Telemetry Prognostic for Upgrading Space Flight Equipment Design, Manufacture, Test, Integration, Launch and On-Orbit Spacecraft Operations

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ABSTRACT

The satellite and launch vehicle industry suffers from a high infant mortality failure rate of ~25%. Infant mortality failures are accepted as normal and to be expected in all industries that produce electronic and electromechanical equipment. As a consequence, the commercial space industry was created to mitigate risk for satellite owners and operators. Any process that results in infant mortality failures is inadequate. Prognostics or pro-active diagnostics corrects this inadequate process by identifying piece-parts and components that will fail within the first year of use during factory test. Prognostics offers to reduce if not eliminate launch failures, launch pad delays, son-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 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 while increasing vehicle/equipment reliability. Telemetry prognostics algorithm determines of remaining-usable-life based on information available in existing equipment telemetry.

I. Introduction

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 electromechanical 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. Telemetry is used sparingly. The more measurements, the more delays in vehicle test and vehicle delivery occur if all unknown telemetry behavior is researched and resolved. 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.

II. Prognostic Technology

Prognostics is the identification of equipment that is going to fail. Prognostics is necessary because current diagnostic technology is inadequate to identify infant mortality failures. 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. 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.

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 First Indicator to Complete Failure from Results of Research Conducted on the Boeing/Air Force GPS satellites.

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-useable-life based on information available in existing equipment telemetry.

An ideal general purpose prognostic system is a data-driven approach that does not require \textit{a priori} knowledge of system\textsuperscript{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-useable-life and even a day of failure for unreliable equipment.

\begin{tabular}{|l|l|}
  \hline
  PROGNOSTICS & DIAGNOSTICS \\
  \hline
  Identifies equipment failures that have occurred, is occurring and will occur and when it will occur & Identifies failures that have occurred and when they occur \\
  \hline
  Identifies equipment failure in process and when & Only identifies equipment failures after they have already occurred \\
  \hline
  Identifies equipment failures that will occur in the future & Only identifies equipment failures after they have already occurred \\
  \hline
  Requires major changes in analysis attitude and behavior & Training is done from example \\
  \hline
  Overcomes shortcomings in diagnostic techniques & Diagnostics were developed from ground test equipment \\
  \hline
  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 \\
  \hline
  All events are considered failure precursors until ruled out by research – analyst doesn’t stand by and watch & Data is recorded and analysis is completed post event \\
  \hline
\end{tabular}
failures occur

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>
<thead>
<tr>
<th><strong>ACTIVE REASONING</strong></th>
<th><strong>PASSIVE REASONING</strong></th>
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<tbody>
<tr>
<td>Reduces fault detection time as well as improve the accuracy of fault diagnosis.</td>
<td>Evaluates symptoms after the fact</td>
</tr>
<tr>
<td>Evaluates symptoms continuously</td>
<td>Records the data and look at it later</td>
</tr>
<tr>
<td>Does fault reasoning</td>
<td>Spurious symptoms could mislead fault localization analysis.</td>
</tr>
<tr>
<td>Does fidelity evaluation</td>
<td>Spurious symptoms are also regarded as observation noise</td>
</tr>
<tr>
<td>Does action selection</td>
<td>Depends on monitoring agents to detect and report abnormality using alarms or symptom events</td>
</tr>
<tr>
<td>Takes passively observed symptoms as input and returns fault hypothesis as output.</td>
<td>Search for root faults based on the observed symptoms</td>
</tr>
<tr>
<td>Process of searching for the best fault explanation of the observed symptoms.</td>
<td>Diagnostic explains a failure based on observed symptoms</td>
</tr>
<tr>
<td>Improves the robustness of fault localization system by analyzing lost, positive and spurious symptoms.</td>
<td>Diagnostics Improves the robustness of fault localization system by analyzing lost, positive and spurious symptoms.</td>
</tr>
<tr>
<td>Assumes each event is a failure precursor</td>
<td>Assumes an event is noise</td>
</tr>
</tbody>
</table>

**Table 1. Comparison of Characteristics Between Prognostics and Diagnostics**

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 prognosticiana’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

