated testing can be stored in TEAMS-KB, an archive for diagnostic/maintenance data implemented using Oracle. These data can easily be exported to other analysis tools such as risk management tools.

QSI performed a study to determine the feasibility of automatically creating a TEAMS model for a subset of the Shuttle wiring that would contain the necessary information to diagnose and repair wiring problems within the entire Shuttle. The MEC1 Shuttle subsystem was the subject of this study. All of the wiring information required for creating the wiring model was supplied via a Shuttle Connector Analysis Network (SCAN) Electronic wire list. This partial wire list contained all the wiring information relative to the MEC1 assembly. Using this NASA supplied SCAN wire list, QSI concurrently created manual and automatically generated wiring models for all wire paths associated with connector J3 on the MEC1 assembly. The manually generated model helped establish the rules of modeling. The automated model was compared against the manual model to verify that the automatically generated model accurately portrayed the actual Shuttle wiring. Once it was ascertained that the automatically generated model was identical to the one created manually, the complete MEC1 model was generated, thus saving significant modeling cost.

Testability analysis was performed using TEAMS to produce reports that provide failure mode coverage metrics and generate an optimized test strategy. The results of the analysis are presented in a number of formats. The primary testability report is the Testability Figures of Merit Summary (TFOMS) Report. The most important information provided by the TFOMS Report is the bar graph entitled Histogram of Ambiguity Size . The histogram provides a graph of the relative number of ambiguity group sizes. The list of specific components comprising the individual ambiguity groups is provided in the Ambiguity Groups (dynamic) test report. The analysis on the MEC1 model indicates a large number of ambiguity groups comprised of three components. This is due to the fact that most wire paths in the sub harnesses are comprised of a wire with a pin at either end. If it was necessary to break this ambiguity further, TDR or SWReflectometry tests could be used to isolate the failure to a single component and, if in the wire, locate it a long the wire. Such tests can be modeled easily in TEAMS, but were left out of the model to reflect current test procedures practiced by NASA.

Other reports generated by TEAMS include Ambiguity Groups, Undetected Faults, the Diagnostic Tree, and FMECA. These are described in more detail in Appendix 9. In discussions with KSC, it was determined that reporting the percentage of actual wire tested would be of more interest in their operations. TEAMS would require modification to report testability results in this format, but the information to do so is already contained within the multi-signal model. Examples of questions that TEAMS can currently answer are:

Question 1: Given the mate and de-mate states of the connectors, how can one assess the maximum achievable fault coverage? (TEAMS analysis computes the percentage fault detection and isolation, but it does not enumerate the covered and uncovered wires.)

Question 2: Connector 5 will be de-mated Tuesday for repairs. If I test all cable runs accessible through connector 5, what percent of all cable runs will I have tested?

The following questions can easily be formulated as set-covering problems and TEAMS could be extended to provide the answers given the information in the multi-signal model:

Question 4: Given a wire network and given enough time to de-mate/test 2 connectors only, which connectors do I de-mate and test to maximize the number of cable runs tested?

Question 5: I need to test the circuit containing run E. Which connector pair do I de-mate to access E, but use opportunities to test maximum number of other cable runs?

Question 6: Suppose connector 8 is hidden and inaccessible. What is the greatest number of wire runs I can possibly test? How many connectors must I de-mate?

Question 7: What are the fewest number of connectors de-mated to test all wire runs?

The TEAMS tool set can be used in conjunction with commercial off-the-shelf (COTS) automated testing tools that already provide the connectivity between the test program and the ATE. TEAMS could also output the test sequence directly in the format (language) required by the ATE. The utility of each approach should be studied to determine the most effective process.

