Avionics Health Management: Searching for the Prognostics Grail[1,2]

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Abstract—The focus of this paper is to present the advances, benefits and challenges in measuring, monitoring and managing the health of aircraft avionics systems as well as the support equipment used to test these systems. Most people are skeptical when avionics and prognostics are used in the same sentence. For the purpose of this discussion, we will grant that most electronic discrete parts fail randomly. However, in the aircraft maintenance arena that point is moot because the lowest repairable level is the assembly on which those discrete parts reside. When an assembly fails or has an intermittent fault (resulting from aging solder connections or other environmental or mechanical factors), it is manifested as a system fault or failure.

As degraded performance trends occur over time, there is an increased probability of predicting with reasonable confidence, when a given assembly is likely to experience an insipient fault or a cause a mission failure. While many of the current USAF maintenance metrics add no apparent value to prognostics capability, a few critical data elements are discussed. An optimum set of metrics is proposed through which the performance of avionics assemblies can be monitored. Considerable insight into the relative performance of a wide range of avionics assemblies has been gained through analysis of test parameters and failure information (typically not archived) that have been captured from automated test equipment (ATE). The automated methodology that captures, statistically processes and archives test data from both the units under test (UUT) and the ATE instruments, is described. The insight gained from this technique has led to cost avoidance in the tens of millions of dollars by reducing No Faults Found (NFF) occurrences, which, in turn, improves mission capability rates and reduces logistics support cost. Specific examples of these benefits to the USAF F-16 fleet are provided.

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1. INTRODUCTION

Conventional wisdom tells us that as products and systems age their performance degrades, and if they have been abnormally stressed during operation the onset of the age related performance degradation will probably occur even earlier than would otherwise be expected. That conventional wisdom was the basis of our Air Force sponsor's hypothesis. If systems are degrading with age and other environmental factors then perhaps applying statistical analysis to test failure information may reveal significant performance trends. The ensuing research necessary to examine this hypothesis lead Total Quality Systems (TQS) Inc. on the long trail in search of the avionics prognostics grail. There have been some advances and benefits along this quest, but there are still many challenges to overcome when working in the operational weapon system sustainment environment. For example, in the Air Force

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two level maintenance concept, there are four or more levels of testing depending on the number of testable next lower subassemblies in the line replaceable unit that was removed from the aircraft. This means that test results as well as repair actions must be collected at each test/repair level in order to develop fault traceability from the aircraft to the lowest repair level.

It has been said that Aircraft don't break, nor do the systems, subsystems and boxes that comprise the aircraft break, but it is the subassemblies and discrete parts that fail causing the next higher assemblies and ultimately the system to fail. In other words to get to the root cause of aircraft mission and system failure, one must go to the lowest repair level to determine if the weakness is in a discrete part, or if the assembly itself is the root cause. Our first challenge was to find an effective source of repair data that could be efficiently used for root cause analysis.

The first effort was to capture the performance test data and statistically process the data to produce trend information suitable for decision support. Work by Hansen and others presented a methodology capable of tracking the performance of aircraft and support equipment assemblies as they were tested and repaired at an Air Force depot. [1] Their paper identified significant variability in performance degradation trends for aircraft assemblies due to the lack of actual operating time and environmental stress information recorded on board or in any legacy data system. Later work by Fitzgibbon et.al. demonstrated the capability of the methodology to effectively monitor the health of automated test stations. [2]

TQS has collected serialized repair history from F-16 depot repair shops for several years. Over this time period, repair records have been captured down to the discrete part replacement level in order to identify the weakest links in a system and to establish the most cost effective level in which to insert current technology. The repair data collection method was established under a contract to apply Flexible Sustainment precepts to the USAF F-16 fleet in order to improve avionics reliability and mission readiness, while reducing total ownership cost. The serialized repair history has provided visibility into the specific units that were failing Line Replaceable Unit (LRU) level testing, but passing circuit card assembly (CCA) or subassembly testing. This phenomenon is referred to in many ways such as, Can Not Duplicate (CND) or ReTest OK (RTOK). We will use the common term No Faults Found (NFF). The first thing that had to be developed was a method to capture the test failure data and associated test limits from each tester in order to decipher what the test differences were at various testing levels.