[3] 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

Model-Based Prognostic Algorithms from GPS

GPS satellites are 3-axis controlled, positive power balance satellites in highly inclined, medium earth orbit. Each satellite uses 3 batteries for providing all Bus electrical power during negative power balance conditions such as lunar and solar eclipses, spin-stabilized early orbit operations and ΔV orbit maintenance maneuvers. GPS satellites have a monthly eclipse season every 5 months. The battery power available is far more than needed. One battery can fail and will not impact the operational capability of each satellite. During non-eclipse seasons, batteries are maintained in a fully charged state using a taper charge to supply small power dissipated through internal battery resistance and wire losses. Lunar eclipses occur with various durations for each satellite several times in a year.
During taper charge, capacity of the battery cannot be determined and so to ensure that each battery has a full charge at the start of each eclipse season, all batteries are discharged down to the cut-off voltage through a 100K resistor over several days and then recharged and placed back into a taper charge. The capacity of each battery decreases by a few percent between each eclipse season. Batteries are sized in capacity so they will provide the necessary power for the entire design life of each satellite.

Battery behavior from telemetry is very well known and well documented. Through the long-term (25 years) analysis of battery load, discharge, recharge, capacity and degradation analysis, an algorithm was developed to predict battery cell failure. This algorithm uses battery load and battery reactance available from telemetry, to predict battery cell failure. Each spacecraft battery resistance and reactance values are known from factory test data and available from the battery supplier.

Hybrid Prognostic

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.

III. 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

IV. Origin of Data-Drive Prognostics

Satellite builders do not control and operate the satellites that they build. Satellite builders may participate in early orbit activities which will get the satellite in its final on-station configuration. They may also provide some failure analysis if paid to do so. Other companies whose sole business is the operations of in-orbit satellites do it. As a consequence, satellite builders do not obtain experience in the long-term behavior of the equipment they design, manufacture, test and launch. Since the personnel at companies that operate satellites do not participate in the satellite design process, they are not developing in depth expertise in the expected behavior of the satellite equipment. Satellite operations personnel are provided satellite operations documentation by the satellite designer that detail the required maintenance activities but do not include expected behavior. This is usually because the satellite builder doesn’t know what to expect either once the satellite is in-orbit. The expertise developed by the satellite operations teams do not generally get into the satellite design process.

The satellite design models are assumed to be correct and infallible and so there is not verification latter in the life of the satellite of the design parameters used were correct. Satellite builders will evaluate spacecraft if they are paid to do so.

In 1978, the U.S. Air Force contracted with Boeing for an engineering team to assist in the integration of the Air Force Global Positioning System (GPS) program into the existing Air Force satellite control network which operated most CIA/NRO/military space control assets. Boeing satellite engineers determined each GPS satellite subsystem performance and the GPS on-orbit support requirements levied on other Air Force program contractors. The Air Force was highly motivated to fund the GPS program because of its multi-service use and better navigation solutions than existing satellite-based navigation systems. GPS was competing against two existing satellite-based navigation systems, APL’s TRANSIT and the NRL TIMATION systems.

At the beginning of the GPS program, the Air Force was highly motivated to make GPS successful and funded due its multiservice applications for navigation services so all technical and financial resources necessary to understand GPS satellites atomic frequency standards, reliability, short-term and long-term stability so that the many future GPS atomic clocks could be designed to be longer-life, more stable and highly compatible with the GPS Kalman filter. Many dozen more GPS satellites were to be purchased by the Air Force during the mission life of the constellation.
A team of Air Force contractors located at Air Force stations and contractor and subcontractor manufacturing facilities around the country participated in the development of telemetry prognostics including: Boeing, Lockheed Technical Operations Company, General Dynamics and Efferton.

In addition to its own contractors, the Air Force funded Boeing to provide an engineering team and subcontractors to evaluate the long-term continuous operating state of each GPS satellite and make design changes to improve subsequent vehicles. There were 25 years of in-orbit experience obtained by the satellite builder analyzing the behavior of on-board equipment from the manufacture and test, launch and in-orbit operations of 12 GPS satellites, each satellite used 3 or 4 rubidium and cesium atomic clocks for navigation signal timing. This information and experience was used by both the Air Force and Boeing to make satellite equipment design improvements.