Findings

1. **Wire harnesses are complex.**
   Each harness carries many functions, is comprised of many hardware components, include many junctions, and branches through the Orbiter. Test coverage of wiring architecture during Orbiter flows is difficult to discern, and selecting test points for optimal test coverage is not straightforward because current test practices are oriented towards functionality.
2. **Test strategies should seek to minimize the number of connector mate/de-mate cycles.**
   For each connector re-mate, SCAN flags that a functional retest is required for all system functions passing through that connector. As functional retest can be expensive in terms of time and labor, any test strategy should seek to minimize the number of mate/de-mate cycles. Determining possible test configurations for automated testing based on routine connector de-mates during Orbiter processing is a challenging analysis. There are currently no tools that would allow KSC engineers to optimize test sequencing and eliminate functional test redundancy.
3. **SCAN and CDF&TDS would have greater utility if they were Web-accessible.**
   Current software tools (SCAN and CDF&TDS) used in Shuttle for wiring have read access through specific Internet domains only. Electronic Notebooks are web accessible but the wiring information is not configuration controlled. The Notebooks are to be used for reference only (see Appendix 2).
4. **Current Orbiter wiring information could be used to develop models for analysis.**
   Orbiter wiring architecture information contained in SCAN or CDF&TDS could be used to automatically generate functional dependency models of Orbiter wiring components and paths in test management software tools, in order to perform test coverage analyses and for test configuration. Model-based tools such as Qualtech s TEAMS tool set can offer additional, detailed information about test coverage, testability, and test plan generation to augment the functionality of the existing SCAN database and associated tools.
5. **It was determined that there is no COTS tool that meets every test management need.**
   Companies are taking COTS CAD tools and adapting them to meet their specific requirements. Taking that as a development model, the Shuttle Program could save time and money by adapting COTS tools to meet Shuttle-specific needs.

6. **Signal paths and electrical circuits are presently documented in hard-copy integrated schematics.**
   These were created using "dumb CAD". Engineering Order changes often accumulate to a large number before drawings are updated. The drawing files are unwieldy and time consuming for systems engineers to use to analyze problems.
7. **Model-based fault diagnoses could reduce the level of effort required to monitor and diagnose systems.**
   Each system on Orbiter currently requires a team of engineers between KSC and BRSS to monitor and diagnose systems during flight or maintenance operations.
8. **A tool to aid in test coverage analysis and test configuration can readily be developed for testing capabilities.**
   Once a model-based tool is developed for the wiring architecture to aid in test coverage analysis and test configuration, it could be readily extended to include the functional information carried by those wires and test sequencing based on functional dependencies, automated diagnostics, and input to risk analysis based on fault propagation and fault tree analysis. It would also capture subsystem expertise and intersystem dependencies and would facilitate system monitoring and diagnostics during flight or maintenance operations.
9. **It is not practical to prioritize wire testing by current criticality rating.**
   Wire testing cannot be practically prioritized by wire criticality, as wire criticality as currently used is somewhat of a misnomer. Currently, the criticality associated with a particular wire is based on functionality of Orbiter systems, and does not take into account any aspects of the wire itself.
10. **There is very little in the way of system-model based tools currently in the SSP that would be an aid in risk analysis.**
    As a result, the cost is high to re-evaluate risk subsequent to a system modification, or on a periodic basis.

Recommendations

1. **There should be a better, systematic accounting of wire test coverage.**
   A Test Management Tool should be developed for this purpose. Test coverage should be tracked for specific wire components, not functions. It would enable wire testing to be accomplished incrementally. It would also provide means of tracking trends of representative samples of wire. Tracking test coverage over time enables probabilistic risk assessments.
2. **A tool to automatically generate an optimal test strategy should be developed.**
   The strategy would take into account such parameters as time available for wire test, SCAN records of available de-mated connectors, and optimal test points to minimize testing. The output is a list of selected test points, maximizing coverage of as-yet-untested wire, minimizing test physical intrusiveness, and minimizing impact on workflow schedule.
3. **Results of the testability analysis should be available in graphical form.**
   Results of the testability analysis should be available in graphical form by linking the covered wire paths with the Test Management wire architecture model, or a similar CAD wiring diagram. This

results in greatly improved visibility of test effectiveness. BRSS is continuing to develop WCAD, a CAD tool for electrical systems design, currently being used for Cargo wiring. An alternative approach to developing TEAMS would be to develop a complementary tool to WCAD that would perform the same set of functions proposed for the TEAMS tool, perhaps building on SCAN functionality

4. **The TEAMS tool set should be augmented to assess the full potential of model-based reasoning.**
   The pilot study demonstrating the utility of the TEAMS tool set should be augmented with the functional test descriptions for a given subsystem in order to assess the full potential of model-based reasoning applied to wire integrity assessment. This could enable automated wire health monitoring.
5. **A general graphics tool should be developed to automatically generate schematic diagrams from SCAN data.**
   This would enable systems engineers to quickly track electrical signal copper paths , for diagnostics and analyses. This could be an extension of tools discussed in Recommendation #3.
6. **A database should be created for further analyses.**
   A database of wire data should be created which would include problem reports, dispositions, and test data. This database would be used as input for a risk analysis, for instance MTBF and FMEA, trend analysis data to anticipate wire defects, and to point to areas of higher risk where more testing should occur.

