Prognostic and Health Management for Avionics

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Abstract— This paper describes methodologies and tools to anticipate in real-time, the onset of failures in electronic equipment. Currently developed techniques for prognostics and health management (PHM), depend on the observation of precursor variables and an imputation from them of impending failure. In electronic systems such variables are difficult, impossible or expensive to obtain, so we propose a novel model-based technique utilizing embedded life models and environmental information obtained from aircraft mounted sensors that measure those parameters that most significantly accelerate failure in electronics, i.e. temperature, temperature variation, vibration and shock. This technology will be referred to throughout this paper as electronics Prognostics and Health Management (ePHM).

1. INTRODUCTION

The ability to anticipate failures in electronics has the potential to significantly reduce support costs and to improve mission capable rate. Support cost is by far the largest contributor to life cycle cost [1]. We expect that successful implementation of ePHM technology will lead to far-reaching changes in the logistics support infrastructure presently required to support today's highly complex avionics.

To understand the driving force for ePHM, it is first necessary to understand the technology trends occurring in the electronics part industries. Their transition away from military specific to commercial electronics technologies is well known and documented. Avionics suppliers are necessarily turning to COTS[1] electronic components and sub-systems partly because of the increasing lack of military qualified components and partly to take advantage of the high-performance components available in the COTS market with the advent of new technologies such as low-k dielectrics, copper interconnect and low voltage. It is also well known that the dominant market segment for commercial components is the high-volume commercial electronics sector (e.g. computer, telecom) and that military needs have little or no weight in this market. The needs of commercial electronics do not routinely include long-term supportability or long product life. There is no incentive for electronic part manufacturers to design for a part life in excess of about 5-7 years [21] [23] [24], particularly when part cost savings can be made by not doing so. Therefore low-volume/long support life industries such as military and aerospace are at risk from life-limited electronic components; a scenario which has not previously been considered in performing life-cycle cost analysis, mission capable rate assessment, safety of flight assessment and logistics planning.

The inescapable conclusion from technology forecasts, from for example the NEMI [2] and SIA [3] (which have proved over time to be actually rather conservative), is that electronic part technology will transform in major ways over the coming years. ePHM will enable equipment users to monitor the remaining life in components, sub-assemblies and equipment and take corrective action at the time and place of their choosing to restore the asset to full capability, capable of completing the next mission or series of flight legs.

The old assumptions of essentially unlimited life and constant failure rate for electronics must be questioned, when the intrinsic life of components and interconnect becomes significantly shorter than that of the systems in which they are used. Electronic systems designers must now think in terms of failures being expected rather than occurrences to be dealt with as they arise. There is a need for an ePHM capability to counter the sharp escalation in support costs that is expected to arise from the widespread adoption of electronic COTS technologies.

System designers currently assume that the rising portion of the well-known 'bathtub' reliability curve is sufficiently far out to not be of concern in life cycle planning. This assumption, although actually incorrect, has historically been of practical use, since the lifetime of components has been longer than the expected equipment life. With the advent of components whose life may not be longer than the system life, the constant failure rate assumption is not valid. Vehicle systems will be subject to wearout (as all electronic systems are) and wearout will no longer be 10 years or more but may occur within 5-7 years [4]. It follows that the planning derived from the constant failure rate assumption will also be incorrect.

Figure 1 shows a schematic of the ePHM process inputs, computations and output. For clarity, the figure shows only three sensor inputs and three models. The actual number of these will be much larger in practice.

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[1] Commercial-off-the-shelf. This term is applied to items which are sold in the commercial market and are not specified or otherwise controlled by the Government

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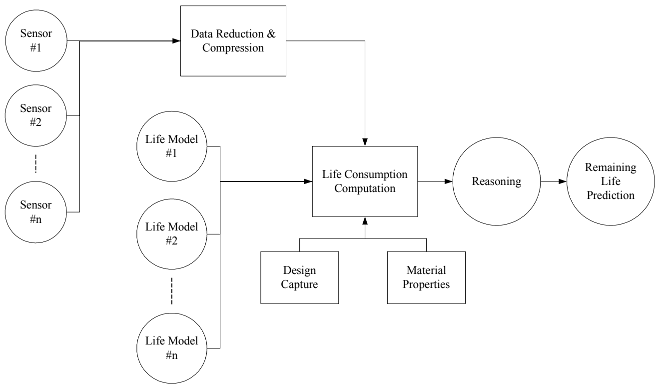

Figure 1: Remaining Life Prediction

Sensor data provided by a variety of on-engine and on-aircraft sensors is first compressed and reduced. This process greatly reduces an otherwise unmanageable quantity of data, without sacrificing a significant amount of information. A life consumption algorithm, utilizing a variety of life models, knowledge of the design and the constituent material properties, then computes the amount of life used with an associated confidence interval for each of the possible failures sites. Since there are sources of uncertainty, such as material properties and the physical dimensions of the various structures making up the electronics assembly, there is corresponding uncertainty associated with the life consumption computation. The reasoning process combines these uncertainties using a decision support system to give a remaining life prediction for the complete system, again with an associated confidence interval.

The confidence interval obtained by this process depends upon the level of certainty that the user desires to achieve. The higher the certainty desired the wider would be the confidence interval. The user therefore has to make an informed trade-off between level of certainty and the economic cost that accompanies high certainty. To achieve high certainty means replacing items well before all useful life has been consumed. This is an economic trade-off decision that is informed by life-cycle cost modeling.

There are a number of related objectives, all of which reduce to life cycle cost minimization. Specifically the objectives are to:

1) Provide continuous and real-time indication of the state of health of an electronic item as it is exposed to various life cycle loads during its normal sphere of operation. The state of health will be measured as the fraction of life consumed
2) Use the state of health indication to provide a forecast of the expected future availability of the equipment
3) Show how to utilize that information to better manage vehicle availability, maintenance and logistics by demonstrating a practical business case development process
4) Show a clear migration path from a demonstrated technology to implementation in a military engine control product.

These techniques have wide applicability to electronic systems of all kinds, though the largest payoff is expected to be from high-value, long-life, severe environment applications such as avionics. Electronics of this type are found in such diverse industries as commercial and military aircraft, ships and vehicles, oil exploration and outdoor telecommunications.

