Expanding the Role of Telemetry in the Aircraft and Space Vehicle Factory Acceptance Test to a Design Driver

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ABSTRACT

The aircraft, satellite, missile and launch vehicle industry suffer from catastrophic infant mortality failures rate at ~25% even after exhaustive and comprehensive factory acceptance testing is completed causing unreliable systems, program delays and cost overruns. The discovery of the presence of deterministic behavior in equipment analog telemetry generated during factory acceptance testing preceding all equipment failures, which is identifiable using prognostic analysis, eliminates infant mortality failures resulting in increased equipment reliability, lower program cost, shorter test and delivery schedule and increased equipment usable life ensuring mission success. The addition of a single, embedded analog telemetry measurement to all active equipment allowing all equipment to be identified during factory testing that fails, and all equipment that will fail within the first year of use, to be identified will allow vehicle builders to lower program cost, use less equipment, use less testing and have a shorter delivery schedule and more reliable equipment and longer equipment usable life expanding the use of telemetry to identifying equipment that will fail well into the future.

INTRODUCTION

Catastrophic equipment failures immediately after the completion of exhaustive and comprehensive factory acceptance testing demonstrates that the factory acceptance test process is inadequate to identify 100% of the equipment that will fail within one year of use. The presence of deterministic behavior in completely normal appearing data (telemetry) from fully functional equipment was documented in published CDRLs on the Air Force Global Positioning System (GPS) program. The source and reliability of the deterministic behavior was confirmed to exist on other Air Force, NASA and commercial satellites and launch vehicles.

This means that telemetry can be responsible for financial, schedule, reliability and usable life improvements by allowing all equipment that fails during test and the presence of deterministic behavior in all equipment that will fail from an infant mortality failure while it is still at the factory, eliminating infant mortality failures. Using prognostic analysis, telemetry can be processed such that deterministic behavior, embedded in completely normal appearing test data from fully function equipment, can be illustrated for engineers, trained in identifying deterministic behavior (prognostics-pro-active diagnostics), can identify 100% of the equipment that will fail from an infant mortality failure during factory test. The identified equipment can then be repaired or replaced while it is at the factory expanding the value of telemetry for mission success.

Some vehicle equipment has no telemetry available to minimize the vehicle weight and power requirements which translate directly into increases in program cost and test schedule delays. If vehicle designers provide at least one analog telemetry measurement embedded into equipment, it can be used to avoid infant mortality failures, reduce the amount of redundant equipment, lower cost, shortening testing and delivery schedules, increase reliability and increase usable life expanding the traditional role of telemetry from an overhead cost, and a cost of doing business to a vehicle design driver.

With electrical and electro-mechanical equipment having at least one embedded analog measurement, prognostic technology is available today to identify all satellite and launch vehicle equipment that will fail within 1 year of use. The addition of prognostic technology to the space equipment and space vehicle factory acceptance testing process will identify all unreliable equipment prior to shipment to the launch pad allowing repair or replacement before shipment for launch and offers to eliminate launch failures, launch pad delays, on-orbit infant mortalities and normal life-time surprise in-orbit failures and extend in-orbit equipment usable life. By using prognostic technology to increase equipment and vehicle reliability, redundancy can be lowered resulting in less equipment testing and reducing overall space vehicle size, program cost, a shorter delivery schedule while increasing vehicle/equipment reliability.

Prognostics is the next logical step in advancing traditional electronic and electro-mechanical equipment diagnostic technology. Prognostics and prognostic health management as part of equipment operations and maintenance is a critical technology for accurately predicting impending failures and providing a mechanism for replacing equipment and parts safely before failure for ground-based equipment and preparing for and executing recovery plans for space-based equipment. Components of a prognostic system are the algorithms for anomaly detection, isolation, prediction and recovery. Some approaches for equipment anomaly prediction require knowledge of the system model. Attempting to use model-based prediction methods when working with complex electrical and electro-mechanical systems is often not feasible because the approximations necessary to develop computationally tractable models of complex systems based on fundamentals of physics are difficult to make without introducing significant modeling inaccuracies in the time and length scale of interest.

Vehicle telemetry gained wide-spread use after use in jet aircraft testing in the late 1950's. Telemetry was back-fitted to missiles and added to launch vehicles and satellites. Without any identifiable payback to the vehicle builders for telemetry, it remains overhead, a cost of doing business.

