REMAINING LIFE PREDICTION OF ELECTRONIC PRODUCTS USING LIFE CONSUMPTION MONITORING APPROACH

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Abstract
Various kinds of failures may occur in electronic products because of their life cycle environmental conditions including temperature, humidity, shock and vibration. Failure mechanism models are available to estimate the time to failure for most of these failures. Hence if the life cycle environment of a product can be determined, it is possible to assess the amount of damage induced and predict when the product might fail.

This paper presents a life consumption monitoring methodology to determine the remaining life of a product. A battery powered data recorder is used to monitor the temperature, shock and vibration loads on a printed circuit board assembly placed under the hood of an automobile. The recorded data is used in conjunction with physics-of-failure models to determine the damage accumulation in the solder joints due to temperature and vibration loading. The remaining life of the solder joints of the test board is then obtained from the damage accumulation information.

1. Reliability Prediction
Reliability is defined as the ability of a product to perform as intended (i.e., without failure and within specified performance limits) for a specified time, in its life cycle application environment. Over time, technology improvements have lead to higher I/O counts in components and circuit cards of electronic products. This has resulted in significant downsizing of interconnect thicknesses, making them more vulnerable in field applications. At the same time, increase in warranties and severe liabilities of electronic product failure have compelled manufacturers to predict the reliability of their products in field applications. An efficient reliability prediction scheme can be used for many purposes including [1]:

- Logistics support (e.g., forecast warranty and life cycle costs, spare parts provisioning, availability)
- Safety analysis
- Mission reliability estimation
- End item availability estimation

A reliability prediction for a product is dependent on its structural architecture, material properties, fabrication process, and the life cycle environment. IEEE standard 1413, titled “Standard Methodology for Reliability Prediction and Assessment for Electronic Systems and Equipment” presents the key parameters of importance in reliability prediction.

Defining and characterizing the product life cycle environment is often an uncertain aspect of a reliability prediction process. Product life cycle environment describes the storage, handling and application scenario of the product, as well as the expected severity and duration of the load conditions for each scenario [2]. Load conditions include temperature, humidity, pressure levels, vibrational or shock loads, chemically aggressive or inert environments, acoustic levels, sand, dust, electromagnetic radiation levels, and loads caused by operational parameters such as current, voltage and power. Life cycle environment characterization also requires knowledge of parameters like the application length, the number of applications in the expected life of the product, the product utilization or...
non-utilization profile (storage, testing, transportation), the deployment operations, and the maintenance concept or plan.

Due to uncertainties regarding the actual life cycle loads for a system, the common practice of design has been to provide a safety margin, i.e., designing for a high stress and recommending operation at a lower value [3]. If the actual life cycle loads are different from the designed ones, this design practice can lead to costly over design or hazardous under design, and consequently, increased investment. Sometimes product “derating” may be performed to increase part life and reduce occurrence of overstress failures and hence the practice of derating can be a way of extending product life for a desired application [4].

The actual life cycle environment for an in-service product can be obtained with the help of sensors placed near and within the product. The physics-of-failure approach uses the material properties, geometry, and product architecture along with the life cycle environmental and operating load distribution1 to assess degradation and predict reliability.

2. Life Consumption Monitoring

Health monitoring is a method of evaluating the extent of a product’s reliability in terms of product degradation in its life cycle environment. By determining the impending failure, based on actual life cycle application conditions, procedures can be developed to mitigate, manage or maintain the product [5].

A product’s health can be determined in two ways, i.e., condition monitoring and life cycle monitoring. Both methods use some combination of physical degradation (e.g., cracks, corrosion, delamination), electrical degradation (e.g., increase in resistance, increase in threshold voltage), and performance degradation (e.g., shift of the product’s operating parameters from expected values) to assess health. Methods employed for health monitoring are non-destructive test (e.g., ultrasonic inspection, liquid penetrant inspection, and visual inspection) and operating parameter monitoring (e.g., vibration monitoring, oil consumption monitoring and thermography (infrared) monitoring) [7].

Condition monitoring is a method of evaluating the product’s current operating state. An example of health monitoring is Boeing’s extended-range twin-engine operations (ETOPS) program. Typical examples of ETOPS are engine condition monitoring (ECM) and oil consumption monitoring [8]. ETOPS operators are required to use ECM programs to monitor adverse trends in engine performance and execute maintenance to avoid serious failures (e.g., events that could cause in-flight shutdowns, diversions, or turnbacks). The ECM program monitors engine parameters such as exhaust temperature, fuel and oil pressures, and vibration. In some cases, oil consumption data and ECM data are combined to identify problems in normal engine operation.

