Application of Health Monitoring to Product Take-back Decisions
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Abstract
Health monitoring is emerging as one of the most promising developments for product in-service reliability assessment and maintenance. This paper presents an overview of the concepts used in current health monitoring approaches, with a focus on Life Consumption Monitoring (LCM). Its application to electronic systems is discussed. In addition to in-service reliability assessment and maintenance, health monitoring could also be effectively used for supporting product take-back and end-of-life decisions.

1 Introduction
A product's health is defined as the extent of deviation or degradation of its actual operating conditions (e.g., physical, performance) from its expected, normal operating conditions. Health monitoring is a method of assessing the degradation of a product health (reliability) in its life cycle environment by continuous or periodic monitoring, and interpretation of, the parameters indicative of its health [1].

Traditionally, health monitoring has been used for providing advance warning of failure or preventing catastrophic failure, reliability assessment, reducing unscheduled maintenance, efficient fault identification, improving qualification methods and improving the design of future products. Environmental directives and legislations [2] [3] now require electronic manufacturers to recover their products after end-of-life. This has prompted the need for efficient product re-use strategies and improved end-of-life economics.

This paper discusses the application of health monitoring methodologies to supporting the implementation of such strategies. An overview of the concepts used in current health monitoring approaches is given. A Life Consumption Monitoring (LCM) methodology is presented, having the potential to contribute to better electronic product take-back and end-of-life decisions. The application of health monitoring to supporting such decisions for electronic products is illustrated by a case study.

2 Product Health Monitoring
The life cycle of a product consists of manufacturing, storage, handling, and operation. Life cycle loads include thermal, mechanical (vibration, shock), environmental (humidity), physical (radiation, electromagnetic interference), chemical (presence of contaminants) and operational loads (electrical stresses, heat dissipation). The extent and rate of product degradation depend upon the nature, magnitude and duration of exposure to such loads.

Product health monitoring can be implemented through the use of various techniques to sense and interpret the parameters indicative of:

- Performance degradation, (e.g. deviation of operating parameters from their expected values);
- Physical or electrical degradation (e.g. cracks, corrosion, delamination, increase in electrical resistance or threshold voltage);
- Changes in life cycle environment (e.g. usage duration and frequency, ambient temperature, vibration, shock, humidity, etc.).

Based on the product's health, determined from the monitored actual life cycle conditions, procedures can be developed to maintain the product [4]. Health monitoring therefore permits new products to be concurrently designed for a life cycle environment known through monitoring.

Health monitoring systems are typically categorized as diagnostic, prognostic, or LCM systems.

Diagnostic systems monitor the current operating state of health to identify potential causes of failure in order to restore the system. These systems are widely used across different industries for fault identification purposes. An example of a diagnostic system is the use of piezoelectric sensors, which detect and analyze the ultrasonic acoustic signals traveling through machinery to report fault or wearout condition [5]. These systems can be used to characterize friction, shock, and dynamic load transfer between moving parts in rotating machinery. Built-in-Test (BIT) systems [6] used for electronics health monitoring are
another example of diagnostic systems. Such systems locate and compare faulty versus acceptable performance based on defined thresholds. BITs can be embedded in the product to experience the same environment, and are extensively used in electronics as software-firmware diagnostic tools.

Prognostic systems monitor the faults or precursors to failure, and predict the time or number of operational cycles to failure induced by a monitored fault. Examples of prognostic systems include Self-Monitoring Analysis and Reporting Technology (SMART) employed in computer hard drives [7]. SMART monitors changes in spin-up times, reduction in data transfer rates, and probe flying height, to warn the user about a possible future drive failure.

LCM is a method of monitoring parameters indicative of a system’s life cycle health and converting the measured data into life consumed [4]. The LCM process involves continuous or periodic measuring, sensing, recording, and interpretation of product parameters to quantify the amount of product degradation. LCM systems have been introduced in the automotive industry, for automotive engine oil monitoring [8], the degradation of which depends upon time, temperature, and contamination related to engine usage. Such LCM systems incorporate Physics-of-Failure (PoF) based predictive models which estimate the remaining life of oil based on the monitored engine usage. The model algorithms are programmed into the engine control modules to inform the driver of the oil life status.