Telemetry developed an industry reputation as expensive, complex, unreliable and unnecessary and so telemetry is used sparingly unless the customer requires more to be used. The more measurements, the more delays in vehicle test and vehicle delivery occur if all unknown telemetry behavior is researched and resolved. The more information to evaluate, the more time spent evaluating it. During equipment and vehicle test, it is highly advantageous for test personnel to simply ignore unusual telemetry behavior since test engineers are working to a tight delivery schedule. Major financial penalties can occur if delivery dates are not met. When anomalous telemetry measurement behavior occurs, it requires engineering time to troubleshoot the circuit/equipment the measurement is associated which slows progress and jeopardizes the test schedule.

Often telemetry measurements will fail during test needing failure analysis to verify it is the measurement rather than the circuit it is attached to which is expense and time consuming. The MTBF for the piece-parts in telemetry measurement circuits are just as unreliable/reliable as any other circuit's piece-parts. Telemetry has been relegated to diagnostic techniques for determining system/equipment test status, performance, equipment operational status and configuration.

Believing that improvements vehicle reliability performance with low cost wasn't possible, the highly unreliable missiles, launch vehicles and satellite suppliers were never required by their customers to predict vehicle reliability and performance and so the wide spread use of telemetry was minimized.

Satellite owners and operator who both operate their own spacecraft will pay for more telemetry measurements than the vehicle supplier want to provide because they have the experience that more information to identify, isolate and diagnose a suspected problem, the more successful the failure analysis will be.

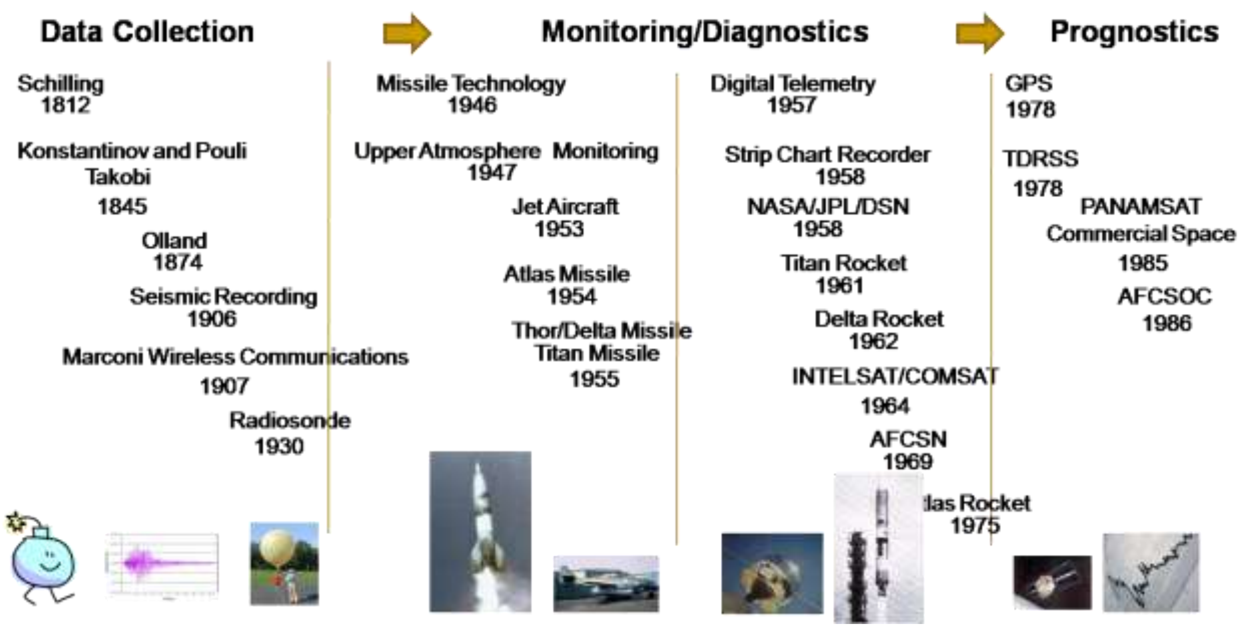

Figure 1. Chronology of the Development and Use of Telemetry, Diagnostics and Prognostics

PROGNOSTIC TECHNOLOGY

Prognostics is the illustration of deterministic behavior and the identification of the deterministic behavior from equipment that is going to fail within the first year of use[1]. Prognostics is necessary because current diagnostic technology is inadequate to identify 100% of the equipment that will fail from an infant mortality failures during factory acceptance testing. Prognostics is the next logical step in advancing traditional electronic and electro-mechanical equipment diagnostic technology. Prognostics and prognostic health management as part of equipment operations and maintenance is a critical technology for accurately predicting impending failures and providing a mechanism for replacing equipment and parts safely before failure for ground-based equipment and preparing for and executing recovery plans for space-based equipment.