3C – Wire Health Monitoring System

Introduction

Thousands of parameters are monitored during ground operations and via telemetry during flight of the Shuttle. Key steps in analyzing the potential for automation of these activities are to first look at the available observation points (sensors, tests) into the system, determine how these data are used in decision-making, determine potential algorithms to assist in the decision-making functions, and then determine the computational requirements for these algorithms and their communication with the system. The capability of algorithms to be supplemented with additional sensor data where it is deemed possible to augment the communication stream with additional parameters pre-existing on the bus needs evaluation. The Shuttle s caution and warning system architecture and existing capability are key sources of information on this issue

The caution and warning system for Shuttle software and electronics provides the crew with visual and aural cues when a system exceeds pre-defined operating limits. There are four classes of alarms used in the caution and warning system: 1) class 1 or emergency, 2) class 2 or caution and warning, 3) class 3 or alert, and 4) class 0 or limit sensing. The class 1 alarms are of two types, smoke detection/fire suppression and rapid cabin depressurization. This is a hardware system only. The hardware includes hard-wired sensors, monitors parameters, and issues alarms. Class 2 alarms are also of two types, primary caution and warning and backup caution and warning. The primary caution and warning system consists of hardware that monitors 120 inputs, compares the input values to limits, and annunciates alarms under out-of-limits conditions. The backup caution and warning system is part of the systems management fault detection and annunciation, guidance, navigation and control, and backup flight system software programs. The class 3 alert system is software designed to inform the crew of a situation leading up to a class 2 alarm or one that may require a long procedure taking over 5 minutes to rectify the problem. Class 0 is also a software system providing information on limits to the crew using an up or down arrow next to parameters on CRT displays. Now that the existing caution and warning system is established, it is useful to look at potential ways to augment this system with more general system functional information and decision support software. A model-based reasoning approach can provide the most comprehensive and flexible health monitoring and diagnostic capability.

Wire Health Management

A health management architecture concept for Shuttle wiring is shown in Figure 7. The health status of the wiring can be determined by performing electrical tests such as continuity, isolation, and DWV, and perhaps in the future more complex tests such as Time-Domain Reflectometry (TDR) and Standing Wave Ratio (SWR) and ultrasound. The test results from continuity, isolation, and DWV can be expressed in terms of a wire path passing or failing the particular test; therefore, the results can be fed directly to the diagnostic reasoning software. In the case of the advanced test techniques, time-series data may require analysis with various signal processing algorithms to determine the values of interesting features that have been shown to be indicative of wire health. The features of the signals can be classified into patterns that are compared to a standard library of patterns for normal system status, damage status, or unknown status. These pattern groups are mapped into the pass/fail domain so that the diagnostic algorithms can also utilize these results. A third category of tests that provide an indication of system health is functional testing. In functional testing, the performance of the system is a direct indicator of system health. If a required function fails to be completed on request, then a failed status is input to the reasoning software. The functions must be mapped onto the system structural information in the model utilized by the reasoning algorithms in order to isolate problems uncovered by functional testing.

Once health status indicators are determined, they can be processed by automated reasoning software. This software provides a combination of functionality from flexible limit checking to model-based reasoning. The results from these analyses can be used to drive the caution and warning advisory system during flight or provide inputs to a maintenance advisory system on the ground. If there are patterns of behavior not well understood, further investigation by engineering may be required.

