Optimization of PHM System for Electronic Assemblies Using Maintenance Aware Design Environment Software

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Abstract

Prognostics and health monitoring for electronic systems has been a field of interest of many researchers in the past decades. Traditionally, implementation of in-situ health monitoring for electronic systems has not been feasible due to time and cost considerations. However, recent research has led to improved sensing techniques and a better understanding of the manifestations and mechanisms of failures in electronic components. This paper outlines a software-based Failure Mode Mechanism and Effect Analysis approach to identifying the critical factors that lead to failure. A system-level model was created to map the interactions between subsystems at a functional level using a standardized taxonomy available in the software package. Also, the associated possible failures modes and mechanisms at every level were defined while modeling the system. This provided a better understanding of the impact of sub-system failure at a system level and enabled the effective interpretation of the Failure Modes, Mechanisms, and Effects Analysis. A model-based simulation of failure propagation was utilized by the software to generate a system-level database of failure modes and effects. This database allowed us to implement prognostics and health monitoring by identifying monitoring needs and reducing redundancy for a specified level of failure coverage. Also, inconsistencies introduced by a difference in interpretation of the standards were eliminated by using a standardized taxonomy. A case study was conducted to demonstrate the application of this approach for sensor set design optimization.

Keywords: Prognostics and Health Monitoring, FMMEA, MADe.

Introduction

Today's competitive marketplace demands that manufacturers identify cost-effective methods for improving the product development process. Traditional product development processes are concerned only with meeting performance specifications. Identifying possible failure modes and mechanisms and estimating useful life and maintenance requirements are typically carried out after system design has been completed. These results have a limited impact on the design of systems. Thus, if the results of these analyses show that there will be an unfavorable impact on the maintainability of the system, corrective actions will have to be carried out by modifying existing hardware, adding sensors, or revamping maintenance procedures [1]. Such maintenance activities have a large impact on the availability of systems and thus result in increased downtime of systems. The electronics industry has been interested in finding an efficient approach to improve the design process that would result in decreased downtime for systems.

Prognostics and health monitoring is one possible approach to increase the failure free operating time of a system. Prognostics is the process of forecasting the reliability of a product based on its current and historic conditions. The reliability of a product is defined as the ability of a product to perform its intended functions for a specific period of time in its life cycle application conditions [2]. Degradation of electronic systems in products such as aircraft systems and medical systems can be catastrophic. There is therefore a need for assessing the health of such systems for safe and reliable operation [3]. PHM aims to achieve improved reliability and maintainability of systems by applying failure analysis, model-based monitoring, and artificial intelligence technology to predict when a system will need to be serviced or replaced. Successful application of PHM requires the integration of system reliability and safety into the design process. An effective PHM solution is implemented when there is sound knowledge of the failure mechanisms that are likely to cause the degradations leading to eventual failures in the system. It is therefore necessary to have initial information on the possible failures (including the site, mode, cause and mechanism) in a product. Such knowledge is important to identify the system parameters that are to be monitored.

Failure Modes, Mechanisms, and Effects Analysis (FMMEA) is a method used to determine the parameters that need to be monitored [4]. FMMEA is a systematic methodology for identifying potential failure mechanisms for all potential failure modes and prioritizing the failure mechanisms [5]. FMMEA is based on understanding the relationships between product requirements and the physical characteristics of the product (and their variation in the production process), the interaction of materials in the product, and their influence on the product's susceptibility to failure with respect to use conditions.

This paper outlines an approach for implementing a software-based approach for carrying out FMMEA for an electronics system. Maintenance Aware Design Environment (MADe) is a model-based software tool that can be used to conduct FMMEA and fault diagnosis for systems. The functional model created in the software environment can be used to predict the system response to component level faults and process their criticality. The tool can also be used to optimize the number and location of sensors to be used for PHM solutions [6].

Prognostics and Health Monitoring for Electronics

Since maintainability has now become a major constraint in developing new systems, it is important to develop techniques to monitor the health of a system and predict its remaining useful life (RUL). These techniques are encompassed in Machine Condition Monitoring (MCM) and/or Condition Based Monitoring (CBM). CBM is a maintenance program that recommends maintenance actions based on the information collected through condition monitoring. CBM attempts to avoid unnecessary maintenance tasks by taking maintenance actions only when there is evidence of abnormal behavior of a physical asset [7].