The major tasks are:

1) Embedded software for the computation of upper and lower confidence bounds of time to failure using probabilistic virtual qualification, life models, statistical methods and Monte Carlo simulation
2) A demonstration of the technology in a prognostic computing module
3) A design, development, implementation and test plan for an ePHM enabled engine controller
4) An economic model of the life cycle cost reductions provided by ePHM

The CALCE Electronic Product and Systems Center has many years of experience in assessing the reliability of electronic products through its virtual qualification software. This software operates by computing accumulated damage under the influence of environmental usage stress conditions.

ePHM is the engineering and science of estimating the probability of failure of an item over some future period. Depending on the techniques used, the forecast period can be quite short, when for example the use of precursor information is relied upon, to much longer periods when a continuous calculation of remaining life is computed from sensor data and life models. This latter approach will be used in this project, since precursor information is not generally available for electronic systems except in a very limited number of cases.

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Background & Problem Statement

Health monitoring for both electronic and mechanical equipment has been used for many years. This section provides a short review of the techniques that have been applied. These techniques relate mainly to health monitoring. The prognostics elements of ePHM have been lacking or have provided a relatively short prediction interval. In relation to electronic systems, the prediction intervals currently available are insufficient to generate any significant cost savings.

PHM Techniques for Mechanical Systems

Prognostics are currently used in rotating component systems such as turbine engines, gearboxes and rotor heads to indicate that a failure is impending. These generally operate by collecting precursor data from sensors, mounted on or near the components, which collect for example acoustic gear noise data or the debris content of oil. Signal feature analysis is performed to detect abnormalities that are related to an impending failure indication by an inference engine using an historical database [5] [6] [7]. This approach can provide warning of failure but is inherently incapable of attaching a confidence interval to the remaining life prediction. In contrast, electronic systems cannot generally provide such kinds of precursor data.

Degradation is unobservable until a catastrophic failure occurs and therefore a new physics-based approach using environmental sensor data and life models, augmented by local part-specific sensors to estimate equipment remaining life is proposed for this project.

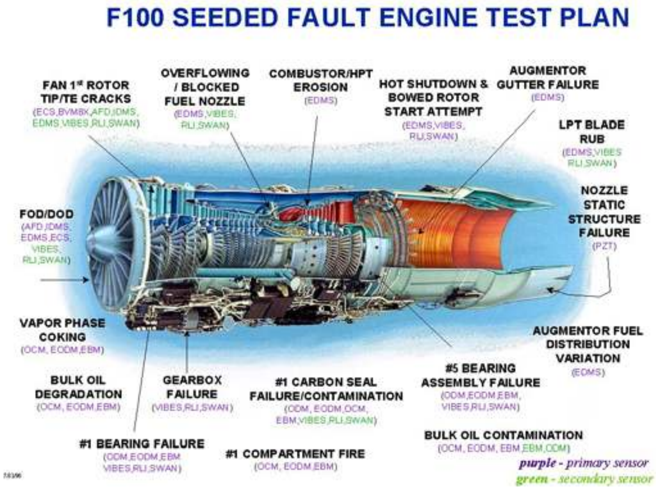

Figure 2: JSF Engine PHM

The figure above shows some of the mechanical prognostic techniques currently being developed for the JSF engine [7]. All of the techniques illustrated above rely upon precursor information to predict the onset of failure.

Existing PHM-like Techniques for Electronics Systems

It has been common practice to implement error detection and sometimes error correction, in dynamic RAM arrays. DRAMS are subject more than any other type of component to single event upsets arising from cosmic rays and alpha particles. Errors may be detectable, or with increased hardware overhead, correctable for single bit errors. Similarly, due to their regular structure, the operating system can to keep track of 'bad sectors', analogous to the bad sector mapping applied to disk drives and map out the failed locations. Electronic part manufacturers apply a similar technique to DRAMS. They selectively laser-cut redundant cells into the array to replace those found to be defective on final test. These techniques rely upon precursors to indicate declining health and are very limited in the types of failure that can be predicted and in the warning period provided. The modeling approach proposed herein is capable of providing failure warning for the much wider array of failures commonly experienced in the field and is able to provide longer periods of warning and with a known relation between the prediction and the confidence level that may be attached to it.

These approaches may be best described as health monitoring approaches. They do not (and cannot) address the prognostic side of the problem.

Reliability Prediction,, Safety Assessment and Logistics Planning

Electronic equipment failure rate is typically illustrated by the well-known bathtub curve. Initial shakeout reliability is characterized by a falling failure rate followed by a roughly constant failure rate and lastly a rising curve as wearout failures begin to occur. The data used to plot this curve is usually of a rather gross kind due to the great difficulty of obtaining detailed fault information from the field and from maintenance shops. The data does not distinguish between the large varieties of failure mechanisms that cause the reported failures. When this is taken into account, the relatively flat portion of the curve is seen to be a consequence of averaging a large number of non-constant failure rate curves. The right hand rising portion has in the past been discounted, as being far beyond the expected service life of the equipment, i.e., will be superceded by more modern alternatives. With the increasing use of COTS, this assumption may no longer be correct [23].

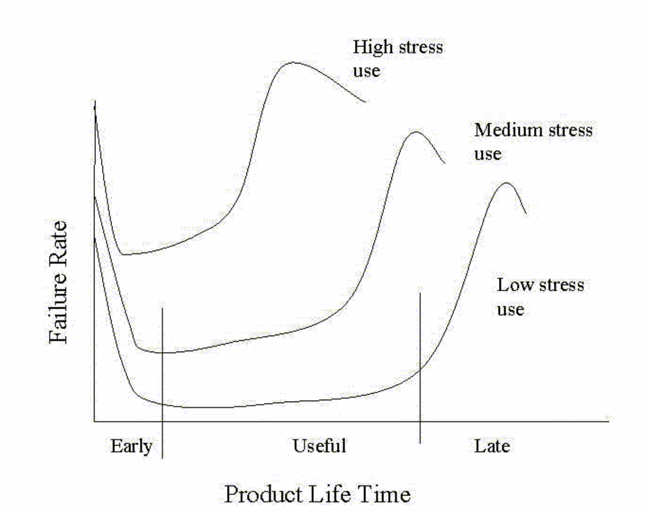

Figure 3: Bathtub Reliability Curve

Electronic systems are usually assumed to be 'as-good-as-new' until either a failure[2] occurs during normal operation, or a fault[3] is detected during a test phase such as commonly occurs immediately after power-up. Faults do not necessarily result in failure, since redundancy can absorb faults to a certain degree. This is commonly modeled as a constant failure rate reliability model. The effects of wearout are typically not considered. Following a repair action, the system is again treated 'as-good-as-new' and passes through repeated use/repair cycles until the system is eventually retired as being beyond economic repair.