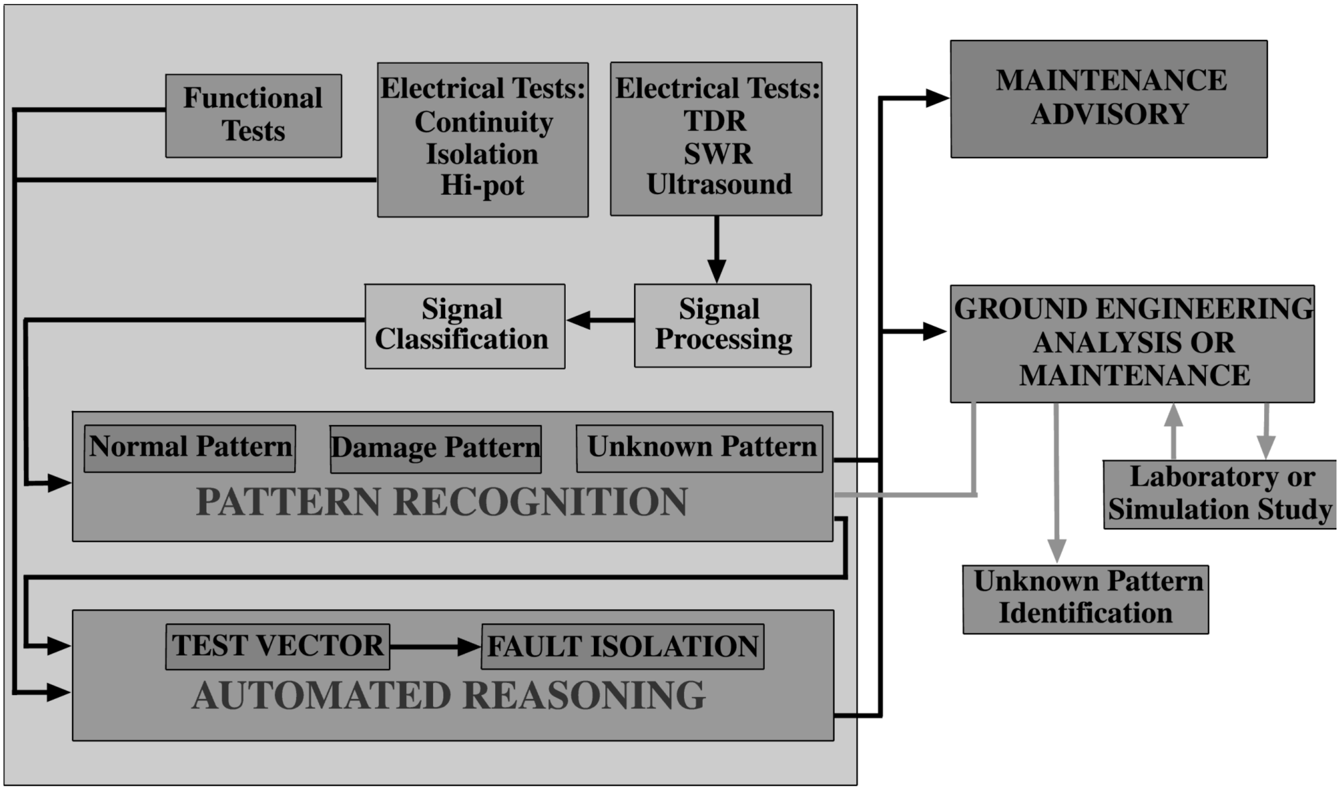


Figure 7. Wire Health Management Architecture.

Future Direction:

While development of an improved in-flight health management system is intriguing, current practice for troubleshooting problems, both on-board and with the large ground support teams, should be analyzed to formulate requirements for improving the state-of-the-practice. In addition, efforts such as the current Shuttle Cockpit Upgrades program should also be leveraged. There is an abundance of information already available in the telemetry stream, and coordination among all the various groups that monitor these data is needed to produce sound requirements for improvement.