Built-in-test (BIT) concept is another health monitoring technique employed for diverse electronics applications [9]. BIT is a hardware-software diagnostic mean to identify and locate faults. Two types of BIT concepts are employed in electronic systems, interruptive BIT (I-BIT) and continuous BIT (C-BIT). The concept of I-BIT is that normal equipment operation is suspended during BIT operation. Such BITs are typically initiated by the operator or during a power-up process. The concept of C-BIT is that equipment is monitored continuously and automatically without affecting normal operation.

Life consumption monitoring (LCM) is a health monitoring method, which can quantify a system’s degradation from the measured life cycle environment data into life consumption. The life consumption monitoring process involves continuous or periodic measurement, sensing, recording, and interpretation of physical parameters associated with a system’s life cycle environment to quantify the amount of system degradation. The purpose is to support decisions related to the operation and maintenance of the system. Arun and Pecht [10] showed how to make the environmental data (vibration and temperature subjected to a test board) compatible with the physics-of-failure (PoF) models to estimate the amount of accumulated damage. The experimental analysis showed that the life consumption monitoring approach is possible for real life applications. The current work shows how to estimate the remaining life (e.g., time in days or distance in miles) of an electronic product from the collected environmental parameters.

A physics-of-failure (PoF) based life consumption monitoring methodology to estimate the

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1Simulation techniques use the data recorded by the sensors and the material geometry to find the load distribution.
remaining life has four steps (see Figure 1). These stages are monitoring critical parameters of the product’s life cycle environment, simplification of the monitored data, physics-of-failure (PoF) damage accumulation analysis, and remaining life estimation based on damage accumulation.

Monitoring the product parameters of the product’s life cycle environment involves continuous measurement of the loads that affect the reliability of the product. Data simplification is the process of converting the measured sensor data into a form compatible with the input requirements of physics-of-failure based reliability assessment models. Physics-of-failure analysis involves using the material properties and geometry of the product and the measured life cycle loads to estimate cycles to failure and hence the accumulated damage for the product in its life cycle environment. The remaining life of the product in terms of physical parameters (e.g., time in days, distance in miles) is obtained from the accumulated damage using a software algorithm.

3. An Experimental Case Study
To evaluate the life consumption monitoring methodology, a test board was placed in the underhood of a car (see Figure 3) and hence subjected to normal driving conditions for thirty-one days. The test board was clamped at two of its four corners to an aluminum bracket making the board act like in cantilever fashion.

The test board for the experiment was a printed circuit board (PCB) manufactured by ACI AppliCAD Inc. The board consisted of eight surface mount leadless inductors. A self-powered data-recording device called SAVER™ [11] (Shock and Vibration Environment Recorder) was used to continuously record the shock, vibration and temperature environment of the test board. The temperature of the environment was measured continuously during the experiment by a temperature sensor (Kele’s Model STR-91S two-wire strap-on RTD sensor) taped on the test board. A single-axis piezoelectric accelerometer (Endevco’s Model 2226C) was mounted near one of the clamping points of the test board to measure vibration. The accelerometer was located to measure the acceleration that excited the board to vibrate out-of-plane. A transistor-relay circuit was placed along with the sensors to record any sudden change in resistance of the solder joints. A sudden change in resistance can be an indication of solder joint failure.

3.1 Life Cycle Environment – Temperature
Due to differences in the coefficients of thermal expansion of components and PWB, solder joints used to attach the components to the PWB, are subjected to creep, which causes plastic strains. Cyclic strains result in cumulative cyclic fatigue damage, which can lead to solder joint fatigue failure. Figure 4 shows the temperature variations on the test board as recorded by the SAVER during the experiment.

Temperature based physics-of-failure reliability assessment models estimate the cycles to failure based on type of temperature cycles. These models can estimate the amount of accumulated damage given the number and type of cycles. Description of temperature cycles requires information about the maximum and minimum temperature, the ramp-up, ramp-down times and the dwell times. Cycle counting algorithms identify the cycles based on a given temperature profile. Cycle counting methods are used to transform a time history consisting of several reversals (peaks and valleys) into an equivalent cyclic history. The temperature profile needs to be in the form of a sequence of peaks and valleys to be used as input to the cycle counting algorithms.