In November 2002, the U.S. Deputy Under Secretary of Defense for Logistics and Material Readiness released a policy called Condition Based Maintenance Plus (CBM+) [8]. The Defense Acquisition Guidebook [9], Section 5.2.1.2: Condition Based Maintenance Plus (CBM+) provides this definition of CBM+: "a set of maintenance processes and capabilities derived, in large part, from real-time assessment of weapon system condition, obtained from embedded sensors and/or external tests and measurements.

The goal of CBM+ is to perform as much maintenance as possible at pre-determined trigger events. A trigger event can be physical evidence of an impending failure provided either by inspection or diagnostic technology, or could be operating hours completed, elapsed calendar

days or other periodically occurring situation (i.e., classical scheduled maintenance).”CBM+ represents an effort to shift unscheduled corrective equipment maintenance of new and legacy systems to preventive and predictive approaches that schedule maintenance based upon the evidence of need [8]. CBM+ thus evolved into the new concept of PHM. PHM is used to evaluate the reliability of a system in its actual life-cycle conditions, determine the initiation of failure, and mitigate system risks [8].

The importance of PHM implementation was explicitly stated in the DoD 5000.2 policy document on defense acquisition, which states that “program managers shall optimize operational readiness through affordable, integrated, embedded diagnostics and prognostics, and embedded training and testing, serialized item management, automatic identification technology (AIT), and iterative technology refreshment.” A 2005 survey of eleven CBM programs highlighted “electronics prognostics” as one of the most needed maintenance-related features or applications without regard for cost [10].

Different approaches to PHM include (1) the use of fuses and canaries; (2) monitoring and reasoning of failure precursors; and (3) monitoring environmental and usage loads for damage modeling. A more detailed discussion regarding these three approaches can be found in Pecht et al. [4]. Implementation of an effective PHM strategy may require integrating different prognostic and health monitoring approaches. The first step is an analysis to determine the weak link(s) in the system based on the potential failure modes and mechanisms to enable a more focused monitoring process. A combination of canaries, precursor reasoning, and life cycle damage modeling may be necessary based on the failure attributes identified using systematic methods such as FMMEA [8]. Fusion of these techniques and technologies with design processes will lead to improved reliability and maintainability of systems.

FMMEA Methodology

Electronic hardware is typically a combination of boards, components, and interconnects, all with various failure mechanisms by which they can fail in their life-cycle environments. FMMEA involves identifying the failure mechanisms and reliability models to quantitatively evaluate their susceptibility to failure. The FMMEA process begins by defining the system to be analyzed, which is viewed as a composite of subsystems or levels that are integrated to achieve a specific objective [5]. A system is divided until the lowest possible level is reached. The system breakdown can be performed by function (i.e., according to what the system elements “do”), or by location (i.e., according to where the system elements “are”), or a combination of both (i.e., functional breakdown by location or vice versa). In a printed circuit board, for example, a location breakdown would include the package, the plated through-hole (PTH), metallization, and the board itself. For each system element, all of the associated functions are listed. For example, the primary function of a solder joint is to connect two materials electrically and mechanically. Hence, failure of a solder joint will relate to its inability to perform as a physical and electrical connection. This analysis is further carried out for each of the system’s elements.

Failure modes, causes, and mechanisms

The FMMEA methodology is based on identifying the high priority failure mechanisms in order to create an action plan to mitigate their effects [5]. High priority failure mechanisms determine the environmental and operational parameters that need to be considered. In order to achieve this, once a system is defined, the potential failure modes are identified for each of the system elements. A failure mode is defined as the effect by which a failure is observed [11]. Failure modes are closely related to the functional and performance requirements of a product. For example, in a solder joint, the potential failure modes are an open or intermittent changes in resistance, which can hamper its functioning as an interconnect. A potential failure mode at any one level in the system may be the cause for potential failure modes in a higher level system or subsystem, or be the effect of one in a lower level component.