It was with the decades on experience evaluating satellite telemetry behavior to determine vehicle response that was used to develop algorithms for predicting a failure using long and short term frequency stability as well as peak-to-peak changes in frequency drift. Simultaneous telemetry behavior from satellite and internal atomic clock performance behavior was provided by the GPS Kalman filter located at the Vandenberg Air Force Station, GPS Master Control Station.
Fig. 8. Example of GPS Kalman Filter Processing of In-Orbit Satellite L-Band Navigation Atomic Clock Performance Behavior with Spikes Present Along with S-band Telemetry Behavior Used to Predict Atomic Clock Failure 6 Months in Advance

Over 25 years of satellite telemetry and results from GPS Kalman filter processing was used to predict, future clock failures. Expanding the use of the algorithm to other spacecraft equipment, algorithms were developed to isolate and identify this behavior using data from GPS in-orbit satellites, satellites at the factory under construction, at the launch pad and to identify previously unidentified telemetry behavior. The ability to predict future equipment failures using telemetry, now named was created and used on the GPS program in the early 1980’s.

Unable to explain why failure behavior was present and what was its source, the ability to predict satellite equipment failures was abandoned by Boeing and the GPS Air Force personnel.

Fig. 9. Boeing/Air Force GPS Block II Satellites Designed Using Results from Telemetry Prognostic Technology on Boeing/GPS Block I Satellites

However, continuous research and use of telemetry prognostics by the founder of Failure Analysis continued on NASA, commercial and Air Force program satellites over the next 30 years.

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.
V. Failure Analysis’ Proprietary Telemetry Prognostics Data-Driven Algorithms Created and Used on GPS satellites Creation of Telemetry Prognostics

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.

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

Table 3. Failure Analysis’ Telemetry Prognostic Algorithms

VI. Impact of Prognostics on Piece-Part Failure Analysis/Reliability

Electrical piece-part component suppliers manufacture their parts to high standards. However, as well as they manufacture their parts, a few will still fail quickly when installed in circuits suffering what is termed infant mortality phenomena. A few more will fail hours, days, weeks, months or years later. Piece-part suppliers manufacture their parts in great quantities. Every part is not tested to make sure that it will function properly for the entire equipment life before it is sent to the customers. Although rated to function in a wide temperature range, piece-parts are not designed and tested to operate in a thermal cycling mode as occurs on spacecraft. Just as concrete disintegrates under expansion and contraction from outdoor temperature cycling, piece-part molecular structure degrades with thermal cycling. Nor will piece-parts operate at the high end temperature for extended periods. Equipment life is tremendously shorted when piece-parts are operated close to 50°C for extended periods, even brief excursions close to 50°C decreases piece-part life.
Electrical piece-parts are not tested in the operating environment in satellites. Due to the orbital path about a planet or moon, the temperature of equipment varies with location in the orbit, sun angles and attitude orientations. External temperatures can cycle from -60°C to +60°C within an hour. Internal temperatures are better controlled and often range from 0°C to +30°C in 1 hour. Thermostatically controlled heaters are turned on to keep the internal minimum temperatures above 0°C. Active thermal control systems such as refrigeration or thermal louvers are used to decrease heat when temperatures rise above 30°C.

The space insurance industry was created to offer relief from risk to satellite owners and operators from piece-part, component failure and infant mortality failures. Current space insurance rates for a launch vehicle and satellite can be as high as 15% the price if the satellite and launch vehicle combined. The insurance will usually cover the first year of in-orbit use since infant mortality failures. The increase in equipment reliability from using telemetry prognostics to design and test a space vehicle with a failure rate as high as 25% can be reduced to as low as 5%, reducing or eliminating the need and cost for space insurance.
VII. Reliability of Remaining-Usable-Life for Data-Driven Prognostics

The highest reliability when using Failure Analysis’ telemetry prognostics is obtained by using telemetry from all environmental operating conditions, diurnal effects, seasonal effects and equipment operating conditions. When the total operating environment and conditions are not available, a decrease in accuracy may occur.