Findings

1. **Access to wire harnesses during flight is currently not sufficient to provide active wire health monitoring using intrusive test techniques.**
2. **Software functions may be extended to utilize more flexible computational techniques.** System health status during flight of the Orbiter is determined using several thousand parameters available through the telemetry link to ground. The Shuttle caution and warning system consists of both hard-wired and software-enabled alarms. There are potential avenues for extension of the software limit checking functions to utilized more flexible computational techniques.
3. **Wire functional status can typically be determined during flight using a combination of measurements that are currently available (voltages are typically reported) and system functional status.**

Recommendations

1. **Modeling of the functional behavior of critical subsystems will be necessary in order to augment existing caution and warning information with wire health status.**
2. **Utility assessment with system functional behavior will help define effectiveness and value of implementation.**
   Assess the utility of augmenting wire component and path information with system functional behavior during ground-based testing/flight preparation first, then determine the feasibility of moving some of the model-based reasoning algorithms on-board or in the control room working from telemetry data. This assessment will help define the effectiveness and value of implementing such a system.

Section 4 – Plan and Scope for Follow-on Work

Approach

NASA should establish a coordinated, agency-wide research and development effort on automated wire test technology. Initial application would be for the Shuttle Orbiter, although wire test techniques validated on the Orbiter would benefit other space vehicles and the entire aerospace community.

A coordinated effort between centers will accelerate the development processes. The Shuttle shares the challenge of managing aging wire with the military and commercial aviation agencies. Cooperation between agencies will expedite development efforts by distributing research information and reducing duplicate efforts.

The development of test instrumentation should be approached in partnership with the leaders in the test equipment industry. NASA should direct test instrument development, qualified specifically to Orbiter requirements. A similar approach can be taken in the development of intelligent test signal processing algorithms and of test management software tools, necessary for full automation of wire integrity test and integration into the Orbiter processing and risk management programs. R&D efforts will be coordinated between test software industry leaders, university researchers, and Ames Research Center as the lead center for DFS.

A phased program of follow-on work could proceed as follows, partitioned into two products, reflecting the recommended development priorities:

Product: automated wire integrity test equipment

1. Establish an integrated, agency-wide wire test program
2. Develop test instrumentation refined for Orbiter wire integrity test
3. Simultaneously, research and develop signal processing techniques for automation

Product: integrated wire test management system

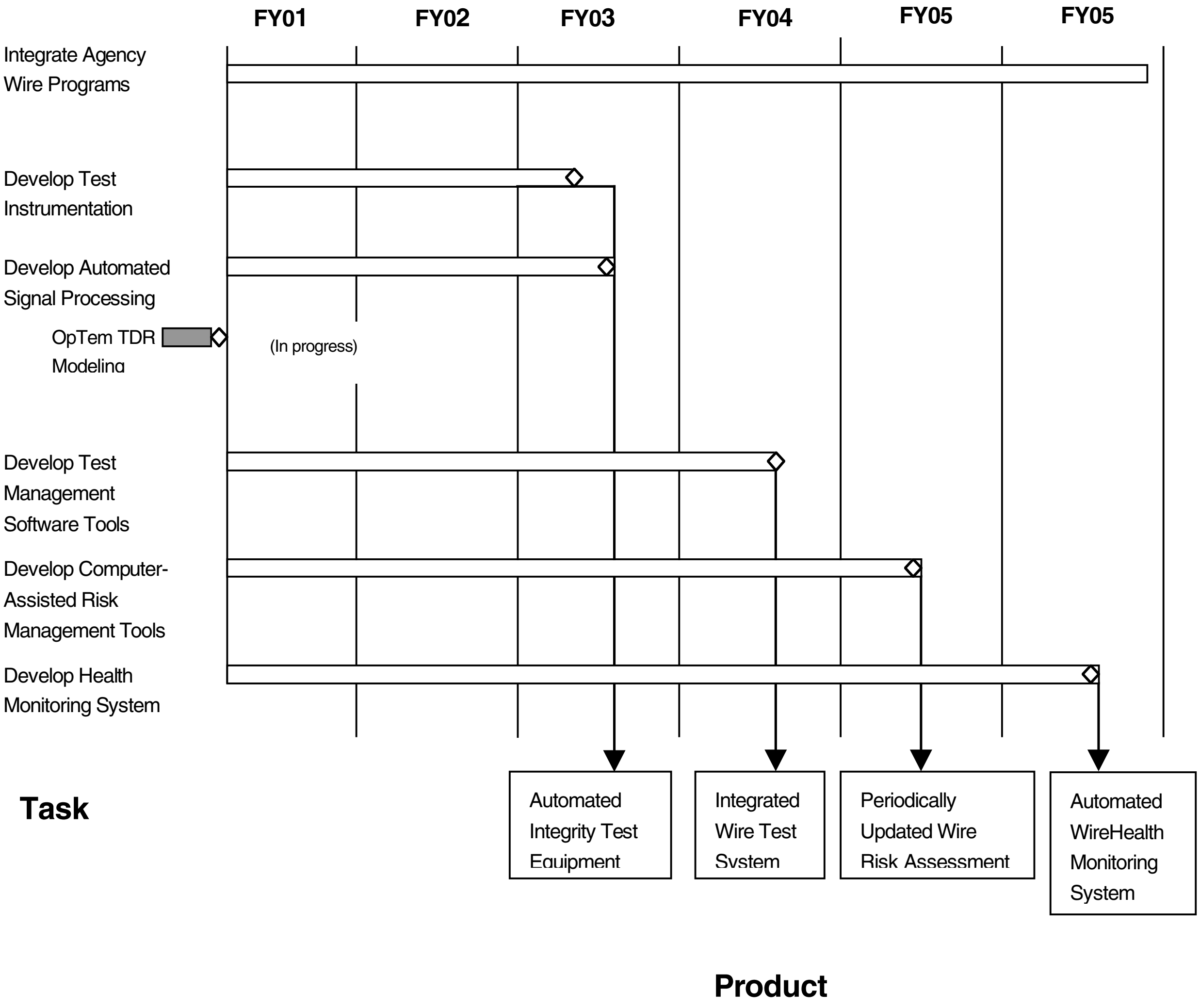
1. Research and develop the ensemble of Test Management Software Tools
2. Develop and incorporate procedures for utilizing test data in computer-assisted wire risk management system
3. Develop algorithms for intelligent Wire Health Monitoring system