The second step in FMMEA involves the identification of the failure causes for each of the failure modes. A failure cause is defined as the circumstances during design, manufacture, or use that lead to a failure mode [11]. It can include environmental and operational conditions. For example, solder joint failures such as an open or intermittent change can be caused by temperature cycling, random vibration, and shock impact. Knowledge of the failure-cause helps us in identifying the failure mechanism that drives the failure mode for a given element.

Failure mechanisms are defined as the physical, chemical, thermodynamic, or other processes that cause failure [12]. The failure mechanisms are identified and classified as either overstress or wearout failures. A catastrophic failure due to a single occurrence of a stress event when the intrinsic strength of the material is exceeded is called an overstress failure [5]. Failure mechanisms due to monotonic accumulation of incremental damage beyond the endurance of the material are called wearout mechanisms [11]. Failure mechanisms frequently occurring in electronics can be classified as electrical performance failures, thermal performance failures, radiation failures, and chemical failures. A list of the potential failure mechanisms in an electronic system is provided in Figure 1.

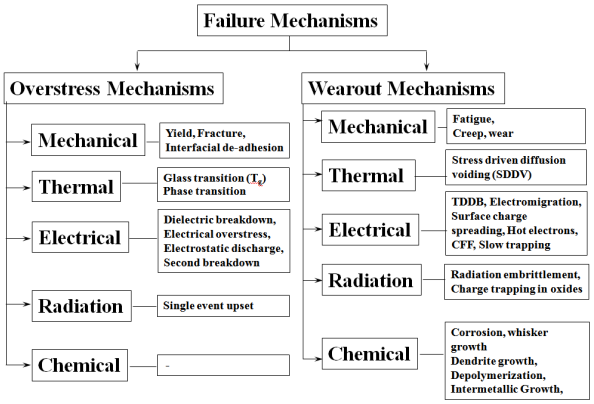


Figure 1: Failure mechanisms in electronics.

Failure mechanism prioritization

Ideally, all failure mechanisms and their interactions must be considered for product design and analysis. Several failure mechanisms may be activated during the life cycle of a product, but in general a small number of environmental and operational loads and mechanisms are responsible for the majority of failures [5]. Prioritization of failure mechanisms provides an

effective opportunity for effective utilization of resources. The methodology for failure mechanism prioritization is shown in Figure 2.

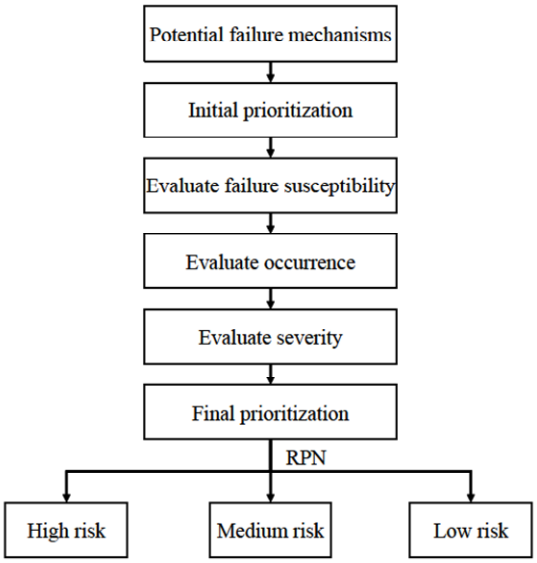


Figure 2: Failure mechanism prioritization [5].

Based on the negligible impact on stress levels due to certain environmental and operating conditions, failure mechanisms that are dependent on those conditions are eliminated from initial prioritization. The failure susceptibility of the remaining failure mechanisms is evaluated based on failure models, stress analysis results (overstress mechanisms), determination of time to failure (wearout mechanisms), and past experience (combined effect of wearout mechanisms). Once the susceptibility to failure is determined, the severance and occurrence ratings are assigned to the failure mechanisms for the environmental and operating conditions experienced by the system to determine the risk level associated with potential failure mechanisms. The occurrence ratings are defined in Table 1. For wearout mechanisms this rating is based on the time to failure (TTF) for the system, and for overstress mechanisms this rating is based on whether the mechanism precipitates the failure of the system or not. A similar rating is given for the severity associated with each of the failure mechanism (see Table 2) based on the impact it has on safety and on the end system functionality. In rating the severity of a failure, the possible worst case consequence is assumed for the failure mechanism considered. Both these metrics are then used to assign a qualitative measure to the risk associated with each failure mechanism.