2. PROBLEM

Achieving highly reliable and maintainable avionics systems is key to meeting modern aircraft needs. Mission capabilities are degraded when avionics faults are not consistently identified and isolated at the various levels of testing and repair. In the past, maintaining consistent flight readiness has been an all to common issue. In the Air Force, all too often a Shop Replaceable Unit (SRU), or LRU indicates a failure on the aircraft and passes when tested on the ground. This is commonly referred to as a NFF condition. There are often discrepancies between test results at the field backshop and repair depots. A great deal of time and money is expended processing units when a depot cannot confirm test failures reported by lower level test activities. Some NFF conditions are caused by intermittent faults. Intermittent faults seldom appear unless a unit is in a stressful operating environment. Lack of fault traceable data such as operating time to failure and environmental conditions when a fault occurred obstruct the potential ability for effective avionics prognostics and failure predictions on an aircraft. In addition, we need repair and test data starting at the aircraft, through the wing and depot repair shops. In order for prognostics to be successful, it is imperative that serial numbers be accurately tracked at all maintenance levels. When a serial number is not entered, prognostic capabilities are limited to population based analysis models.

3. HISTORY

In search of the prognostic grail, there has been substantial progress made. The first step in classical failure prediction efforts is to keep records of failure history. Initially, standard Government 80 column punch cards were used to collect data. Legacy databases were then developed using this format. The data collected was limited and often not useful. Data was difficult to enter and retrieve. In addition, there were long lead times required between data entry and retrieval. Data is often stored in several isolated databases making data fusion and analysis difficult. These databases provide visibility only to the Part Number (PN) or National Stock Number (NSN) level. Data is neither identifiable nor retrievable by Serial Number (SN). Traceability by serial number from the aircraft through the lowest repair level is needed for effective maintenance and prognostics.

TQS improved upon these databases by implementing a new generation data collection system named Defense Repair Information Logistics System (DRILS). DRILS utilizes LRU and SRU serial number based tracking of repair and replace actions at the field and depot. It enhances the quality and value of data collection by providing real-time access and analysis to the repair data. With this system, one is able to find parts causing the most failures, as well as costs associated with the repairs. DRILS also provides the ability to identify trends in the number of failures, isolate NFF occurrences, and predict part usage for an aircraft. UUT repair history by serial number can be tracked with this system as well. Using DRILS data, one can quantify the part failures on an aircraft and keep an efficient supply chain on target.

Next, TQS developed a Test Program Set (TPS) test results data collection, storage, and analysis system called Insight. With this system, test results are automatically captured and stored by UUT serial number. Insight taps into individual instrument Control and Support (C&S) software to automatically collect voltage, current, and impedance test results. Data collected includes: test number, limits, units, and results. Insight provides UUT history of test results traceable by serial number to the individual test step level. It also allows you to view and analyze population distributions of test results.

Figure 1, illustrates the collection and statistical processing of repair and test data from DRILS and Insight databases. With DRILS and Insight, the prognostics vision or ability to predict part failure begins to take root. With repair actions and test results related to a particular serial number, statistical methods can be used to predict when a unit is likely to fail.