Telemetry prognostic algorithms were developed and used to predict failures in atomic clocks first on the U.S. Air Force Global Positioning System (GPS) Block I satellites. Unable to understand the success of these algorithms, many years of research was completed into the failures of complex electronic and electro-mechanical systems. For many decades, failure analysis used information around the time of the equipment failure to identify the characteristics of the data at the time of the failure ignoring telemetry from up to 1 year before the failure. This information was used to understand and quantify the failure process at the time of failure and be used to make an improvement in subsequent units. By researching a large number of equipment failures over many years from space equipment used across many complex systems, a new understanding of the equipment failure process was obtained.

Failure Analysis' telemetry prognostic algorithms are unique and their performance will be different than prognostic algorithms from another source. Failure Analysis' algorithms were developed from analyzing telemetry from failures on satellites and launch vehicle telemetry.

The following table is a list of the algorithms in alphabetical order developed and used on the Air Force GPS program to identify failure behavior in normal appearing telemetry.

Prognostic Algorithm	Purpose
Baseline Analysis	Determines change in normal behavior is occurring
Change Analysis	Determines change in normal behavior
Comparison Analysis	Determines change in normal behavior
Data Integration	Compiles data for cluster analysis
Data Base Creation	Creates minimal amount of telemetry for analysis
Day-of-Failure (DOF)	Identifies day of equipment failure
Digital Processing	Improves resolution of failure signature
Discrimination Analysis	Identifies normal telemetry from failure behavior
Mathematical Modeling	Predicts normal telemetry behavior
Multi-Variant Limit Analysis	Identifies telemetry to be analyzed for failure behavior
Rate-Change Analysis	Identifies telemetry to be analyzed for failure signature
Remaining-usable-life (RUL)	Determines when equipment will fail
Statistical Sampling	Reduces telemetry databases before analyzing
State Change Analysis	Identifies telemetry to be analyzed for failure signature
Super Impositioning	Enhances normal telemetry behavior for analysis
Super Precision	Improves resolution of final telemetry diagnostic products
Telemetry Authentication	Eliminates unreliable telemetry eliminating false positives
Virtual Telemetry	Creates future normal telemetry behavior

Table 3. Failure Analysis' Telemetry Prognostic Algorithms

The behavior of these characteristics of this new found process was what was used in the prognostic algorithms which clearly illustrate equipment that is going to fail in the future. It is the knowledge that a failure process occurs which is unlike any process suspected in the past and the experienced gained by identifying a failure in process that is utilized to eliminate and manage failures advantageously that forms the foundation of prognostic technology and makes it superior to diagnostic technology.

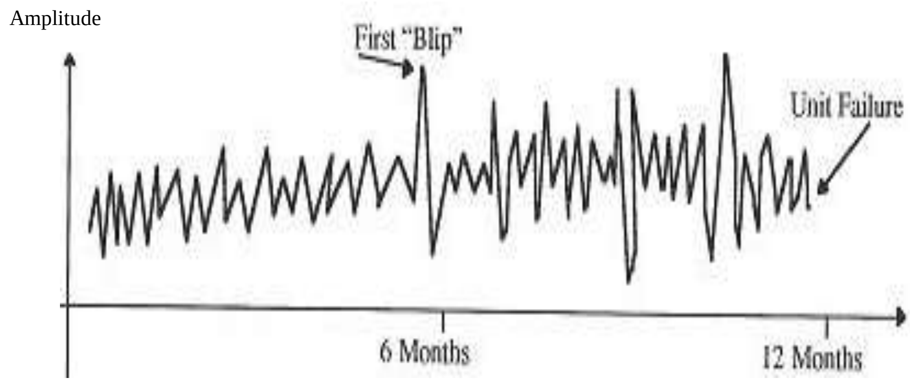

Fig. 3. Example of a Long-Term Piece-Part/Circuit/Telemetry Behavior for Complex Electronic and Electro-Mechanical Equipment from Start of Deterministic Behavior (First Blip) to Complete Unit Failure