Table 1: Occurrence Rating [5].

Rating	Criteria
Frequent	Overstress failure or very low TTF
Reasonably Probable	Low TTF
Occasional	Moderate TTF
Remote	High TTF
Extremely Unlikely	No overstress failure of very high TTF

Table 2: Severity Rating [5].

Rating	Criteria
Very High or Catastrophic	System failure safety related catastrophic failure
High	Loss of function or severe injury
Moderate or Significant	Gradual performance degradation or minor injury
Low or minor	System operable under reduced performance or no injury
Very Low or none	Minor nuisancnce

The final prioritization of the failure mechanisms is performed by rating the failure mechanisms according to three risk levels, namely “low”, “moderate”, and “high” using the risk matrix [5] presented in Table 3. Further prioritization within a given risk level may be performed depending on the product type, use conditions, or needs and objectives of the organization. This rating is carried out using a risk priority number (RPN). Higher RPNs are assigned to mechanisms that have higher levels of risk associated with them.

Table 3: Risk Matrix [5].

		Occurrence				
		Frequent	**Reasonably Probable**	**Occasional**	**Remote**	**Extremely Unlikely**
Severity	**Very High or Catastrophic**	High Risk	High Risk	High Risk	*Moderate Risk*	*Moderate Risk*
	High	High Risk	High Risk	*Moderate Risk*	*Moderate Risk*	Low Risk
	Moderate or Significant	High Risk	*Moderate Risk*	*Moderate Risk*	Low Risk	Low Risk
	Low or minor	High Risk	*Moderate Risk*	Low Risk	Low Risk	Low Risk
	Very Low or none	*Moderate Risk*	*Moderate Risk*	Low Risk	Low Risk	Low Risk

Modeling in the Maintenance Aware Design environment (MADe)

Initially developed by PHM Technology Pty. Ltd. for application to aerospace systems, the Maintenance Aware Design environment (MADe) provides a suite of software tools that could be used to design, assess, and optimize Prognostics and Health Management systems for use in a wide variety of high risk industries where safety and reliability are critical, including mining and offshore applications.

MADe utilizes a software based approach to FMMEA modeling and is considered to be an enhancement of and a front end methodology for PHM [1]. The availability of failure knowledge is a basic requirement for generating PHM systems capable of fulfilling their objectives. This includes knowledge of the failures that can be generated during system operation. These failures may occur due to defects within a component or due to the effects of failures that propagate throughout the system. This knowledge is also crucial to the design of sensing systems. If a sensor only covers an incomplete set of system elements, then the diagnostic and prognostic capability of the PHM system is degraded.

A major drawback while carrying out an FMMEA is the loss of information between the various departments (e.g., design, manufacturing, assembly) involved in the product development process. This is attributed to the difference in taxonomy and terminologies used while carrying out the FMMEA at different stages of product development. MADe eliminates this problem by forcing the designers and engineers to use a standardized taxonomy while carrying out the FMMEA thereby improving the overall product development process. This allows for effective implementation of a PHM solution.

The MADe system capabilities are shown in Figure 3. The system modeling tool (Failure Knowledgebase or the FMECA Database Generation Tool) generates hardware and functional system models that can be used to predict the system response to component level faults and process their criticality. The tool aims to provide a rapid and affordable means of generating and continuously updating system and failure knowledge bases. This database is then used to identify the monitoring requirements of the system to create a PHM solution [6].