Launch failures and infant mortality failures have become completely acceptable\(^4\). In any industry, infant mortality failures are considered a normal part of doing business. This is an outcome of the infant mortality failures have occurred in the industries that first used electrical components in their systems. Prognostics will decrease the number of launch vehicle and satellite infant mortality failures significantly.

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\(^4\) Learn more about the reliability of remaining usable life for data-driven prognostics.
With the high infant mortality failure rate that occurs for satellites and launch vehicles, the space insurance industry was created to reduce the risk to satellite system owners and operators by insuring the launch vehicle and up to one year of mission life against financial loss. Current premium rates are about 15%-30% of the total cost of the launch vehicle, satellite and any financial losses that occur as a result of a failed satellite and fluctuate with current failures and successes.

By increasing vehicle reliability with prognostics, the need for insurance decreases significantly to where premium prices could be less than 5%.

For military and government satellite programs which self-insure, the number of failures could be reduced from 25% to less than 1% a year saving the American taxpayers many $Billions a year.

VIII. Telemetry System Design

In theory, telemetry system capacity or the number of individual channels available for engineering data is determined at the first system design iteration done to support a proposal in response to a request for proposal (RFP) from a spaceflight equipment customer. Each technical group of the system, called subsystems, is polled for what they determine will be their initial telemetry channel capacity. The telemetry systems engineer adds all the measurements requested from the different technical areas, analog and digital, and determines system capacity, sampling frequency and conversion requirements. Usually a 10% overcapacity is used in the event that additional measurement channels are needed as the design matures.

In practice, a program decision is made to use in-house telemetry units or commercially available units with a fixed telemetry channel capacity and performance. The capacity is allocated by subsystem and each subsystem will use what ever number of telemetry channels is allocated. Additional telemetry channel capacity can be added later but it usually requires another electrical box to be added to the electrical harness. This is a complex change and effects system reliability after the design is mature. Every time a change is made in the design that affects the electrical design, something may get changed that was not supposed to causing unknown future system problems.

Commercial satellite builders frown on large capacity telemetry systems. One strategy to reduce system cost for the satellite builder is to reduce the number of telemetry measurements/channels. More telemetry channels require additional wiring, encoding capacity which means larger, heavier wire harnesses, heavier and a more complex signal conditioning and telemetry channel encoders. Increasing system mass, electrical power needs, complexity and reducing reliability with no return.

Another complicating factor for telemetry is when equipment fails, the telemetry from the failed unit can often appear exactly as if it is also invalid. Determining whether anomalous telemetry represents a change in operating behavior, a failed telemetry circuit, a real equipment failure or is just invalid telemetry originating somewhere in the communications equipment requires significant engineering experience and diagnostic capability. Failure Analysis’ telemetry prognostics technology determines if telemetry is valid.

IX. Impact of Prognostic Technology on Spacecraft Design Process
Telemetry, the generation of information and transmittal to another location, was used as early as 1812 in the development of land mines. Over the next 150 years, telemetry developed a reputation by management as expensive, unreliable, unnecessary; a cost of doing business with no inherent value. Test engineers argue for more measurements to provide equipment and system performance information as well as diagnostic information to identify equipment that failed as well as equipment operating status and configuration. Added to aircraft, missiles, launch vehicles and satellites in the 1960’s, the number and use of telemetry measurements remain controlled by program management.

Large satellite owners and operators such as NASA, Air Force and INTELSAT recognize the value of telemetry as the end user and requested higher number of measurements by satellite and spacecraft builders. In the commercial satellite industry, owners are mostly not technically experienced in satellite design and do not usually specify the number of telemetry measurements and what equipment is to be instrumented but rely on the satellite builders to use whatever they suggest. For fixed-price satellite contracts, program profits and vehicle complexity are impacted significantly by the number of telemetry measurements used, keeping the number to a minimum. For commercial communications satellites, TWTA’s have the priority for vehicle weight and power. Because of the weight and power penalty for additional telemetry measurements, the number is kept to a minimum.