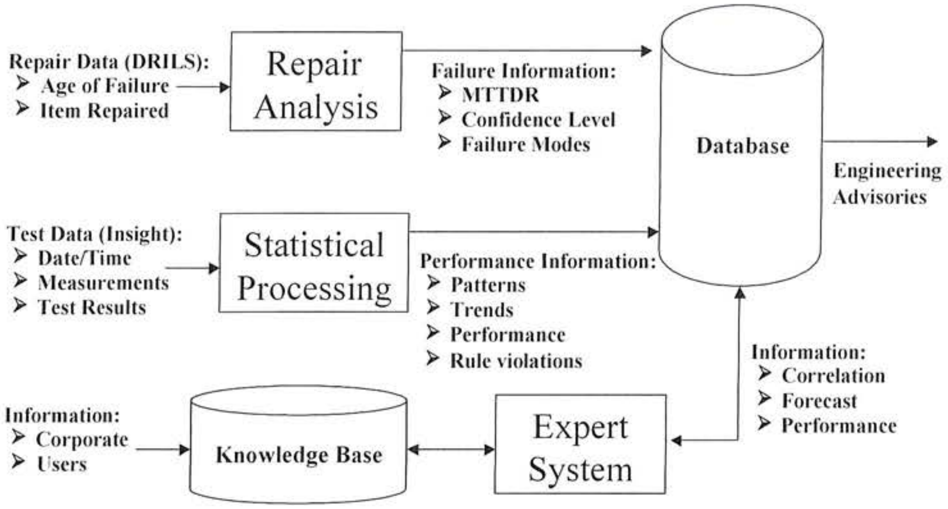

Figure 1 - Data Collection and Analysis

The data from these systems can be used to solve other problems such as the reduction of NFF occurrences at various repair levels. The following examples illustrate how DRILS and Insight have been used to support avionics repair activity.

1. Cannon XPDG: Shortly after we started DRILS, we developed a report to breakout the NFF rates of Air Force F-16 bases. The report indicated that Cannon AFB was submitting a slightly higher than average number of avionics components that resulted in NFF conditions. A drill down into the report revealed that approximately 28% of XPDG units sent in by Cannon resulted in NFF. Hill AFB assigned a team to work with Cannon to identify what was going on. The team discovered that Cannon was pre-screening the boxes from supply before they went to the flight line. The field tester indicated that the XPDG was bad. The depot tester was indicating that the item was good (NFF). A test station void was identified. Since a solution was implemented the number of XPDG NFFs submitted fleet wide have significantly decreased.

2. MLPRF SRU NFF**:** This initiative has reduced the number of SRU NFF occurrences in two ways. First, we tracked the serial numbered SRUs that were removed during LRU repair to the SRU shop. Then we compared the LRU and SRU test results. From this we found that the Frequency Synthesizer had a testing discrepancy between the LRU and SRU shop. The LRU Shop was testing frequency agility at 10kHz. The SRU Shop was testing frequency agility at 2kHz. The operational requirement was 2kHz, so the LRU test software was changed to test frequency agility at 2kHz. Second, we found that the MLPRF was experiencing intermittent faults due to the floating ribbon cable assembly. We found that when an intermittent fault occurred the technician would remove and replace the SRU that failed. When he did this, the intermittent pin soldered to the ribbon cable would make contact and then the LRU would pass. The technician thought he was repairing the fault, but if he had just removed and replaced the same serial numbered SRU and the intermittent pin made contact, the LRU would pass. This lead the LRU shop to resolder the multi-layer ribbon cable in each serial numbered MLPRF. Now, when a MLPRF is repaired, we can use DRILS data to see when the resoldering procedure was last performed.

3. F-16 LRU NFF Project: This project investigated the feasibility of reducing NFFs experienced between the wing backshops and the depot maintenance areas. Often a LRU would fail a test on the wing IAIS tester. When sent to the depot and retested on the depot AIS, the LRU would pass all tests resulting in a NFF condition. A procedure was developed to track LRUs by serial number from the wing

backshop to the depot. When a NFF was found, the LRU was transported to either the 388th or 419th backshop and retested on their IAIS in order to reproduce the wing failure. The failure results from this retest were then used to compare Test Program Set (TPS) test differences between the IAIS and AIS code. This project was only possible because of the ability to track each LRU from the wing, to the depot, to the 388th/419th, and finally to the test results by serial number. This project demonstrated the value that could be obtained by capturing wing and depot test data using the Insight database.