A systems engineering approach should be taken in which Shuttle Program requirements and constraints are established, trade studies are conducted to select the most promising commercial test technologies and software platforms, continuous risk assessment is performed to account for both program risks and wire safety risks, and finally an implementation and operation program is established.

The final product is an integrated wire test management system.

A detailed timeline and list of follow-on projects follow.

Development Plan Timeline



Development Plan

Following is a top-level development plan, estimating the costs and timelines for follow-on work based on the above approach.

1. Establish an Integrated NASA Wire Safety Program

NASA is in need of an integrated effort that addresses all aspects of electrical interconnectivity. An agency-wide program should be initiated under the auspices of the Design for Safety Program that will assure integration and complementary activities within the agency; and will coordinate and pursue joint development efforts with FAA and DOD to raise the level of technologies and tools to assure the highest level of safety in electrical systems for all aircraft and spacecraft.

Elements of this program should include the following:

- DFS to act as agency lead for all wiring related development activities
- Coordination between all NASA centers on technology development and applications
- Participation from all NASA centers that are either developing methods or have programs which would benefit from wire integrity assurance technologies
- Glenn —new technologies for electrical interconnectivity
- Langley —Aging Aircraft program
- JSC —Wire testing systems; test bedding and implementation
- KSC —Wire testing technologies and systems; test bedding and implementation
- MSFC —T BD
- Goddard - TBD
- Represent NASA to DOD/FAA working group on wire;
- Represent NASA to Executive Branch Interagency Working Group on Wire Test Methods and Test Technology Development
- Develop of Signal Processing Methods and Technologies
- Develop Test Management Software Tools
- Materials research on wire insulation
- Develop methods of wire protection

- Develop circuit protection devices
- Develop tools to track wiring problems for trending and risk analysis

2. Develop Test Instrumentation

Automated wire integrity testing is an emerging field, with many development opportunities. There are numerous promising test technologies; however, in every case the test instrumentation must be developed for greater sensitivity to wire defects in the Orbiter environment. Some of the challenges will be to minimize the invasiveness of test techniques, apply them in the limited space and access areas of the Orbiter, and to their minimize impact on the Orbiter processing flow timeline.

Objectives

Assess automated wire integrity tools for the Space Shuttle Orbiter.