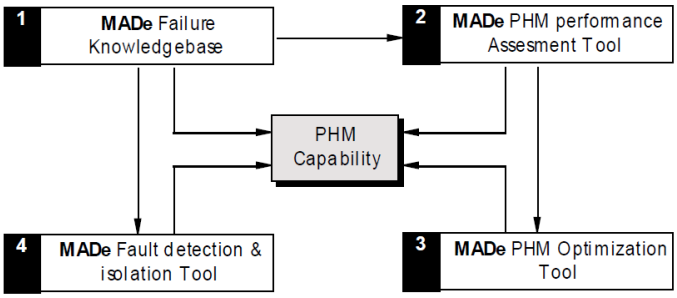


Figure 3: MADe software capabilities [1].

The system monitoring design tools (PHM Performance Assessment and PHM Design Optimization) are used to optimize the number and location of sensors in energy transmission systems and enable real-time "what-if" analysis to determine the impact of trade-offs, such as weight reduction via reducing the number of sensors, on fault coverage. The Advanced Fault Detection & Isolation Tool uses the hardware system model and system monitoring design tools to generate a Model Based Diagnostic (MBD) application. The application uses artificial intelligence and model-based simulations of the system to offer advanced real-time diagnostic analysis [6].

System modeling and failure analysis

The MADe system modeling and failure knowledge base tool aims to identify potential operational and diagnostic problems in the conceptual stages of the system design and provides a guide to make the necessary capability and requirement trade-offs to optimize the design of the final system. The system modeling tool is used to generate the functional and system models that can be used to predict the system response to part-level faults and process their criticality. MADe uses a standardized taxonomy for defining failure [6]. The definitions for the failure concepts in MADe are provided in Table 4. System modeling in MADe is hierarchical and at each level a failure diagram (Figure 4) of the concerned level is defined by defining the cause, mechanism, and fault. The flow of system modeling is described in detail in the Figure 5. Functional models are built for the system using generic MADe library components, known as functional areas, and linking them to create a block diagram.

Table 4: Failure Concepts in MADe [13].

Concept	Definition	MADe modeling approach
Failure Mode	The way in which an item fails to fulfil its function. It represents the state of the functional flow, not the physical state of the item.	Stated as a combination of function, with flow nouns to define inputs and outputs. Causal links between input and output flows define the causality of the function.
Fault	The damaged state of a system element that renders it unfit to fulfil its function. It defines the physical state of the system.	Modeled in a failure diagram using a standardized list of descriptors for physical damage.
Mechanism	The physical process of degradation.	Modeled in a failure diagram using a standardised list of failure mechanism terms.
Cause	The abnormal state of input, loading, or environment that leads to the degradation of an item.	Modeled in a failure diagram using a standardized list of causes.
Loss/Symptom	Change to the appearance, behavior etc. of a part, pair or component that can be used to identify failure.	Modeled in a failure diagram using a standardised list of symptoms.
Function Flows	Interactions between components are modeled as functional flows	Modeled in the functional flow defined at component level.

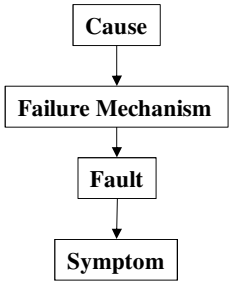


Figure 4: Failure diagram in MADe.

The links represent functional relationships between the components, and these functional relationships are expressed using the functional ontology developed by Stone and Wood [14]. The functional description is a two-part verb-noun statement that is formed by selecting one verb and one or more nouns from a standard list of terms [6]. Each functional area in the model is connected using lines representing functional flows between components. This is converted into a directed graph that is used to propagate the flow through the system. Causal connections between the faults at the various hierarchical levels of the system depict the propagation of the fault through the system. This modeling approach (Figure 6) allows the software to identify the parameters that need to be monitored to identify each failure mechanism.