Figure 2: This picture shows the data-recording device with the external temperature and vibration sensor. External temperature and vibration channels were used to monitor the under-hood environment.

Figure 3: This picture shows the experimental setup where the test board is mounted in the under-hood environment of a car. The vibration sensor was glued near the clamping point of the board and the temperature sensors were taped to the board.
Temperature data collected by the sensors is a random variation of temperature and does not follow a peak valley sequence. The temperature profile here consists of two sets of temperature cycles, e.g., temperature cycling due to ambient temperature change and temperature change due to engine On-Off cycle. The data is converted to a sequence of peaks and valleys using the ordered overall range (OOR) method [13]. For this analysis the screening level was chosen to be 0%, i.e., all the points, which are peaks or valleys, were chosen as input to the cycle counting algorithm. Figure 5 shows the acquired temperature data converted to peaks and valleys.

Figure 4: This picture shows the temperature profile on the test board in the under-hood environment, as recorded by the data-recording device.

Figure 5: This picture shows the environmental temperature profile converted to the peaks and valleys using the Ordered Overall Range (OOR) method. The set of peaks and valleys were used to identify the number of temperature cycles.

The sequence of peaks and valleys (temperature time history) are converted to temperature cycles using the rainflow cycle counting method [14], [15]. The rainflow cycle counting method finds the cycles and necessary information (e.g., maximum, minimum temperature and the time ranges).

3.2 Life Cycle Environment - Vibration

Vibration that excited the printed circuit board is measured by the accelerometer in the form of acceleration (g values). Hence the data recorded by the data-recording device is in the time domain. But the physics-of-failure reliability assessment models require information about vibration in frequency domain, which is typically represented as power spectral density (PSD) as a function of frequency.

The power spectral density is calculated from the sampled data (i.e., the type of data recorded by SAVER) using the Cooley-Tukey method, which is based on fast fourier transform (FFT) of the original sampled acceleration data [16]. Figure 6 shows the PSD vs. frequency of the vibration. This vibration data was used for vibration analysis.

Figure 6: This picture shows the Power Spectral Density (PSD) vs. frequency plot for the clamping points of the board. This was the vibration that excited the board.

The displacement of each component was estimated through numerical analysis using cacePWA[4]. Figure 6 shows the estimated displacement of the board caused by vibration. From the displacement information, radius of curvature of the board was estimated to be almost the same.

3.3 Life Cycle Environment – Shock

During the experiment the car faced an accident, where it was hit from the back by another car. This resulted in two shock (vibration) profiles subjected to the board for small periods of time (in the order of 100 milli-seconds). A shock is different from vibration in a sense that the

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2 The ordered overall method (OOR) is a data simplification method, which allows the user to convert an irregular history into a regular sequence of peaks and valleys (which is essential for fatigue analysis), and also specify the range (i.e., upper limit – lower limit) of the reversals to be eliminated.

3 Signals can be analyzed in several domains, such as the frequency, time, and amplitude domains. Translation of information from one domain to another may often be required to get more information from the signal.

4 CalcePWA is a virtual qualification tool developed by CALCE Electronic Products and Systems Center, University of Maryland, College Park.
acceleration values are very high compared (at least higher by an order) to the vibration environment and it acts over a very small period of time. Figure 8 shows the recorded shock at the instant of crash. In this case the maximum value of acceleration is 23g (in both directions) as compared to 2g in case of recorded normal engine vibration. Figure 9 shows the shock profile caused during dis-engagement of the cars, which was after approximately 20 minutes of the first shock.

Failure due to shock is considered to be an over-stress mechanism and overstress models are usually used for vibrational shocks to find out whether the board can sustain the impact or not. But for life consumption monitoring we require to estimate the accumulated damage. For this purpose the acceleration data was converted to frequency domain. An overstress analysis was also conducted for both the shock profiles with the maximum acceleration values, which showed no over-stress failure.

Design capture is the process of collecting geometrical (dimensional) and material information about a product to generate a model of the product. This step involves characterizing the product at all levels, i.e., parts, circuit cards, as well as physical interfaces.