Space vehicle design is often dictated by the customer request-for-proposal (RFP). During the equipment design process, test points are used to determine circuit performance and operating status. Test points can become telemetry measurements and provided outside the equipment for testing and diagnostic purposes. With the knowledge that telemetry can provide the information necessary to predict future failures, increasing equipment reliability, operability, serviceability and equipment availability, circuit designers will be motivated to add measurements to all circuits that may not have received measurements in the past. This will increase the circuit complexity slightly and vehicle mass and even electrical power needs however the many cost saving paybacks and increased reliability, equipment life and payload services for providing measurement data to equipment testers and equipment operators can easily justify the added expense, complexity of telemetry measurements on all active circuits.
For the first time in the history, a financial reward exists to the space equipment and vehicle builder for using telemetry.

X. Impact of Prognostic Technology on Equipment and Vehicle Level Acceptance Test Process

Historically, equipment and vehicle acceptance testing is used to force piece-parts or components to fail and find piece-parts that have already fails to perform within desired performance specifications.

During space equipment manufacturing and test, identifying piece-parts that are in the process of changing performance significantly will eliminate infant mortalities, shorten manufacturing and test schedules and increase equipment reliability.

Identifying piece-parts that will fail in the near future allows for the replacement of the piece-arts and the continuation of the manufacturing and test of the equipment while it is still on the ground. Also, when piece-parts begin to change behavior immediately after completing testing, an infant mortality failure will occur.

By using existing commercially available data acquisition and analysis products that have a test instrumentation interface, the test data collected during the entire manufacturing and test process can be displayed and piece-parts that change performance can be identified and be replaced.
The most difficult part of finding piece-parts that are in the process of failing is recognizing the failure signatures within normal appearing data. Historically, unfamiliar measurement behavior has been attributed to system noise and discounted for further investigation.

The time to fail from the start of failure is unique for every failure and no two piece-parts or component failure signatures look the same, so one cannot use pattern recognition techniques to spot changing piece-parts nor can one use one failure precursor behavior to identify another.

Fig. 17. Commercially Available MS Windows Data-Driven Prognostic System

[6] Using available commercially off-the-shelf software for data acquisition, storage and display, failure behavior in test data can be recorded and displayed for analysis to identify failure behavior. Today’s data acquisition and display software can store large quantities of time-series data taken during equipment test for display allowing failure behavior to be identified. Failure behavior has not been identified until known due to their obscurity. They are not similar to each other and can be easily confused with normal behavior.
XI. Impact of Prognostic Technology on Space Vehicle Integration

Today’s large satellites and launch vehicles use hundreds of thousands of piece-parts for on-board electrical circuits. Piece-part reliability says that piece-parts fail in a characteristic and predictable manner. During this time of failures, some piece-part failures are found during acceptance testing. However, piece-parts embedded in equipment do not stop failing at acceptance testing. A smaller number of them continue to fail, some sooner, some later. During vehicle integration activities, flight equipment is received from suppliers and installed into the vehicle’s electrical harness for electrical power and data communications systems for routing power and telemetry.

During this time, piece-parts that have begun to fail after acceptance testing is completed can be identified using telemetry prognostics. By operating the equipment and recording telemetry, failure signatures present in telemetry for equipment with piece-parts in the process of failing and those that will fail in the future can be identified. This allows for the repair or replacement of unreliable equipment that may fail during acceptance testing before acceptance testing is initiated. As telemetry is collected and stored from equipment that is operating during satellite integration activities, all the equipment with piece-parts that are changing behavior can be identified and replaced increasing overall equipment reliability while stopping infant mortality failures after the satellite is in-orbit.

Impact of Prognostic If the piece-parts that are going to fail prior to or during vehicle integration are identified prior to integrating the equipment into the vehicle, vehicle integration will be shorter. Part of vehicle integration is the checkout of the equipment installed. By integrating only equipment that will operate successfully as expected, engineers will not need to perform diagnostic techniques to determine if their equipment integration activities resulted in an electrical problem. The integration schedule will be shorter requiring fewer hours to integrate spacecraft equipment.