The development and use of prognostic algorithms on satellite and launch vehicles is extremely difficult. [2] It was accomplished with the funding paid by the U.S. Air Force over 6 years, who was extremely motivated to have the GPS program exceed performance expectations during multi-service testing. The Air Force was willing to pay for all facilities, technical resources and management resources requested by Boeing GPS space and ground system manager and program management from many companies and organizations. This is why prognostics wasn't developed in the past. Prognostic algorithms are the result of a combination of information and experience from many sources generally not obtained in traditional space systems design and test process.

The successful use of prognostic algorithms requires extensive training and experience, without which, the results could be unsatisfactory and costly. Prognostics requires properly trained and experienced prognosticians to identify behavior in data that appears exactly the same as normal appearing behavior. No two failures signatures are alike and so the experience gained in identifying one failure cannot be used to identify another. The ability to identify failure behavior is obtained through training by others who have successfully identified failure behavior.

Components of a prognostic system are the algorithms for equipment failure detection, isolation, prediction. Some approaches for equipment failure prediction require knowledge of the system model. Attempting to use model-based prediction methods when working with complex electrical and electro-mechanical systems is often not feasible because the approximations necessary to develop computationally tractable models of complex systems based on fundamentals of physics are difficult to make without introducing significant modeling inaccuracies in the time and length scale of interest.

Prognostics offers to change the entire design, manufacturing and test process to improve reliability to eliminate infant mortality failures reducing if not eliminating launch failures, launch pad delays, on-orbit infant mortalities, surprise in-orbit failures and extend in-orbit equipment usable life by identifying unreliable equipment long before its shipped to the launch pad. For the first time, all the information to identify unreliable equipment can be financially justified. Prognostics technology adds many financial rewards for using telemetry, easily justifying the need for increasing the number and resolution of telemetry measurements.

Using telemetry prognostics in the space flight equipment and at vehicle factories, upgrades space equipment processes by identifying unreliable piece-parts and assemblies during equipment test, reducing the time to test equipment, identifying equipment that has failed, is failing and will fail, increasing reliability and eliminating infant mortalities. The shorter equipment and vehicle test time reduces cost. Telemetry prognostics algorithm determines of remaining-usable-life based on information available in existing equipment telemetry.

An ideal general purpose prognostic system is a data-driven approach that does not require *a priori* knowledge of system[2]. The prognostic system would learn the characteristics of the monitored system so that anomalies could be predicted more quickly as it is learned, and remaining life estimates could be given with smaller associated uncertainty.

Telemetry prognostics is the use of telemetry as an engineering data source in data-driven prognostic technology. Prognosticians, using prognostic algorithms identifies telemetry behavior that are transient, unrepeatable, and have gone undetected by the most experienced design and test personnel for the past 60 years.

Data-driven telemetry prognostics uses previously recorded and real-time telemetry to illustrate behavior that can be used to predict electronic and electro-mechanical circuit/systems failures. Satellites, spacecraft, missiles and launch vehicles are well suited for prognostics since telemetry is available, collected and stored regularly. A data-driven approach, utilizes telemetry to improve the reliability of space equipment beyond all expectations making current reliability analysis obsolete.

Prognostics technology is an evolutionary step forward in traditional diagnostics technology for both hardware and software. Telemetry prognostics technology can be used by prognosticians to identify equipment that has failed, is failing and will fail for up to one year in advance. Prognostic technology uses engineering data to identify circuit/equipment behavior that are precursors to catastrophic failure.

Prognostics uses 2 major improvements to diagnostic analysis; proactive diagnostics and active reasoning.

Failure Analysis' data-driven telemetry prognostics technology also provides the determination of remaining-usable-life and even a day of failure for unreliable equipment.