The potential failure mode identification step involves using the geometry and material properties of the product together with the measured life cycle loads acting on the product to identify the potential failure mechanisms, failure sites (e.g., part interconnects, board metallization, and external connections), and failure modes (e.g., electrical shorts or opens) in the product. This task is best performed through virtual qualification, which is a simulation-based methodology used to identify and rank the potential failure mechanisms.

Reliability assessment step involves identification of appropriate physics-of-failure models for the identified failure mechanisms. A load-stress analysis is conducted using material properties, product geometry, and the life cycle loads. With the computed stresses, and the failure models, an analysis is conducted to determine the cycles to failure and then the accumulated damage is estimated using a damage model.

3.4 Damage Accumulation

Damage is defined as the extent of a part or product’s degradation or deviation from its normal operating state. The aim of damage assessment is to convert the number of cycles to failure values obtained from the physics-of-failure analysis into a metric for life consumption. Many models have been proposed for quantifying damage caused by operation at a given stress level and for adding damage increments to predict failure under multi-loading conditions. The Palmgren-Miner cumulative damage theory, which is a linear damage theory, was used for
analysis. It was proposed by Palmgren in 1924 and later developed by Miner in 1945 [17]. The term linear refers to the algebraic addition of the fractions of the total consumed life and the exponent of unity used for the damage fraction, and not to the linearity of the damage process.

The Palmgren-Miner hypothesis states that the damage fraction \( D_i \) at any stress level \( S_i \) is linearly proportional to the ratio of the number of cycles of operation \( n_i \) to the total number of cycles that would produce failure \( N_i \) at that stress level. In other words,

\[
D_i = \frac{n_i}{N_i}
\]

and failure is predicted to occur if

\[
\sum_{i=1}^{j} \frac{n_i}{N_i} \geq 1
\]

Accumulated damage at the end of each day of experiment was estimated using the physics-of-failure models and Palmgren-Miner theory\(^5\). The results obtained are shown in the form of a bar chart (see Figure 10). 7%, 61% and 16% damage accumulation was estimated because of temperature, vibration and shock respectively.

The damage of the solder joints was tracked experimentally in terms of resistance increase of the joints. The resistances of the joints were measured everyday during the experiment. The measurements were done when the car is off. An event detector circuit was put in series with the components (lead less inductors) to track any abrupt change in resistance. The event detector recorded four events, where the resistances of the circuit increased by 50% of the initial value. Figure 11 shows the resistance change of the circuit with time. The picture also shows the time where there were changes in resistance for a short duration of time (in the order of seconds). This data was collected from the transistor-relay circuit placed to monitor sudden change in resistance.

\[
RL_N = \left[ \frac{1}{ADR_N} \right] N - N
\]

where \( RL_N \) is the predicted remaining life at the end of \( N \)th day and \( ADR_N \) is the accumulated damage ration till day \( N \).

If there is a wide variation in system usage, undesired fluctuations in predicted remaining life may occur by using the equation shown in equation 3. We may see an increase in remaining life, which is many times confusing. Increase in remaining life occurs in the calculation when the usage on a particular day is much below the usual value there by bringing down the average damage per day.

\(^5\) Estimated damage of 100% damage corresponds to the predicted end-of-life of the board.
The remaining life at the end of a particular day can also be estimated by subtracting the life consumed on that day from the predicted remaining life on the previous day. This approach makes the use of an iterative formula to find out the remaining life. For calculation on a particular day the total lifetime is assumed to be same as that of the previous day.

\[
RL_N = RL_{N-1} - DR_N \times TL_{N-1}
\]

(4)

where \(RL_N\) is the remaining life at the end of day \(N\), \(TL_N\) is predicted total life at the end of day \(N\) and \(DR_N\) is the damage ratio accumulated at the end of day \(N\).

The iterative method (equation 4) can be used in cases where the system usage is widely different. Figure 12 shows the estimated remaining life for the experiment using the iterative method. We only need the remaining life at the end of previous day instead of all the data, which decreases the required storing space. The rest data can either be erased or kept in back up memory.

![Figure 12: This picture shows the predicted remaining life as a function of time. The remaining life prediction was done using the iterative method](image)

4. Summary

This paper demonstrates a practical life consumption monitoring methodology applied to an automobile environment. A test board was subjected to the under the hood environment (temperature, vibration and shock) of an automobile. The collected data was made compatible with physics-of-failure models. Damage accumulation was calculated using Miner’s rule, to calculate the remaining life of the test board. The method for remaining life estimation has been discussed in the paper.

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6. References