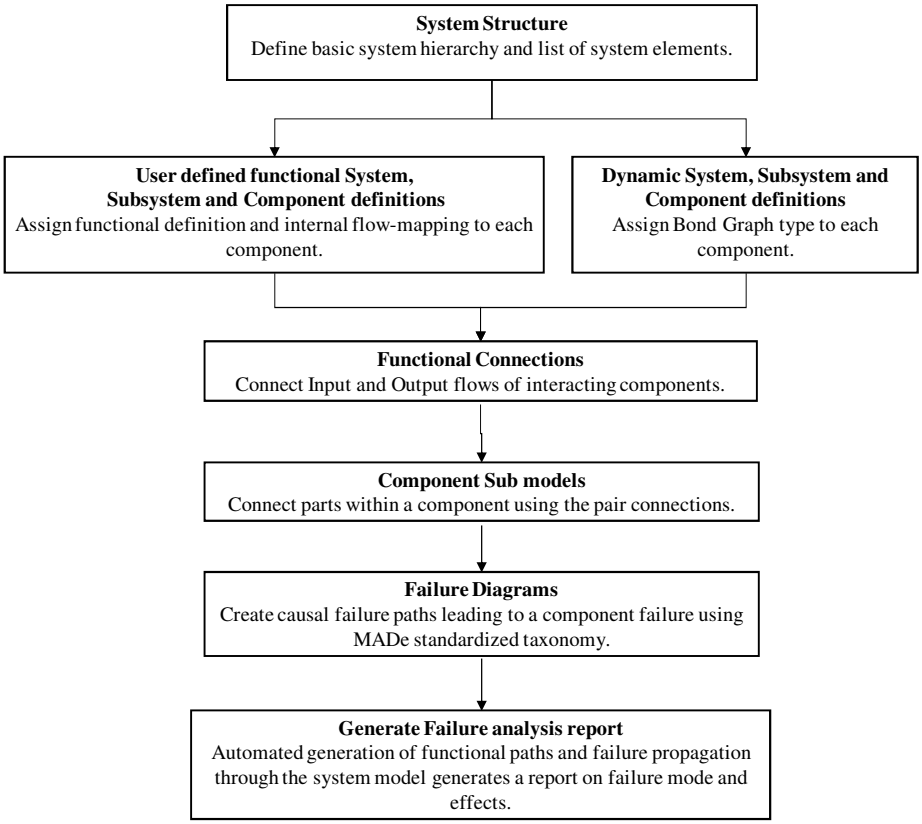


Figure 5: Workflow for system modeling in the MADe environment.

The failure analysis, which follows the system model creation in MADe, creates a propagation table that generates a steady state and transient response of each element to each failure mechanism that can occur in a system. The failures are then prioritized based on their criticality. The criticality properties are defined at the component level and propagated through the system using a Failure Concept Map (FCM) [13]. Each failure mechanism is associated with an occurrence, detectability, and severity rating. This allows for easy evaluation of the risk priority number (RPN) for each failure mechanism. RPN is found by combining the occurrence and detectability of the failure mechanism at the component level and the severity of its system-level effect. For multi-level systems, the probability of a system-level effect is calculated by propagating the occurrence value for a component failure mechanism through the system using the FCM, which consists of failure paths that are constructed to link each mode-effect pair from the component level through the system hierarchy (causal connections) to the system level.