4. PSP: A problem was identified shortly after installation of a new power supply in the PSP. It was discovered that the PSPs with the new power supply would fail on the IAIS test station in the field, but when inducted into the depot it would pass on the AIS test station. This occurred on only those PSPs with the new power supply. It was determined that the IAIS could not handle the new power supply increased current drain on power up, but that the AIS could. The new power supply was modified to reduce the current on power up. This modification only applied to the new power supply. By researching LRU repair records in DRILS we could identify which serial numbered PSPs had the new power supply.

TQS's next effort was to augment the serial number traceability from aircraft to the lowest repair level by collecting Maintenance Fault List (MFL) data. See Figure 2. After an aircraft flight, MFL data was downloaded from the Data Transfer Cartridge (DTC). However, because tracking was only possible to aircraft tail number and not to the individual LRU level, the data was found to be of limited value. Repair and Replace (R/R) actions at the field and depot level were not traceable back to the aircraft failures and faults. If the MFL data were entered into DRILS and Insight along with the associated LRU serial number at the flight line, then the MFL faults could be traced to other repair actions.

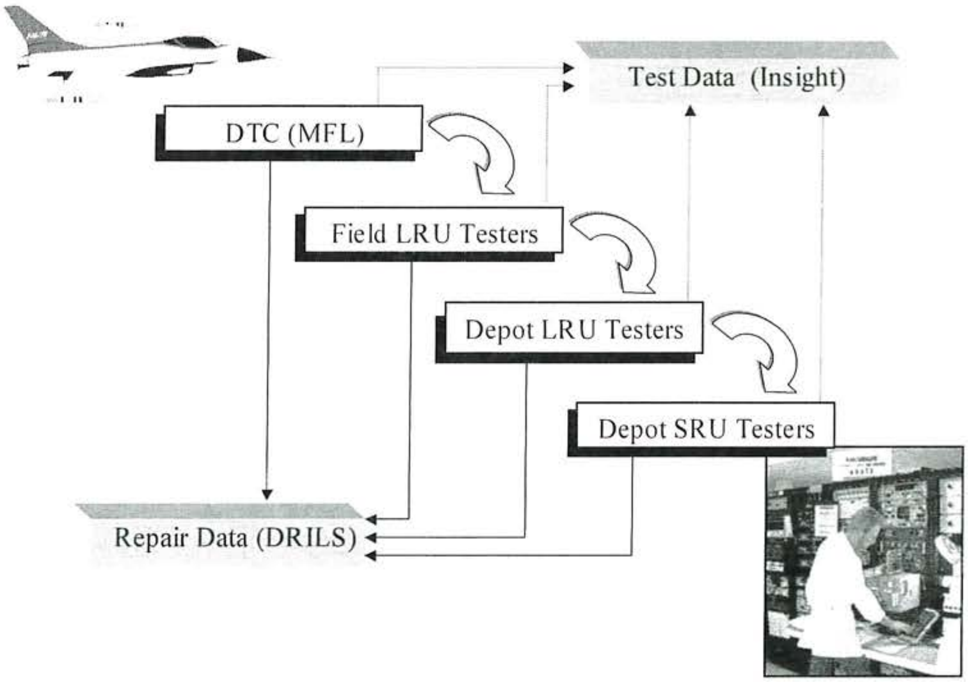

Figure 2 - Repair Level Data Collection

4. PROBLEMS IN FAILURE FORECASTING

The drawback with current prognostic methods is that for the most part, they are population-based reliability predictions. These work well to predict percentages of parts that are likely to fail within a time frame but cannot accurately predict when each serial numbered part will fail. In order to get closer, a few additional critical data elements are required. These include operating time, and environmental operating conditions data such as: temperature, humidity, air pressure, vibration, and LRU power supply over/under voltage. Putting these additional variables into a prognostics model can theoretically provide much greater accuracy.