The implied assumption is that reliability can be modeled as a constant failure rate, i.e. a failure is equally likely to occur at any point in time, irrespective of the exposure of the equipment to its various environmental loads and previous repairs. This measure of reliability is commonly known as mean-time-between-failure (MTBF) and is modeled statistically by the exponential distribution. The measure is computed by dividing equipment operating-hours over a period by the number of equipments failing within the same period. Consequently, this measure is an aggregate measure for a fleet and does not relate to individual equipment. This reliability measure is often used in system safety calculations and logistics planning. The MTBF assumption naturally leads to the simple approach of providing multiple redundant channels to achieve (supposedly) the required low probability of failure defined in FAA Advisory Circulars or the system requirements.

The ideas above lead to the concept of failure free operating period (FFOP)[4], i.e. a period dependant on stress, operating conditions and material properties, during which no failure will occur. This concept is currently applied to physically large structures, such as aircraft wings and turbine engine rotor discs using stress/strength calculations and crack growth theory. They have not so far found any wide application in electronics. The ideas of damage accumulation tracking and threshold detection lead naturally to the ability to forecast failure events through monitoring of the usage environment and models of failure mechanisms and to the annunciation of system state to the equipment user.

ePHM has the potential to mitigate the risks associated with new technology (possibly short life) COTS components and assemblies by providing a physics-based methodology to measure the degradation with time of electronic components and assemblies and to forecast (with some level of confidence) the expected occurrence time of a failure.

Mission Capability

Once it becomes possible to predict a probability of mission completion, a new avenue for life-cycle cost minimization is opened up so that an informed trade-off can be made between the cost of early repair and the cost of mission loss.

The assumption that all available assets (e.g., aircraft) are in the same state of health is incorrect. Assets will have experienced a variety of loads that have consumed a variable amount of life. Thus, the ability to selectively deploy an asset would enable a manager to make the best use of the available assets to perform the range of missions that they face. The value of ePHM is that it enables a risk-informed trade-off to be made between the cost of an asset being unavailable when required and the cost of wasted equipment life through being replaced before it has consumed all its life (i.e., has failed). It is expected that for high value items such as avionics, the cost of asset unavailability will far exceed that of additional maintenance actions being performed.

Logistics Support Cost

The life-cycle cost of a piece of equipment includes the cost of acquisition and the cost to support it throughout its life, which may be 20 years or more for aircraft. A significant component of the life cycle cost comes from the infrastructure that an organization supports such as repair shops and maintenance staff. Support cost is by far the most dominant contributor to life-cycle cost and therefore any inroads that can be made in reducing it will provide a high payoff. Life-cycle cost models have to consider not only the intrinsic reliability, or equivalently the repair cost of the equipment, but also the equivalent cost of not completing the next operating period or mission, keeping the spares pipeline filled, the number and location of repair facilities and the transportation time of materials to those facilities.

The most common approach to avionics maintenance is to replace on supposed failure, i.e. unscheduled maintenance. Current built-in-test techniques are typically only capable of detecting operational irregularities or the existence of a hard

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[2] A system state such that the system is not capable of accomplishing its required functions.

[3] A system state such that the systems ability to sustain further faults without entering the failed state is impaired.

[4] More formally defined as a period of time during which no failures resulting in loss of function will occur.

fault condition and thus do not provide any prognosis of impending hardware failure. Consequently, individual failures must be treated as unpredictable events and planning can only be done based on an assumed or estimated MTBF.

The constant failure rate assumption pervades the maintenance planning function in which the required number, type and location of spares is determined. Maintenance planning is the process of provisioning the fielded system with spares, supporting test equipment, personnel and facilities so that the probability of the user asset (airplane, vehicle etc.) completing the next operating period successfully can be maintained at some pre-assigned level. Maintenance planning operates at all levels of indenture of the asset, i.e., line replaceable unit (LRU), shop repairable unit (SRU) and component, and assigns quantities and replenishment levels at each of the sites designated for repair actions such as remote and centralized workshops and OEM workshops. In essence, a supply chain pipe to support the end item throughout its geographical area of operation is established. The central input to this process is the system reliability, usually expressed as an MTBF, since all the required quantities and rates of replenishment are calculated from this.

System designers currently assume that the rising portion of the bathtub curve is sufficiently far out to not be of concern in life cycle planning. This assumption, although actually incorrect, has been of practical use since the lifetime of components has been longer than the expected equipment life. With the advent of electronic components, whose life is may not be longer than the system life; the constant failure rate assumption is not valid. Vehicle systems will be subject to wearout (as all electronic systems are) and wearout will no longer be 10 years or more but may occur within 5-7 years [4]. It follows that the planning derived from the constant failure rate assumption will also be of poor fidelity.

Obsolescence, Technology Insertion & Life Consumption Impact

The obsolescence problem is well recognized as a serious impediment to long-term support of avionics. Manufacturers are responding with various short-term tactics such as last time buy. More far-sighted manufacturers have recognized that a long-term solution to long-term support lies in the design, i.e. avionics must be designed so that continuous technology refresh is affordable. Ideally, a system would never become obsolete because it never fails and then there is no need for repair. Even in this ideal scenario, replacement may be necessary to accomplish functional upgrades for unplanned capability extension.

Thus with a continuous technology insertion program, avionics will necessarily have to use the components and technology then available from the commercial sector and manage the risk of life limited components. ePHM is the means by which that might be accomplished so that support costs do not rocket out of control.

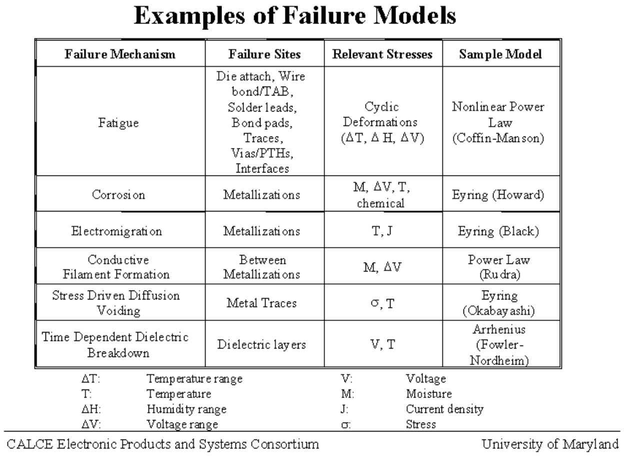
Continuous replacement and upgrade may render the limited life of electronics irrelevant if the life is in excess of the technology refresh time. In order to answer this, it is necessary to consider what are the likely upgrade times and the life limits of avionics. Different types of system will likely produced different answers to this question. Even when the answers are known, there will be occasions when the avionics does not achieve its design life due to operational factors outside the control of the designers.