Approach

1. Perform comprehensive trade study of wire test technologies. Examples might include Time Domain Reflectometry with Complex Impedance Spectroscopy, and Standing Wave Reflectometry.
2. Develop theoretical models for evaluation of each test technique.
3. Develop Orbiter wiring architecture test beds to validate test technologies in laboratory experiment and operational environments.
4. Develop methods of automating those test technologies.
5. Perform on-going cost-benefit and risk analysis, to select and implement the most effective test technologies within the Shuttle Program.

Projected Timeline

In the first year, requirements would be established and trade studies performed. Equipment would be evaluated for further development. The second year would include development of off-the-shelf technologies. The third year would conclude the qualification, validation, and deployment of the test instrumentation.

3. Develop Automated Signal Processing

This Pilot Study has identified a number of test technologies, such as TDR and SWR, which are sensitive to wire defects. Each requires an expert test operator to apply instrumentation and analyze and interpret complex results. Signal processing techniques can be developed to automatically analyze data for simple pass/fail wire integrity tests.

Objectives

NASA should take the lead in the signal processing end of emerging wire test technologies. As TDR data, for example, is complex but might prove to be, NASA engineers and computer scientists have broad experience in applying signal processing and analysis to even more complex signals. The NASA experience base can be readily applied to the creation of signal analysis techniques.

Approach

1. (In progress) Analyze Wire Integrity Test Bed TDR data to develop rules to discern wiring architecture features and defects for input into automated signal processing algorithms.
2. (In progress) Develop theoretical models to predict the response of TDR signals to various wiring architecture features and different defects on a variety of wire types.
3. Implement a set of rules in an automated signal processing algorithm to locate and identify wiring features, faults, and defects.

Projected Timeline

A quick-look analysis of the CM Tech ECAD TDR data, was conducted as part of the Wire Integrity Test Bed during this pilot study. The application of signal processing techniques to this data could take more than one year.

A separate task of developing a theoretical model of wire response to TDR is already underway. It is scheduled for completion this fiscal year (2000).

A three-year project could include:

FY01: a trade study of the most promising test technologies

FY02: theoretical modeling of application of the technology to Orbiter wire

FY02-FY03: analysis and post processing of test case signal data

FY03: validation of signal processing in the practical Orbiter environment

4. Develop Test Management Software

Objectives

Develop cost effective Test Management Software tools for the Orbiter.

Approach

1. (In progress) Develop TEAMS —SCAN Test Coverage Analysis Tool.

2. Further develop the software translator to incorporate rules for translation of all wire and fault types from SCAN database to TEAMS.
3. Translate complete Orbiter wire architecture from SCAN to TEAMS.
4. Modify TEAMS to provide the additional feature of test coverage in terms of number of wires tested (in addition to current method of fault coverage information already calculated).
5. Modify TEAMS to provide graphical output on architecture model of test coverage.
6. Evaluate requirements for an operational tool for test coverage analysis.
7. Perform trade study of COTS test management tools, useful for applying automated test in the Shuttle Program in the most cost-effective way.
8. Using test coverage tool from previous TEAMS-SCAN development activity, evaluate several different cases for automated testing based on Orbiter flows at KSC and OMDP periods at KSC.

Projected Timeline

FY01: Develop TEAMS-based test coverage analysis tool

FY01: Perform trade study of COTS test management tools for Orbiter

FY02-FY03: Develop software for automated generation of AV&V and Integrity test programs from CDF&TDS database

FY02-FY03: Develop software for test data archive, trend analysis, and outputs to automated Risk Management tool

FY04: Integrate the Test Management System, conduct validation tests

5 & 6. Develop Risk Management Tools and Wire Health Monitoring System

Additional follow-on tasks would be to develop risk management and wire health monitoring tools. These would facilitate periodic updates to wire risk assessments and Orbiter Processing Facility (OPF) and in-flight automated wire health monitoring, respectively.

Development of these products is a natural follow-on to development of Test Management Software Tools because they re-use wire connectivity models, and perhaps build on software procured and developed in that earlier activity. Although both are important programs to pursue, investigating Health Monitoring only comprised 10% of the WIRe study charter, and computer-assisted wire risk assessment is actually outside the scope of the study. An accurate estimate of the scope and cost of these efforts is impractical at this time.