In the past, the Weibull analysis has been implemented as one failure forecasting method. This method has been extensively tested in many aeronautical applications. Successful cases are mostly represented by mechanical applications. A typical mechanical component has three distinct failure phases in its life cycle: 1) infant mortality failures, 2) random (normal life) failures, and 3) wear-out failures. All of these failures are highly related to the way the component is physically stressed. Many people believe electrical and electronic components have different behavior. Failure analysis experts claim that electronic components exhibit an 'exponential failure distribution', which means that electronic components fail randomly. They do not have 'infant mortality' and 'wear out' cycles. We will grant the traditional argument regarding individual electrical components; however taking the standpoint that environmental stress can affect overall circuit board lifetimes. Experience has shown that failures are dependent on the physics of each component. For example, electrolytic capacitors, resistors, mechanical relays, and semiconductors, have a set of unique failure modes and life cycle. Depending on the physics of the component, recent studies have shown substantial correlation between component failure and environmental stress. [3] Aircraft avionics have multiple mechanisms causing failure. Figure 3 relates a few common stress factors to various failures on a circuit board.

As shown in Figure 3, failure modes such as solder joints, connectors, and burned traces can be accelerated by environmental stresses. Not having records of the operation environment for LRUs and SRUs is yet another factor limiting the accuracy of current prognostics models. Other environmental stresses relating to premature failures of avionics systems include humidity and vibration. A humid environment can lead to metal corrosion on circuit board contacts. This can cause increased contact resistance on board connectors. Some plastics can absorb the moisture leading to dangerous conductivity of plastic. Moisture on an unprotected circuit board can lead to short circuits and reduced dielectric strengths of many insulators. [4] Vibration and physical shock are also proven to have detrimental effects electronic circuitry. These stresses can cause loosening of connections on circuit boards and aircraft wiring. Even though vibration and g-forces may be within specifications, extended stresses of this type can indeed decrease the MTTF. Moreover, lack of this data hinders the ability to accurately estimate the extent to which these factors accelerate failure. Health state and avionics functionality could be estimated more accurately by monitoring environmental conditions. [5]

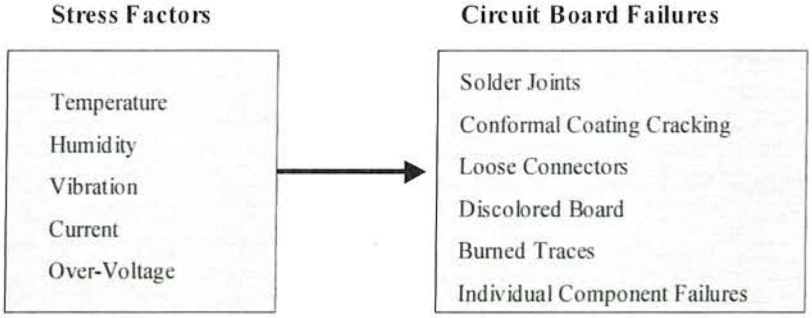

Figure 3 - Stress Factors Relating to Circuit Board Failures

The rate of recurrence of actual failures on a circuit board depends on the extent of environmental stress as well as the operating time. The trouble is that a comprehensive set of environmental failure datum is not currently available for avionic parts. The current failure datum consists of repair dates at most. The estimated MTTF are actually MTTDR (mean-time-to-depot-repair). The estimated failure dates are very inaccurate based upon this data alone. To assist in effective MTTF predictions, an accurate "time stamp" of actual operating time would help tremendously. "Correlation in time is the most obvious deficiency in the current federated avionics diagnostic approach." [5]

MTTF should also be associated with a component and a failure mode. Current failure datum sources do not group or do not allow grouping of failure datum by failure mode. During one study, an attempt was made to correlate 'item repaired' with 'failure mode'. This process was inaccurate mainly because repair action records did not describe the component that failed, but the component that was replaced, or, as in most cases, all components that were replaced. In many cases, the procedure to fix a problem is a trial-and-error procedure where parts are replaced until the problem is fixed. In some cases, good parts are replaced as well as the defective parts. Large ambiguity groups result in unnecessary replacement of good components. A solution to this problem would include a procedure that improves the correlation between the actual component(s) responsible for the failure and the specific test failure identified by the ATS.