This points to the desirability of avionics manufacturers developing a through-life product plan in close consultation with customers further up the supply chain. Thus to make a decision on whether ePHM for a particular system is a net cost reducer and should be pursued, requires a forward business plan and an economic modeling capability to examine various ‘what-if’ strategies where a ‘value’ is assigned to some of the more imponderable attributes such as mission success.

Typical Electronic Failure Mechanisms

A short description of some of the commonly occurring failure mechanisms in electronics is provided below. This list is meant to be illustrative only and by no means a comprehensive list of failure mechanisms in electronics. There are many sources of life models, such as books and journal papers. They can then be used within the same structure and improved ones substituted as the technology matures.

Table 1: Examples of Life Models



Examples of Failure Models

Failure Mechanism	Failure Sites	Relevant Stresses	Sample Model
Fatigue	Die attach, Wire bond/TAB, Solder leads, Bond pads, Traces, Vias/PTHs, Interfaces	Cyclic Deformations (ΔT, ΔH, ΔV)	Nonlinear Power Law (Coffin-Manson)
Corrosion	Metallizations	M, ΔV, T, chemical	Eyring (Howard)
Electromigration	Metallizations	T, J	Eyring (Black)
Conductive Filament Formation	Between Metallizations	M, ΔV	Power Law (Rudra)
Stress Driven Diffusion Voiding	Metal Traces	σ, T	Eyring (Okabayashi)
Time Dependent Dielectric Breakdown	Dielectric layers	V, T	Arrhenius (Fowler-Nordheim)

ΔT:	Temperature range	V:	Voltage
T:	Temperature	M:	Moisture
ΔH:	Humidity range	J:	Current density
ΔV:	Voltage range	σ:	Stress

CALCE Electronic Products and Systems Consortium University of Maryland

Electromigration—In electromigration, the action of the flowing current causes die metallization to be removed from one part of the trace and accumulated at a nearby place. This eventually leads to an open circuit trace or a short circuit between adjacent traces. Electromigration has an intrinsic incubation time dependant on material, geometry and current density so that the probability of failure is zero until the accumulated damage exceeds a threshold. Studies have shown that the rate of electromigration in the newer copper metallurgies has a slower rate of development than that in the more common aluminum metallurgy. Models for this failure mechanism exist [8] [9].

Hot Carrier Degradation & Negative Bias Temperature Instability (NTBI)—Hot Carrier Effects are manifested in two distinct wearout mechanisms. These are Hot Carrier Degradation (HCD) and Negative Bias Temperature Instability (NBTI). Hot carriers effects are the result of high-energy carriers, either holes or electrons, entering the gate oxide of a transistor leading to the degradation of the oxide's properties. Hot carriers are produced as current flows through the channel from the source to the drain. A small number of these hot carriers gain enough energy to be injected into the gate oxide. This results in charge trapping and the generation of interface states. Over time, this leads to a shift in the performance characteristics of the device and eventually to a reduction in performance. This is referred to as HCD. Device lifetime can be determined by defining failure as a percentage shift in threshold voltage, change in transconductance, or a variation in drive or saturation current. NBTI is caused by hole trapping and interface state generation as well and results in threshold voltage shifts and delays within a CMOS device.

Solder joint fatigue—Just as a paper clip that is bent many times will eventually break, a solder joint will develop cracks as the temperature cycles, caused by relative motion of the package and printed circuit board. These cracks originate from small discontinuities or inclusions in the material and eventually propagate right through the solder fillet and cause a failure. The mechanism can exhibit cyclic intermittent failure as the crack is physically forced closed again by the relative motion of chip and board under temperature variation, vibration and shock. There are many sources of models for solder joint failure for all of the major attach technologies such as through-hole, surface mount, ball grid array etc and the associated lead configuration variations.

Time dependant dielectric breakdown (TDDB)—Dielectric Breakdown occurs in silicon dioxide films when the local electric field is sufficiently high to cause avalanche multiplication in the dielectric. That is, silicon dioxide is a dielectric with a property analogous to a 'band gap' of the order of ~9 eV. When the applied electronic field is sufficient, normally around 10 mV/cm to 15 mV/cm - the electrons that tunnel in from the cathode cause impact ionization within the dielectric and the consequent current destroys the material through sheer Joule heating. In silicon dioxide this is a run-away phenomenon, because the holes, either tunneled in from the anode or produced by the impact ionization, are trapped (hole mobility in silicon dioxide is 10-5 cm^2/Vsec), creating a positive charge cloud that further enhances the electronic field. The electrons (mobility ~30 cm^2/Vsec) hence are multiplied and cause the destruction. Clearly, the phenomenon is triggered when the electronic field reaches the critical value required to cause carrier multiplication. Due to the minute imperfections in the film, the electronic field is normally not perfectly uniformly distributed, so that this phenomenon tends to take place in a local region, and the current flow and the consequent destruction occur in a filament in the film, in effect a localized explosion occurs. This results in a total denaturing of the region and typically causes a short between the gate electrode and source/drain or substrate electrodes. If the film is close to perfectly uniform, the breakdown phenomenon takes place, but the local current densities are not excessive, and the film is not physically destroyed. However, this non-destructive breakdown typically results in films that are filled with trapped charge, and consequently device threshold voltages are shifted. In either scenario, the device ceases to function. The use of the Q^5_{BD} concept in reliability predictions strongly depends on the behavior of Q_{BD} as a function of stress current density. This can be used for intrinsic reliability estimates of gate oxide and the switching degradation [10] [11] .

Tin Whiskers—The commercial drive to eliminate lead (Pb) from electronics has resulted in an interest in the use of tin (Sn) finishes as an economical lead-free (Pb-free) plating option. Many electronic part manufactures are providing pure tin (Sn) finishes and others are in the process of transitioning. The re-emergence of tin-plating has renewed concern over the threat of failure due to tin whiskering, first reported in the 1940s. Due to the threat of tin whisker induced failure and the concern for the reliability of electronics that perform mission critical services and have long operation periods, the CALCE Consortium has posted an alert, warning manufacturers of electronic hardware that tin whiskers represent a current failure risk that must be addressed. Tin whiskers have been identified or are highly suspected in the costly failure of a number of electronic systems. Although new plating processes have been developed that appear to reduce the risk of tin whisker growth, there is currently no industry-accepted test for determining the propensity of tin whiskers to grow on a finished surface. At present, new electronic systems may be at risk due to the introduction of components with pure tin finishes.