Based on the knowledge of the product degradation mechanisms, appropriate health monitoring systems can be developed. Figure 1 illustrates a typical failure progression timeline from the beginning of the life cycle, which corresponds to the manufacturing phase for electronic components or sub-assemblies, to system failure. Whereas diagnostic systems can be implemented from the beginning of the product life cycle, the domain of a prognostic system typically only commences after a fault or defect condition has been observed. In a system combining both diagnostic and prognostic tools, the remaining life of the product can be predicted using both the data monitored by the diagnostic system and prognostic models. By contrast, LCM can be initiated from the beginning of the product life cycle and continue to assess the degradation of the product by monitoring its life cycle environment in order to provide an estimate of the remaining life in the application environment.

The application of diagnostic and prognostic tools to electronic products can be challenging in comparison to their application to, for example, mechanical systems. This is due to mechanical systems failures being typically caused by wearout mechanisms (such as fatigue, creep, or corrosion), which can be detected and prevented using periodic maintenance and replacement. Wear and damage in electronics is comparatively more difficult to detect and inspect due to geometric scale of electronic component parts being of the order of micro- to nano-scale, and their complex architecture. In addition, faults in electronic parts may not necessarily lead to failure or loss of designated electrical performance or functionality [9], making it difficult to quantify product degradation. Consequently, it is generally difficult to implement prognostic or diagnostic systems in electronics, that can directly monitor the faults or conditions in which fault occurs.

Furthermore, mechanical systems and structures have more ready and mature sensing, fault diagnosis, and prognostics technologies as compared to electronic systems. Hence it is comparatively easier to quantify the degradation in those products. Additionally, due to the complexities of electronic systems it may be difficult to quantify the improvements due to in-situ health monitoring and prognostics on solid theoretical or experimental basis.

![Figure 1. Failure progression timeline](image-url)
3 CALCE LCM Approach for Electronic Products

The CALCE LCM process described in this paper is a development of the methodology proposed in [4]. The original methodology focused on the estimation of accumulated damage of solder joints in electronics, with temperature and vibration assumed to be the dominant environmental parameters that can cause failure due to solder joint fatigue. The present methodology extends that presented in [13] to system level analysis, through the inclusion of other possible failure mechanisms.

The present LCM process is illustrated in Figure 2. It comprises of six steps to estimate the remaining life of an electronic product, which consist of: (i) Failure modes, Mechanisms and Effect Analysis (FMMEA), (ii) virtual reliability assessment, (iii) monitoring of the appropriate product parameters, (iv) simplification of the monitored data, (v) stress and damage accumulation analysis, and (vi) remaining life estimation. FMMEA and virtual reliability assessment have been incorporated in the present improved methodology, to determine the dominant failure mechanism in a given life cycle environment and the corresponding environmental and operational parameters. In addition, step 6 has also been incorporated to determine the product remaining life based on the accumulated damage information.

The application of the LCM methodology outlined in Figure 2 to electronics health monitoring is illustrated based on two case studies [4] [10]. The test vehicle consisted of an electronic component-board assembly placed under-the-hood of an automobile and subjected to normal driving conditions in the Washington DC area. The test board incorporated eight surface-mount leadless inductors soldered on to an FR-4 substrate using eutectic Pb-Sn solder. These components had a nominal ambient temperature operating range of -55 °C to 125 °C. The board was bolted at its two corners to an aluminum bracket, which made the board act as a cantilever in the presence of vibrations. Solder joint fatigue was identified as the dominant failure mechanism. Temperature and vibrations were measured in-situ on the board in the application environment. The monitored environmental data, stress and damage models developed were used to estimate consumed life.
The remaining life of the test board, estimated by LCM, is compared in Figure 3 with estimates obtained using similarity analysis, SAE handbook data, and the actual measured life. As shown in Figure 3, the remaining life estimated by either similarity analysis or using data from SAE handbook differs significantly from the actual life of the board, whereas the remaining life estimated by LCM is in excellent agreement with actual life. The discrepancies between either similarity analysis or SAE estimates and actual life are attributed to the fact that neither approach accounts for the accident that the car experienced on day 22 [4]. LCM could account for this unforeseen event since the operating environment was being monitored in-situ.