PROGNOSTICS	**DIAGNOSTICS**
Identifies equipment failures that have	Identifies failures that have occurred and

occurred, is occurring and will occur and when it will occur	when they occur
Identifies equipment failure in process and when	Only identifies equipment failures after they have already occurred
Identifies equipment failures that will occur in the future	Only identifies equipment failures after they have already occurred
Requires major changes in analysis attitude and behavior	Training is done from example
Overcomes shortcomings in diagnostic techniques	Diagnostics were developed from ground test equipment
Prognostician actively monitors data to provide knowledge of whether a failure has occurred, is occurring or when a failure is likely to occur	After the fact response, if error messages are used, diagnostician waits for error message if any action is taken
All events are considered failure precursors until ruled out by research – analyst doesn't stand by and watch failures occur	Data is recorded and analysis is completed post event
A fault propagation model is assumed to encompass parametric data related to acceptable operating ranges, behavior and identification of degradation of functions over time.	Suspect behavior is considered system noise, any action is taken after completion of events
Requires highly skilled and trained personnel, must have in-depth knowledge of what is being actively monitored	Allows lower skilled personnel, doesn't require in-depth understanding of what's being monitored, diagnostician just sits and waits to complete event
Requires training across several disciplines	Common throughout many industries
Stops life threatening situations from occurring	Inadequate for mission critical events

Table 1. Comparison of Characteristics Between Prognostics and Diagnostics

ACTIVE REASONING	PASSIVE REASONING
Reduces fault detection time as well as improve the accuracy of fault diagnosis.	Evaluates symptoms after the fact
Evaluates symptoms continuously	Records the data and look at it later
Does fault reasoning	Spurious symptoms could mislead fault localization analysis.
Does fidelity evaluation	Spurious symptoms are also regarded as observation noise
Does action selection	Depends on monitoring agents to detect and

	report abnormality using alarms or symptom events
Takes passively observed symptoms as input and returns fault hypothesis as output.	Search for root faults based on the observed symptoms
Process of searching for the best fault explanation of the observed symptoms.	Diagnostic explains a failure based on observed symptoms
Improves the robustness of fault localization system by analyzing lost, positive and spurious symptoms.	Diagnostics Improves the robustness of fault localization system by analyzing lost, positive and spurious symptoms.
Assumes each event is a failure precursor	Assumes an event is noise

Table 2. Comparison Between Active Reasoning and Traditional Passive Reasoning

Telemetry prognostics grew out of the need to augment diagnostic techniques that fell short in understanding equipment failures and what occurred when equipment failed. Traditional diagnostic techniques were developed in the 1930's and 1940's and expanded during the cold war based on the understanding that equipment failed when it failed. As a result, very little analysis occurred that tried to identify if there were any tell-tale signs of the impending failure present in data prior to the actual catastrophic failure. As a result, knowledge of failure behavior prior to an actual failure is not recognized as occurring.

A prognosis denotes the prognostician's prediction of whether a failure will progress, and when the equipment/circuit will fail.

Data-driven prognostic algorithms use available data from a system to determine normal behavior and failure behavior. Our data-driven prognostics is independent of the vehicle or source of data. Generate prognostics. As the name implies, data-driven techniques utilize monitored operational data related to system health. Data-driven approaches are appropriate when the understanding of first principles of system operation is not comprehensive or when the system is sufficiently complex that developing an accurate model is prohibitively expensive.

ADVANTAGES OF DATA-DRIVE PROGNOSTICS

- The same algorithms are used for every circuit, unit, satellite and launch vehicle (no NRE)
- Can be deployed quicker and cheaper compared to other approaches
- Can provide system-wide coverage
- Vehicle/system independent
- No additional information required than normally collected
- Insensitive to the amount of data available
- Insensitive to noise
- Insensitive to the number and resolution of measurements available
- Best suited for aerospace equipment where quantities are few, designs are unique and subject to change based on piece-part availability

DISADVANTAGES OF DATA-DRIVEN PROGNOSTICS

- Extremely difficult to be successful

- Requires significant training and experience
- Mistakes can be costly
- May not be used real-time
- Encourages more measurements to be added to increase the number of circuits it can be used with increasing initial cost

Model-based prognostics is the use of a-priori knowledge to identify changes in behavior which can be identified as failure behavior. This a-priori knowledge can be obtained from several sources; experts and/or operational experience. When all acceptable operational behavior can be defined, model-based prognostics is suitable for use with pattern recognition systems. Model-based prognostics incorporate physical and operational understanding (physical modeling) of the system into the estimation of remaining useful life (RUL). Modeling physics can be accomplished at different levels. At the micro level (also called material level), physical models are embodied by series of dynamic equations that define relationships, at a given time or load cycle, between damage (or degradation) of a system/component and environmental and operational conditions under which the system/component are operated. The micro-level models are often referred as damage propagation model. Micro-level models need to account in the uncertainty management the assumptions and simplifications, which may pose significant limitations of that approach.