2. TECHNICAL APPROACH

Electronics Life Modeling

ePHM will be developed starting from the foundations laid by the CALCE virtual qualification process that has been developed over the last 10 years (see for example [18] [19] [20]). In this process, life consumption is modeled using life models, material properties, the design definition and life cycle environmental profile information. This is illustrated in Figure 4 below. The life models used require calibration of model constants by regression fitting against test data. This is carried out as a one-time function during model development. Prognostic cells (made by the Ridgetop Group

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[5] Charge density at breakdown

in the form of IP[6] design cells) are able to provide precursor type information by being embedded within custom ICs, or (with lower accuracy) implemented as a stand-alone component. The output from these cells will be used to re-calibrate the life models on the fly based on the actual experienced environment and the failure time indicated by the cell.

A similar process will be followed in ePHM, except that real-time life cycle environmental data will be collected using on-board sensors and the models executed in real time, providing a continuous calculation of life consumed.

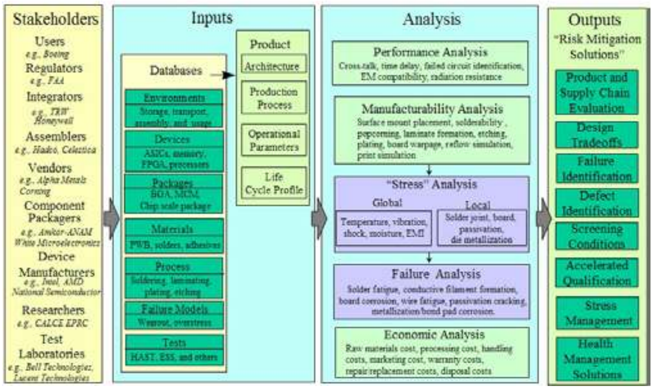

Figure 4: Virtual Qualification Process Flow

Sensors for ePHM

A wide variety of sensors is available commercially and is used currently on engines for normal performance control. ePHM will tap into these available sensors. In addition, the project will determine the types and location of additional sensors where those existing are not able to provide the right kind of information. One particular and specialized sensor is the prognostic cell provided by the Ridgetop Group [22] [25]. This can be incorporated into an integrated circuit as IP or as a standalone item. Figure 5 illustrates the principle of operation of prognostic cells. The design of the cell is tuned to the particular application so that it provides a failure warning prior to failure of the host part.

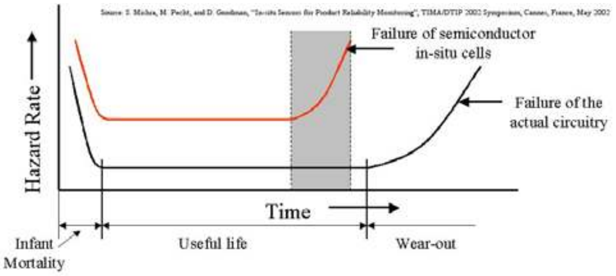
Source: S. Mishra, M. Pecht, and D. Goodman, "In-situ Sensors for Product Reliability Monitoring", TIMA/DTIP 2002 Symposium, Cannes, France, May 2002

Figure 5: Prognostic Cells

The warning provided by the prognostic cell has an inherent degree of uncertainty associated with it as illustrated in Figure 6. Therefore, it is necessary to use probabilistic techniques and reasoning to translate this warning period into a forecast of system failure.

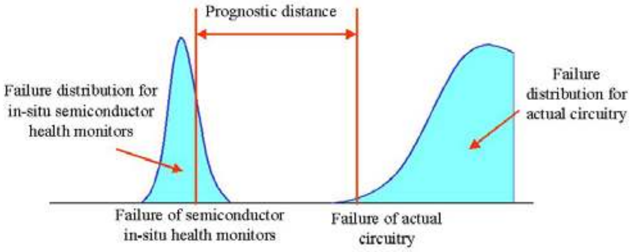

Figure 6: Prognostic Cell Warning Period

Sensors provide large volumes of data that can become unmanageable unless a data reduction process is undertaken on the raw data. The damage accumulation models are not especially sensitive to infrequent, but large, excursions away from the mean. This property enables data reduction algorithms such as Ordered Overall Range or Cycle Counting algorithms to reduce the data volume by an order of magnitude without sacrificing a significant amount of information.

Reasoning in ePHM

There is some uncertainty inherent in the knowledge of the material properties and dimensions of the structures comprising electronic components and an electronic system and of the environment actually experienced. Thus to provide an estimate of remaining life requires the fusion of models and sensor data to provide an estimate of equipment failure time. The modeling of uncertainty is a key aspect of ePHM, since the objective is to estimate a lower bound on time-to-failure at a user selected confidence level. This will give a set of different options depending on the factors affecting the behavior of a particular structure, joint, solder interconnects, etc.

ePHM implies proactive, risk-informed decision making for optimizing health management. The goals of ePHM can only be achieved if tools that support decision-making are incorporated. Decision-making support is a requirement due to the large number of influencing factors and complexity of the decision scenarios. Optimum decisions require all of the influencing factors to be weighted with costs, different action sequences, consequences of each one of the action sequences on other components, etc.

The inputs to the decision support tool are the estimated times to failure and confidence interval from all the failure sites and the output of the cost model. The tool output would be a recommendation for a maintenance action, an index of health and annunciation of an imminent failure along with information to assist a maintenance technician in isolating the location of the damage site to the lowest repairable item.

Life Cycle Cost Modeling

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[6] Intellectual Property

The premise of ePHM is that through observing failure precursors (health monitoring) or tracking environmental stress history and Physics of Failure models (life consumption monitoring), the remaining life in a system can be forecasted, thus enabling either prognostics (predicting the probability of success or failure under some future stress) or maintenance scheduling. Studies like the one shown in Section 3, powerfully demonstrate the potential of ePHM for electronic systems, however, such studies do not address if (or exactly how) a specific application's life cycle cost can actually be reduced. Two fundamental questions remain:

1) What systems should ePHM be applied to? The potential advantages of systems with known remaining lives over random-failure-based life cycle planning are clear. Basing an electronic system on maintenance schedules determined from monitoring and/or prediction will significantly reduce expensive unscheduled maintenance activities and reduce the risks of unanticipated failures (improved availability). However, a system subject to maintenance planning may have a greater overall volume of maintenance activities and may throw away significant remaining life in some system components. Even if ePHM elements could be successfully integrated into a system, scheduled maintenance of electronic systems would not make sense for every system. Whether or not it is economically viable to utilize ePHM concepts in a specific electronic system, depend on many characteristics of the system and of its application, e.g., the system's content, expected availability, and the consequences of failure.
2) If elements of ePHM are going to be applied to a system, how should the results be interpreted? The prediction of life consumed (or life remaining) is a potentially very useful result, but exactly what is the best way to use it? Given uncertainties in the determination of life remaining, uncertainties in the damage threshold that are relevant, and uncertainties in the forecasted future environmental stresses, what is the optimum interpretation of the ePHM results for use in maintenance planning? … then back to question 1 – with that interpretation, does it make economic sense to do it?