Another problem in forecasting deals with population based prediction models. The contemporary method of avionics maintenance assumes a standard mean time between repairs (MTBR) for all instruments having the same part number. This type of prediction is based on part population distributions. Historically, population distributions have played a significant role in failure analysis. Components that belong to the same population have highly correlated failure distributions (Weibull). Population distribution can contribute to accurate failure forecasting but is not a complete solution in itself. In actual applications, the accumulated operating time of particular SRUs and LRUs will vary. Enhanced data collection methods should capture the operating time for instruments according to unique serial numbers, in a manner similar to tracking aircraft engine or heavy equipment engine operating hours. [6] The accuracy of the failure forecast using the Weibull method is affected by five major factors: a) uncertainty in the failure datum, b) uncertainty in the failure mode, c) uncertainty in the date of manufacture, e) the lack of knowledge of the actual operating time, and f) the lack of knowledge of the stress levels applied to the item. [7]

5. CRITICAL DATA ELEMENTS NEEDED

Methods to log LRU and SRU operating time (elapsed time interval) and stresses applied to the avionic systems are key to future prognostics. Focus must be applied to capturing data that include operating time, and stress levels such as but not limited to; temperature, vibration, on-off cycles, g-forces, and component operating environment. For many avionics applications, the accuracy of failure forecasting is severely compromised by the lack of operating time knowledge. Figure 4 illustrates how combining aircraft environment stress monitoring with traditional failure data can reduce the uncertainty of failure prediction.

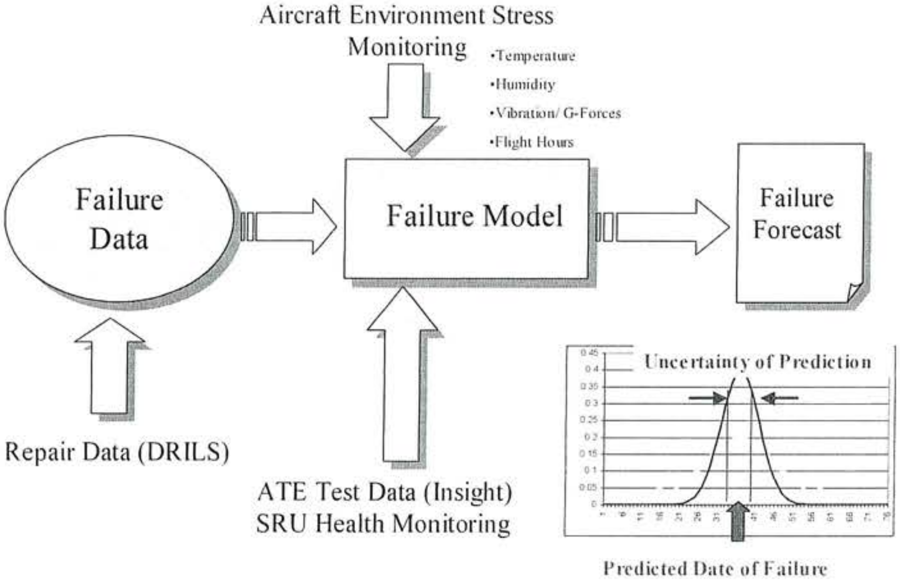

Figure 4 - Failure Forecasting with Stress Monitoring

Collecting this data for legacy aircraft systems is problematic. It's difficult to collect the necessary environmental data without modifying the avionics of the aircraft. It may be possible however to capture a few of the critical data elements such as operating time, g-forces, and on-off cycles through pilot and maintenance logs. The collection of other elements such as temperature, humidity, and vibration would require dedicated sensors capable of capturing and storing this data. Again, it is necessary that all data be tracked by the serial number of each LRU and SRU.