XII. Impact of Prognostic Technology on Launch Vehicle Readiness Activities

Launch readiness consists of all the activities necessary to attach a satellite to a launch vehicle upper stage for later deployment. During this activity, the satellite equipment is operated so that engineering staff can evaluate vehicle telemetry just before launch to ensure that no equipment has failed before launch. Telemetry prognostics used during launch readiness offers the last opportunity to evaluate telemetry for failure signatures in equipment that indicate equipment piece-parts or components have begun to change operating performance. In the event that equipment with failure signature is identified, the equipment can be repaired or replaced prior to launch eliminating an infant mortality failure.

Since unreliable equipment has been removed, the likelihood that space equipment will become unreliable during integration is less shortening integration time.

XIII. Impact of Prognostic Technology on On-Orbit Satellite Operations

Satellite on orbit operations includes analysis of satellite telemetry to identify the performance and operating status of satellite equipment. Satellite telemetry is usually narrowband, however since it is available for recording and processing continuously, large quantities are collected and stored. Because of the large amount of telemetry to analyze, software is used to detect engineering measurement data limit violations and configuration changes, desired and surprise changes. Trending of analog telemetry data is common. Limits are sometimes provided by the satellite manufacturing personnel to the mission control personnel. Trending may predict limit violations.

Using telemetry prognostics, future satellite bus and payload failures can be identified and predicted. Once identified, an up-coming failure can be postponed or even halted completely by powering down the equipment and powering up the back up unit/circuit. Once equipment with a failure signature in telemetry is identified, the thermal environment can be changed. Equipment with lower operating temperatures last longer than the same equipment operating at higher temperatures. Lowering the thermal environment will increase the useful remaining life of the equipment. Although space flight piece-parts are specified to operate well within the operating behavior expected inside a satellite, their failure rate is a function of its operating temperature.
Using prognostics can significantly decrease and possibly eliminate the downtime for the satellite payload. Prognostics allows the engineering personnel to know what equipment is likely to fail, eliminating surprise failures and provide time to develop a plan for implementing before the satellite equipment has failed and avoid possible dangerous, fast-paced recovery activities. When equipment that will fail in the near future is identified whose failure will impact the operations of the payload, the backup equipment can be powered on during a period when the payload services are of lower demand. In this way, high reliability payload services can be maintained.

The relationship between the flight equipment reaching the predicted remaining-usable-life is defined as a probability of success (Ps).

Anyone can believe they are using prognostics, it is the results that matters. Since there so few actual telemetry measurements that indicate failure behavior during and after test, it is easy to assume that there was no unreliable equipment.

There are two types of errors that can occur with prediction failures. A false positive is when there is no equipment failure but the results come back as positive. Sometimes, when an event is very rare, and/or when a test has a high rate of error, there may be more false positives than actual positives. A false negative is when there actually is an equipment failure but the results come back as negative. A finding of no failure, when there actually was a failure, would be a false negative. Both types of errors can be devastating; some programs have been devastated when they were told that they had a failure was going to occur when it actually did not. Others have not completed the necessary contingency actions at the time needed because their failure was not predicted.

![Graph showing the probability of reaching a duration of remaining life (%) versus months of remaining usable life.](image)

**Fig. 18.** Failure Analysis’ Telemetry Prognostic Technology Accuracy for the Day-of-Failure algorithm Performance
XIV. False Positives and False Negatives

Fig. 19. Reliability of the Results Using Telemetry Prognostic Algorithms Based on Insufficient Data

With adequate training and experience by prognosticians, the reliability of prognostic technology is strongly related to the capture of equipment behavior during all different operating conditions. Because there are many sources of data that can be interpreted as failure behavior, the more data available from each environmental and operational condition that can be used to identify failure behavior, the more reliable the results.

These false results cannot be completely eliminated, but they can be reduced. People can demand a second opinion.