Life cycle cost analysis will be used as a vehicle for supplying a common metric with which to measure the impact of ePHM approaches and as a platform with which to study how to interpret ePHM analysis results optimally. Modeling to determine the optimum schedule for performing maintenance for systems is not a new concept. Traditional applications of maintenance modeling include production equipment [12] and the hardware portions of engines and other propulsion systems [13]. However, maintenance modeling has not been widely applied to electronic systems where presumed random electronics failure is usually modeled as an unscheduled maintenance activity, and wear-out has always been assumed to be beyond the end of the system's life. There is nothing precluding the use of conventional scheduled maintenance modeling techniques on electronic systems if either health monitoring or life consumption monitoring could be practically demonstrated. Advanced logistics concepts such as Autonomic Logistics [14] will be capable of performing tasks such as maintenance tracking, scheduling, and components ordering automatically by downloading critical diagnostics and prognostics information during system operation. Autonomic logistics moves away from traditional calendar-based maintenance toward dynamically scheduled condition-based maintenance and deferred maintenance activities (maintenance schedules adjusted in coordination with operational schedules)[7], [15]. Existing maintenance and logistics models can optimally plan maintenance once a system exists, but they are not intended to support business case development, technology insertion planning, design decision making and strategic life cycle planning performed at the conceptual/tradeoff level. Therefore, a new high-level maintenance decision planning model will be developed that enables a robust (with uncertainty) determination of the optimum maintenance plan based on various interpretations of the health monitoring and life consumption forecasts.

The results from a simple demonstration version of the new model that considers fixed scheduled maintenance intervals and life consumption monitoring ePHM are shown in Figure 7 and Figure 8. The demonstration model considers only one LRU (Line Replaceable Unit) within a larger system.

Figure 7 shows the effective life cycle cost per unit as a function of a fixed scheduled maintenance interval for several LRU time-to-failure distribution widths. In this example, the time-to-failure was modeled as a symmetric triangular distribution with a most likely value of 5000 operational hours and various widths as indicated on the figure (25 year operation life at 2500 hours per year assumed). For short scheduled maintenance intervals, virtually no expensive, unscheduled maintenance occurs, but the life cycle cost per unit is high because large amounts of remaining life in the LRU are thrown away. For long scheduled maintenance intervals, virtually every instance of the LRU fails prior to the scheduled maintenance activity and the life cycle cost per unit becomes equivalent to an unscheduled maintenance model. As the time-to-failure distribution of the LRU becomes wider (i.e., the time-to-failure is less well defined), a practical fixed scheduled maintenance interval becomes more difficult to find and the best solution approaches an unscheduled maintenance model.

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[7] Note, electronic systems are not currently part of the JSF autonomic logistics system other than in a nominal manner.

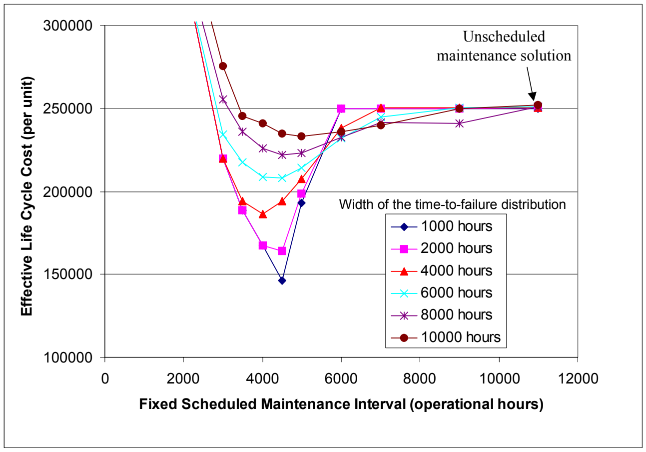


Figure 7: Variation of effective life cycle cost per unit with a fixed scheduled maintenance interval.

Data points represent mean values from a 10,000 sample Monte Carlo analysis.

Figure 8 shows the effective life cycle cost per unit as a function of the safety margin assumed for a life consumption monitoring ePHM methodology. In this example (as with Figure 7), the time-to-failure was modeled as a symmetric triangular distribution with a most likely value of 5000 operational hours and various distribution widths. The LCM methodology forecasts a unique time-to-failure distribution for each instance of the LRU based on its unique environmental stress history. For this example, the LCM forecast was modeled as a symmetric triangular distribution with a most likely value set to the time-to-failure of the LRU instance and a fixed width measured in operational hours. From Figure 8 it can be seen that the width of the time-to-failure distribution has little effect on the LCM-based results. For all but the narrowest distribution on the LRU time-to-failure, the LCM-based methodology yields lower life cycle costs then either unscheduled maintenance or scheduled maintenance with a fixed interval. The effective life cycle cost is very sensitive to the width of the LCM forecasted time-to-failure distribution for the specific LRU (one case with a 2000 hour width is shown in Figure 8).