ADVANTAGES OF MODEL-BASED PROGNOSTICS

- Best suited for high volume, consumer electronic products, where equipment manufacturers produce millions of units requiring modeling but the cost is spread over many units.
- Can be used with pattern recognition systems.
- Disadvantages of Model-based Prognostics
- Requires system modeling which is expensive, time consuming and requires experts.
- Models must be rewritten for every design change or modification
- Uses simple limit checking software

HYBRID PROGNOSTICS

Hybrid approaches attempt to leverage the strength from both data-driven approaches as well as model-based approaches. It is rare that the fielded approaches are completely either purely data-driven or purely model-based. Hybrid approaches can be categorized broadly into pre-estimate fusion and post-estimate fusion.

BENEFITS AND USE FOR PROGNOSTIC TECHNOLOGY

Electrical equipment across all industries suffer from infant mortality failures. Surprise equipment failures force the delay in many launches. The more complex the equipment, the higher the return rate of failed equipment in the field to the company. When equipment that is going to fail in the near future can be identified, many benefits exist such as:

- Reduced number of equipment returned to the builder
- Reduction in the time to integrate and test space vehicle equipment
- Lower cost to produce space vehicles

- Shorten testing schedule
- Stop launch vehicle failures from occurring
- Stop in-orbit infant mortality failures from occurring
- Manage and control equipment failures
- Offer higher reliable payload services
- Reduction in payload down-time for critical payload services

CONCLUSION

Telemetry is used to identify equipment functional performance and status during factory testing activities and in the field. Using prognostic analysis, telemetry can be used at the factory to identify the equipment that will fail within one year of use, eliminating equipment infant mortality failures. The cost and added complexity of embedding telemetry in all active circuits and assemblies can be justified from the financial paybacks, increase reliability, lower program cost, shorter test and delivery schedule and longer equipment usable life and the elimination of infant mortality failures in the field using prognostic technology.

REFERENCES

1. Losik, Len, *Stopping Launch Pad Delays, Launch Failures, Satellite Infant Mortalities and On-Orbit Satellite Failures Using Telemetry Prognostic Technology*, Proceedings from the International Telemetry Conference, October, 2007.
2. Losik, Len, Sheila Wahl, Lewis Owen, *Predicting Hardware Failures and Estimating Remaining-usable-life from Telemetry*, Proceedings from the International Telemetry Conference, October, 1996.
3. Losik, Len, Sheila Wahl, Lewis Owen, *Predicting Hardware Failures and Estimating Remaining-usable-life from Telemetry*, Proceedings from the Small Satellite Conference, August, 1996.
4. Losik, Len, Sheila Wahl, Lewis Owen, *Predicting Hardware Failures and Estimating Remaining-usable-life from Telemetry*, Proceedings from the International Telemetry Conference, October, 1997.
5. Losik, Len, *An Introduction to Predicting Hardware Failures and Estimating Remaining-usable-life from Telemetry*, SanLen Publishing, Sacramento, California, 2002.
6. Losik, Len, *Predicting Hardware Failures and Estimating Remaining-usable-life from Telemetry*, SanLen Publishing, Sacramento, California, 2004.
7. Pecht, M, Gu, J, *Prognostics-Based Product Qualification*, IEEE Aerospace Conference, Big Sky, MT, March 7-14, 2009.
8. Feldman, Kiri, Sandborn, Peter, Jazouli, Taoufik, *The Analysis of Return on Investment for PHM Applied to Electronic Systems*, Proceedings of the 1st International Conference on Prognostics and Health Management, Denver, CO, Oct 6-9, 2008
9. Mathew, Sony, Das, Diganta, Rosenberger, Roger, Pecht, M, *Failure Mechanism Based Prognostics*, Proceedings of the 1st International Conference on Prognostics and Health Management, Denver, CO, Oct 6-9, 2008.
10. Feldman, Kiri, Sandborn, Peter, *Analyzing the Return on Investment Associated With Prognostics and Health Management of Electronic Products*, 2008 ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE), Brooklyn, New York, USA, August 3-6, 2008.