A false positive, also known as a false detection or false alarm, occurs when a prognostician identifies a suspect failure precursor from telemetry that is caused by something other than a piece-part or component failure. False alarms reduce reliability of telemetry prognostics since people will discount the results.
Our objective is to have no false positives and no false negatives. We do this by keeping a man-in-the-loop. The best performance for identifying a failure precursor is the trained and experienced prognostician. Software is used in fields such as radiology, identifying cancerous tumors in X-rays. However, the number of false positives is much higher using software than with a radiologist. When a false positive occurs in someone’s X-ray the result is simply to have another X-ray taken. In the satellite and launch vehicle industry if a false positive occurs, it could delay a launch which could add costs of many millions of dollars (Space Shuttle is around $5,000,000.00/day) or cause the catastrophic loss of the usefulness of an entire satellite costing as much as $300,000,000.00.

Likewise for a false negative to occur, missing a failure could cause a surprise failure putting a spacecraft and astronaut at risk.

Over the 25 years of using telemetry prognostics starting with GPS satellites, there have been no false positives and no false negatives.

XV. Analog Measurements Needed for Using Telemetry Prognostics

Failure Analysis’ telemetry prognostics technology doesn’t require any other analog measurements than what are available today on flight equipment and in vehicle telemetry systems. However, instrumentation of equipment is necessary to use prognostic technology.

The number and types of analog measurements per unit includes circuit voltage, current and unit temperature. Prognostics has been highly successful with only one measurement per unit.

Although insensitive to sampling frequency for telemetry measurements for identifying failure behavior, sampling frequency can impact the accuracy of the determination of remaining-usable-life.
The remaining usable life for equipment can be determined by understanding the piece-part failure characteristics determined under test in an operating circuit. This information is considered proprietary by the piece-part manufacturer since it is an indication of the quality of their products and not available in the popular domain.

Based on the analysis of many in-flight piece-part failures, historically, piece-part failure occurs over a very long period of operational life once the failure precursor is identified. This period can be as long as 1 year. We use a technique shared by companies that build spacecraft to agree on mission life. Spacecraft usable life, called the mission life is determined by quantifying the expected life of all piece-parts and mechanical systems on a vehicle. Mission life will not exceed the shortest life of any non-redundant circuits or mechanical systems. If there are no life-limiting piece-parts or mechanical systems, mission life is derived by quantifying the risk to the company of meeting a mission life based on past vehicle mission life actually reached. Since there is not a financial penalty other than loss of in-orbit incentives, for a company if the mission life isn’t achieved, companies will claim very long mission life, over 20 years. This is confirmed with the actual life of many in-orbit satellites, some of which have operated for over 40 years.
To accurately predict remaining-useable-life for equipment that has been predicted to fail, Failure Analysis maintains a database of flight equipment failures that were analyzed and found to have failure precursors and analysis that resulted in no failure precursors. This information is used to determine the probability of success (Ps) of a circuit with a failure precursor identified reaching its predicted remaining-useable-life. This is the same technique that is used by spacecraft building companies to decide their satellite mission life. Satellite mission life that a company will agree to is based on a history of the mission life of their past satellites in-orbit lifetimes.

![Comparison Between Telemetry Prognostics RUL, Actual RUL and Average Actual RUL](image)

**Fig. 23. Failure Analysis’ Data-Driven Telemetry Prognostic Algorithms Results for Duration of Remaining Life**

Failure Analysis maintains a historical database of flight equipment failures researched over the past 32 years consisting of several hundred years of telemetry and uses a probability of success (Ps) to determine the day of failure and remaining-useable-life based on actual satellite equipment failures.

Any prognostic algorithm should have a zero false positive and false negative rate. The use of any prognostic algorithm will only remain useful if it is accurate and reliable. Telemetry prognostics has been used with over 100 satellite and launch vehicle electrical and electro-mechanical units. Current accuracy performance of our remaining-useable-life algorithm has been 100% accurate.