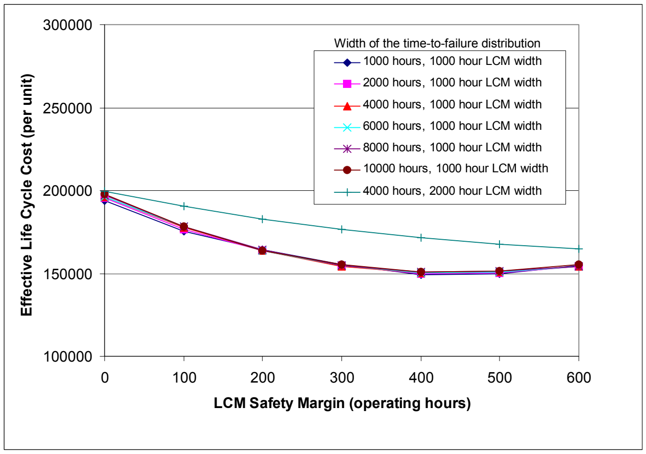


Figure 8: Variation of effective life cycle cost per unit with the safety margin for a LCM-based maintenance- planning scheme

The simple model shown here will be extended to include:

1) Treatment of health monitoring ePHM approaches (optimizations of prognostic distances)
2) Probability of failure based on life consumed calculations
3) Multiple failure mechanisms and failure sites, and support of more detailed distributions

An analysis will be performed using the high-level model to understand the impact of the confidence level with which life consumed can be predicted and how damage thresholds should be determined and interpreted (it is anticipated that damage thresholds will not be static, varying with respect to internal and external temporal factors). The feasibility of including a version of the model within the ePHM Decision Model for use in an embedded system will be explored.

Figure 9 shows the planned activities. The model discussed above will be adapted for use with the Mitigation of Obsolescence Cost Analysis (MOCA) tool [16] developed by University of Maryland in a previous Air Force MANTech program, in order to assess the impact of electronic part obsolescence and maintenance schedule on design refresh planning. In Phase II of this program, we plan to adapt the model for use with detailed logistics and maintenance modeling environments in order to perform maintenance schedule optimization on real systems.

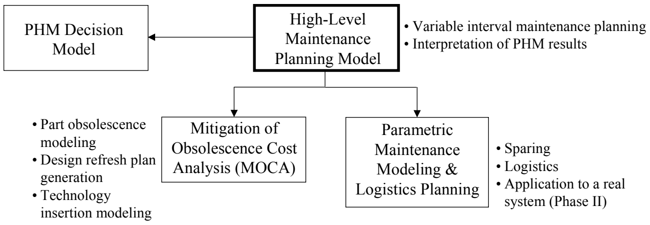


Figure 9: Planned Life Cycle Cost Activities

3. EXAMPLE OF APPLICATION

As a specific example of the application of physics-of-failure to an on-vehicle electronics item, CALCE has estimated the life remaining in a test electronics module mounted under the hood of a car. Two experiments were conducted, one with the module located on the exhaust manifold (Figure 10) and the second with the module mounted cantilever fashion (Figure 11) on the chassis inside the engine compartment.

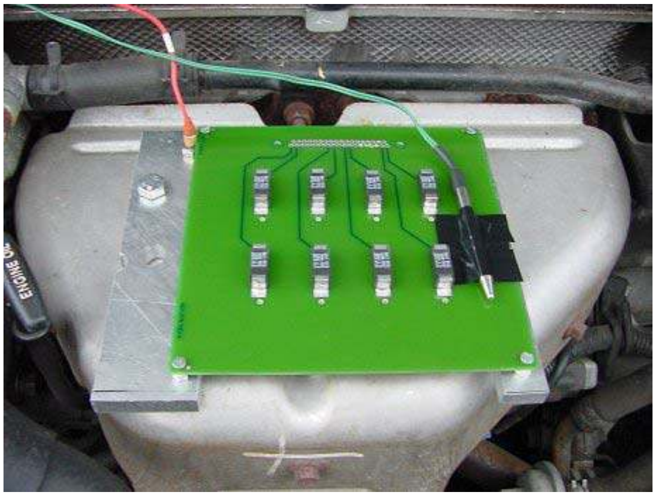


Figure 10: LCM Test Board Mounted on Car Exhaust Manifold

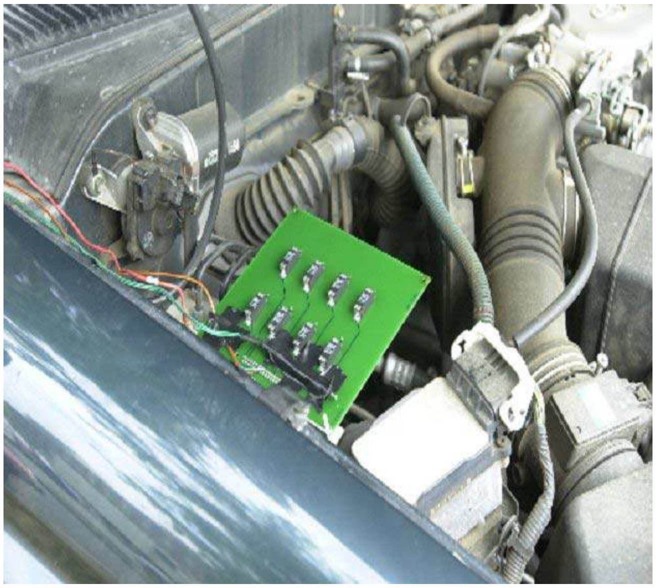


Figure 11: LCM Test Board Mounted on Car Chassis

An environmental sensor electronics package was used to monitor the environment. The data analysis steps and remaining life assessment process steps are shown in Figure 12.

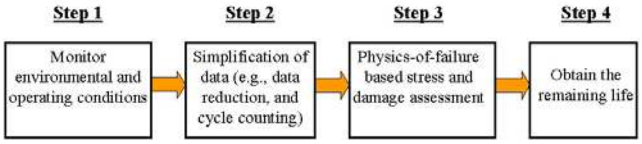
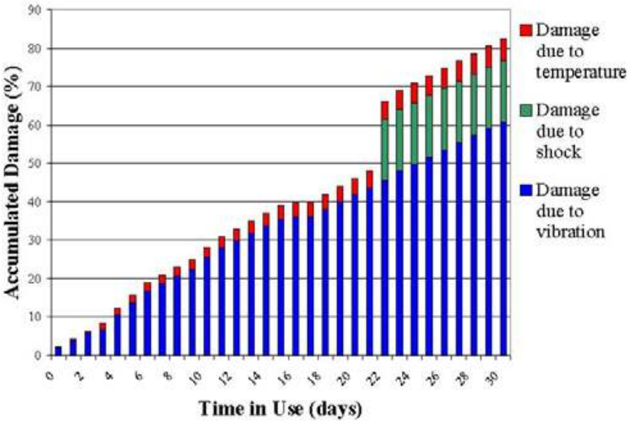


Figure 12: Remaining Life Assessment

These experiments sought to demonstrate, that under combined environment conditions (i.e. simultaneous temperature cycling and vibration), separate computations of damage accumulation could be additively combined to produce an overall damage accumulation. This is illustrated in the figure below where the individual and combined accumulated damage is plotted as a function of elapsed time (this particular car suffered an accident after 22 days resulting in an additional shock component being added.