4 Health Monitoring for Product Take-back Decisions

Product take-back signifies responsibility of manufacturers for their products over the entire life cycle, including disposal. The motivation driving product take-back is the concept of Extended Producer Responsibility (EPR) for post-consumer electronic waste [11]. The objective of EPR is to make manufacturers and distributors financially responsible for their products when they are no longer needed.

End-of-life product recovery strategies include repair, refurbishing, remanufacturing, re-use of components, material recycling and disposal. One of the challenges in end-of-life decision making is to determine on an application specific basis what subset of components should be re-used and what subset should be disposed of in order to minimize system costs [12]. Several interdependent issues must be considered concurrently to properly determine the optimum component re-use ratio, including assembly/disassembly costs and any defects introduced by either process, product degradation incurred in the original life cycle, and the waste stream associated with the life cycle. Among these factors, the estimate of the degradation of the product in its original life cycle could be the most uncertain input to make end-of-life decisions. This task requires the knowledge of the entire history of the product’s life cycle. This could be effectively carried out using health monitoring.

The methods of assessing product degradation for recovery reported in the literature have focused on the use of non-destructive testing. For example, Reyes et al. [13], developed an acoustic test to assess the reusability for AC induction motors used in photocopiers. The Applied Research Lab (ARL) at Penn State University [14], developed a low-cost assessment approach for the usability of paints beyond the expiration dates based upon monitoring of the paint conductivity and polarization as a function of frequency, to extend the shelf life of stock.

While the above approaches are based upon tests conducted after the product is returned or considered expired, efforts to develop in-situ monitoring techniques enabling product recovery have also been reported. Scheidt et al., [15] proposed the development of special electrical ports, referred to as green ports, to retrieve product usage data that could assist in the
recycling and re-use of electronic products. Klausner et al. [16] [17] proposed the use of an integrated Electronic Data Log (EDL) for recording parameters that are indicative of product degradation. The EDL was implemented on electric motors to increase the reuse of motors. In another study [18], domestic appliances were monitored for collecting usage data by means of electronic units fitted on the appliances. This work introduced the Life Cycle Data Acquisition Unit (LCDA) that can be used for data collection and also for diagnostics and servicing. Middendorf, et al., [19] suggested the idea of development of life information modules to record the cycle conditions of products for reliability assessment, product refurbishing, and re-use.

Designers often establish the usable life of products and warranties based on extrapolating the accelerated test results to assumed usage rates and life cycle conditions. These assumptions may be based on worst-case scenarios of various parameters composing the end user environment. Thus if the assumed conditions and actual use conditions are same the product would last for the designed time as shown in Figure 4 (A). However, this is rarely true, and usage and environmental conditions could vary significantly than those assumed. Consider products that are equipped with life consumption monitoring systems for providing in-situ assessment of remaining life. In this situation, even if the product is used at a higher usage rate and in harsh conditions, it can still avoid unscheduled maintenance, catastrophic failure, maintain safety, and ultimately save cost. These are typically the motivational factors for use of health monitoring or life consumption monitoring as shown in Figure 4 (B).

One of the vital inputs in making end-of-life decisions is the estimate of degradation and the remaining life of the product. Figure 4 (C) illustrates the scenario where a working product is returned at the end of its designed life. Using the health monitors installed within the product the reusable life can be assessed. Unlike testing conducted after the product is returned, this estimate can be made without having to disassemble the product. Ultimately, depending on other factors such as cost of the product, demand for spares, cost and yield in assembly and disassembly the manufacturer can choose to reuse or dispose. For example, in the case study of section 3, assuming that the car is deemed unusable and is returned by the customer after the accident on day 22, the manufacturer could use the collected data to estimate the remaining life of the board and decide on its reuse or disposal.

5 Summary

Health monitoring is emerging as a popular alternative over traditional reliability assessment methods. Different approaches used for implementing health monitoring were outlined. The applicability of LCM for electronic products was emphasized. The use of health monitoring in accurately estimating the product
degradation to assist end-of-life decisions was presented.

6 Literature