![Ariane 44B Launch Vehicle Used to Launch the Commercial SCC SUPERBIRD B Geostationary Communications Satellite Used with Telemetry Prognostic Algorithms](image)

**Fig. 24. Ariane 44B Launch Vehicle Used to Launch the Commercial SCC SUPERBIRD B Geostationary Communications Satellite Used with Telemetry Prognostic Algorithms**
Fig. 25. Lockheed Martin/Navy Fleet Ballistic Trident Missile Program Office Independently Validated Failure Analysis’ Telemetry Prognostic Algorithm Results

<table>
<thead>
<tr>
<th>GPS NAVSTAR Satellite No.</th>
<th>Satellite Failure</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS#1 Rubidium Loop</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FS#2 Rubidium Loop</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>FS#3 Rubidium Loop</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FS#1 10.23 MHz VCXO</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FS#2 10.23 MHz VCXO</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FS#3 10.23 MHz VCXO</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>SGLS Transmitter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
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<tr>
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<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Reaction Wheel #2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Battery #3</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Examples of Satellite Equipment Failures Successfully Predicted (X) on GPS Block I Satellites Using Telemetry Prognostic Algorithms

<table>
<thead>
<tr>
<th>Satellite Failures</th>
<th>RUL</th>
<th>Accuracy of Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>XMTR A</td>
<td>&gt; 6 Months</td>
<td>100%</td>
</tr>
<tr>
<td>XMTR B</td>
<td>&lt; 6 Months</td>
<td>100%</td>
</tr>
<tr>
<td>Gyro A</td>
<td>&gt; 6 Months</td>
<td>100%</td>
</tr>
<tr>
<td>Gyro B</td>
<td>&lt; 6 Months</td>
<td>100%</td>
</tr>
<tr>
<td>Gyro C</td>
<td>&lt; 6 Months</td>
<td>100%</td>
</tr>
<tr>
<td>Tape Recorder A</td>
<td>&lt; 6 Months</td>
<td>100%</td>
</tr>
<tr>
<td>Tape Recorder B</td>
<td>&lt; 6 Months</td>
<td>100%</td>
</tr>
</tbody>
</table>
Table 7. Results from Using Telemetry Prognostic Algorithms with Launch Vehicles

<table>
<thead>
<tr>
<th>LV</th>
<th>Satellite Payload</th>
<th>Prognostics Used?</th>
<th>Launch Successful</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITAN</td>
<td>?</td>
<td>Yes</td>
<td>?</td>
</tr>
<tr>
<td>ATLAS</td>
<td>GPS 1</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>ATLAS</td>
<td>GPS 2</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>ATLAS</td>
<td>GPS 3</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ATLAS</td>
<td>GPS 4</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ATLAS</td>
<td>GPS 5</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>ATLAS</td>
<td>GPS 6</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ARIANE</td>
<td>SUPERBIRD</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 8. Results from Using Telemetry Prognostics Algorithms with Missiles

<table>
<thead>
<tr>
<th>Missile Name</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITAN</td>
<td>No failures predicted</td>
</tr>
<tr>
<td>ATLAS</td>
<td>No Failure predicted</td>
</tr>
<tr>
<td>TRIDENT</td>
<td>Telemetry prognostic technology was validated by Lockheed Martin</td>
</tr>
</tbody>
</table>
Fig. 29. Air Force/Martin Titan 34D Launch Vehicle Telemetry Prognostics was Used With

Fig. 29. NASA/EUVE Satellite In-Orbit Tape Recorder B Failure Results Using Telemetry Prognostic Algorithms for Processing 3 Years of Real-Time and Stored Telemetry Illustrating Circuit Failure Precursor (red) Just Prior to Complete Failure (blue)
Fig. 30. Traditional Diagnostic Telemetry Processing and Display for NASA/EUVE In-Orbit Satellite Tape Recorder B Failure Telemetry Using Telemetry from Around the Time of Complete Failure (blue)

XVII. Conclusion

Telemetry prognostics lowers program costs, shortens delivery schedules as it upgrades satellite and launch vehicle design, manufacturing & test process, increasing equipment reliability while managing launch failures and eliminating in-orbit infant mortality failures. Failure Analysis’ telemetry prognostic algorithms are flight proven; and available for use today.

REFERENCES