The experimental results are shown below.

Table 2: Remaining Life Results

Initial VQ prediction based on SAE environmental handbook data	34 days
Life Consumption Forecast	46[8] days
Actual life (to 15 readings > 300ohms)	38 days

4. BUSINESS RISKS

The increasing penetration of COTS into military electronics threatens to undermine many long held assumptions and beliefs about how systems should be designed and supported. The COTS vendors do not make any concessions to military (or other low volume) users since the market share for such products is relatively small. Military (and other harsh environment electronics such as commercial avionics, oil exploration and outdoor telecom) are becoming increasingly exposed to escalating maintenance costs both from the increasing electronics content of modern aircraft and from the potentially shorter life of systems built from COTS components. Failure cannot

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[8] This forecast was reduced to 40 days when the additional damage arising from the accident was factored in

be completely prevented but can be managed for minimum cost if failure forewarning is provided. ePHM for electronics provides such warning.

The maintenance sector is presently centered on the idea that electronics failures cannot be anticipated but can only be dealt with as they occur. This has lead to a complex and scattered support infrastructure, necessitated by the need to provide timely repairs at all points within the operating area or to provide rapid delivery of needed spares from a few central locations to the point of use. The use of ePHM promises to enable significant economies to be made in the support infrastructure by relieving the need for rapid reaction to failures.

The benefits come at the cost of additional hardware and software carried within the electronics and the penalties attached to the loss of useful life arising from replacement before failure. It is common for certain mechanical components to be replaced on a very conservative schedule, especially where these components are highly critical such as turbine discs where the consequences of failure are severe. ePHM aims to provide a much better assessment of the actual life remaining, given its usage history. One of the objectives of this project is to provide a determination of whether these additional costs can realize a net reduction of life cycle cost at the asset or fleet level.

5. BENEFITS

The benefits of ePHM arise from two main areas; 1) the pool of assets on which it is deployed can achieve higher rates of net availability, 2) the cost of supporting those assets can be reduced.

The following benefits are expected from ePHM. These benefits are especially significant in all high-value, low-volume electronic equipment where there is substantial cost associated with loss of availability.

Reduction of unexpected failures with consequent reduction of unscheduled maintenance actions—ePHM enables annunciation of expected failures to the pilot and flight line maintenance crew. Maintenance crews can also interrogate the system to see what life remains and whether this is sufficient to complete the next mission. Maintenance actions can then be accomplished while the asset is not required for a mission, thus improving mission capable rate.

Reduction in scheduled inspections—Scheduled inspections are often undertaken at a rate sufficiently high to find out-of-specification equipment prior to the mission. With the warning period provided by ePHM, the rate at which such inspections are needed can be reduced.

Deferred maintenance possible—With proper system design, faults may be absorbed to certain extent. The annunciation of these through ePHM allows them to be accumulated until the asset returns to its home base to receive the necessary repairs. The avoidance of costs associated with unscheduled repairs, such as asset and crew down time, special spares shipments, and replacement crews can be a major cost saving as well as reducing the number of non-mission capable assets.

Reduction in the required number of repair stations and stores locations—The ability to control the occurrence of maintenance actions leads to the ability to control the location at which they occur, thus reducing the required number. In addition, foreknowledge of spares requirements allows them to be delivered ‘just-in-time’, thus reducing the spares stockholding levels. This leads to a substantial simplification of the spares supply chain.

Reduced turn-around-time for shop and flight line repairs—The data collected and continuous monitoring used in ePHM can be helpful to flight line and shop maintenance personnel in locating a faulty item. The CND (or RTOK) problem is well known and has resisted many attempts at reducing it. This is in spite of advances in BIT and ATE. The accumulated damage information provided by a ePHM system assists in localizing a problem and informs the test most likely to reveal it.

Improved mission reliability and safety—Vehicle dispatch criteria do not presently incorporate any measure of health. The assumption is that all assets are ‘good-as-new’. ePHM will demonstrate that this is not correct and that the probability of mission success is in part determined by the remaining useful life. ePHM enables identification of those assets that have sufficient remaining life to accomplish the planned mission.

Ability to adjust asset usage according to its actual state of readiness—Presently mission planners have no way of knowing which of their available assets is most likely to be able to complete the planned mission. ePHM offers the prospect of being able to select the most likely set of assets and return other through maintenance to be brought up to standard. The net effect of this will be an overall increase in fleet availability.

Improved pilot awareness of system status—ePHM provides estimates of life remaining and thus mission planning is undertaken utilizing this information and an expected mission profile. Actual missions can be expected to depart from the plan on occasions due to unforeseen circumstances. Real time life consumption monitoring allows system state to be continuously monitored and diagnostic/warning information provided to the pilot.

More realistic system safety calculations—Safety calculations have traditionally been based upon a constant failure rate assumption. The achievement of a given safety level is usually achieved by hardware redundancy, often to 3 or 4 levels for the most critical functions [17]. The calculation of system safety has traditionally been made using the constant failure rate assumption, typically using prediction methods based on MIL-HDBK-217 or some variant of that. Improvements in hardware reliability consistently achieved by avionics manufacturers have not yet been fully incorporated in these calculations. Since MIL-HDBK-217 is no longer supported, new technology components are increasingly not represented by the methodology. The use of virtual qualification, pioneered by CALCE, and the data provided by ePHM allows an objective assessment of be made of the system architecture choices and whether a reduced level of redundancy can meet the objectives with consequent simplification of the hardware, cost reduction and improved reliability.

6. CONCLUSIONS

PHM techniques for mechanical systems have been in development for a number of years and are now beginning to see actual implementation. ePHM is a natural, low cost, extension to this, providing an ‘all-in-one’ solution for PHM on major sub-assemblies such as engines.

The major technological pieces necessary to construct an ePHM system (failure and cost models and modeling tools, prognostic cells, sensors, statistical techniques) are all sufficiently mature to contemplate ePHM. It remains only to put these pieces together into a workable solution.

There is significant commercial potential for this technology in many high-value, low-volume electronic equipment markets such as military systems, avionics, and oil exploration and in comparatively high volume industries such as automotive and outdoor telecommunications equipment. All of these industries have significant (and increasing) concern with unscheduled maintenance requirements, initiated by unannounced equipment failure. The ability to deliver ePHM in a product, and therefore offer a marked reduction in support cost through increased asset availability, is an attractive feature providing a competitive advantage and an opportunity to increase market share.

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