The repair and test history of an individual LRU or SRU is another essential component for a functioning prognostic model. TQS has advanced this component of the model through the development of the DRILS and Insight database systems. This history data incorporates ATE test measurements and repairs performed on the unit. By combining history data with environmental stress data, data analysis and intelligent learning models can use trends and/or degradation characteristics to identify units that are likely to fail soon.

6. CONCLUSIONS

Our hypothesis is that by capturing environmental stress data in addition to repair and ATE test data; we can detect significant failure trends related to each avionics component. This will enable a more accurate prediction of MTTF as well as provide visibility into NFF occurrences. Intermittent failures could more easily be resolved if the operating environment is known, particularly when the specific environmental conditions at the time of failure can be established. In military applications, the ability to characterize environments reduces the number of NFF maintenance events, which can typically account for 35% to 65% of the faults in avionics systems. [8] By adding real-time environmental stress monitoring capabilities within a design, the replacement of near end-of-life parts can be established on the basis of accumulated stress, resulting in more effective prognostics and reduced risk on an aircraft.

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BIOGRAPHY

Larry Kirkland *is a Senior Electronic Engineer at the USAF Ogden Air Logistics Center (OO-ALC), Hill AFB Utah. Mr. Kirkland has over 37 years experience with the United States Air Force in Test/Diagnosis and ATE. He worked as an Electronic Repair Technician on the F-4 & F-16 aircraft. He has worked as an Electronic Engineer in Test/Diagnosis on the F-4, F-16, F-111, & B-1 aircraft. Mr. Kirkland has numerous papers published at Test, Software Technology and AI conferences. He has been published on numerous occasions in IEEE Engineering Magazines. Mr. Kirkland is a past Chairman of the IEEE "AI Human Interface Group" and co-chairman of the IEEE "Interoperability in Knowledge-based systems for sensor-based applications" group. He holds a Bachelor of Science degree from Weber State University. Post-graduate work is from University of Phoenix, Weber State University, University at Hartford and Utah State University.*

Tony Pombo *has over 30 years performance in aircraft maintenance, reliability and sustaining engineering, specializing in advanced diagnostics at depot, field, and laboratory levels. As Program Manager of the Design Engineering Program (DEP) Phase II Small Business contract, Mr. Pombo had management oversight of the Falcon Flex business practice for F-16 reliability based logistics and performance based acquisition. He has fifteen years business development and marketing experience including five Phase I, three Phase II and two Phase III SBIRs, all focusing on advancing state of the art for avionics diagnostics, fault isolation and traceability from the aircraft to the lowest test and repair level. This research and development has provided statistical process monitoring and pattern generation for part and serial number avionics assemblies as well as the associated automated test equipment (ATE). He provided the vision to incorporate Expert Systems technology for pattern recognition and advisory generation based on performance trends, for engineers and technicians.*

Kody Nelson *is a graduate student at Utah State University. He will complete his Master's Degree in Electrical Engineering in Spring 2004. He has a minor in mathematics and Japanese. Presently, Mr. Nelson is participating in SBIR AF01-296 Tracking Current Flow through Units Under Test. He has helped in the research and development of non-intrusive current measuring sensors and power supply data collection processes for units under test. As an intern, he assisted in diagnostics and failure analysis of Flash Memory products at Micron Technology.*

Floyd Berghout *has over thirty years experience in software development, including Minuteman and F-16 embedded software. Mr. Berghout also has extensive experience with software requirements analysis, design, coding, test, and documentation on numerous projects while working for TRW and Hill Air Force Base. Mr. Berghout earned an MS and BS in Electrical Engineering from the University of Utah.*