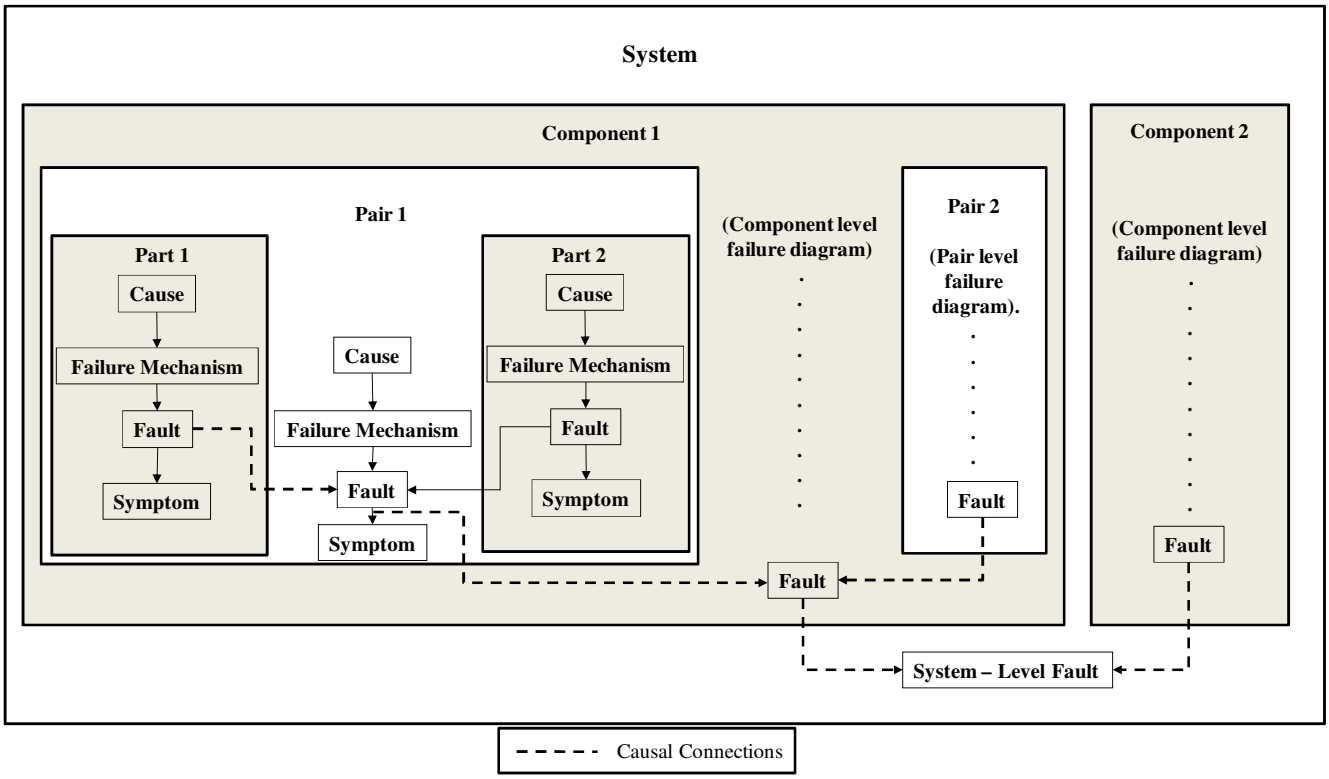


Figure 6: System modeling in MADe.

For an electronic system all possible failure causes, modes, and mechanisms are first included in the failure database for MADe. The modeled system is then subjected to failure analysis, which generates a failure propagation table followed by a criticality analysis. The criticality analysis is then used to determine the critical failure modes that are to be monitored for improved system-level reliability.

System monitoring in MADe

The system monitoring design tools are used to optimize the number and location of the sensors in energy transmission systems and enable real time "what-if" analysis to determine the impact of trade-offs, such as weight reduction by reducing the number of sensors, on failure coverage. Failure coverage is defined as the percentage of failure mechanisms that can be uniquely identified with their distinct signatures during failure analysis. The results of the failure analysis are imported into the sensor analysis module and used to conduct sensor set design.

The symptoms of a fault include all of the observable energy perturbations by which a fault can be detected through the system. The set of system responses (symptoms) of each failure mode are then used to carry out two tasks: sensor discrimination and sensor minimization [6]. Sensor discrimination involves the use of all system responses to distinguish between failure modes. This is carried out by analyzing the fault/symptom table that is generated using failure propagation. Diagnostic rules are applied that identify the response signal values that will be detected for each fault.

Sensor minimization involves the creation of a diagnostic set that contains the minimum number of system responses required to distinguish between failure modes. The diagnostics set therefore contains a list of symptoms that can be used to uniquely identify faults and

correlates it to the symptoms. This table is then used to generate the sensor sets. Sensor sets are then generated from the fault/symptom table by optimizing (minimizing) the number of symptoms (i.e., the sensors) while preserving the observability of every fault.

Built in test (BIT) can also be defined for any component to provide better failure coverage. If a model-based diagnostic application exists for a symptom, virtual sensors can be added in the model by representing them as a number of "physical" sensors that provide equivalent coverage [6].

Case Study—FMMEA of a Laptop Computer

A case study was conducted by implementing the FMMEA of a laptop computer using MADe. A laptop computer is a complex system that integrates devices for input/output, computation, storage, cooling, and power. A system-level FMMEA was carried out by dividing the system into various subsystems. The divisions were mainly based on the functionality of each system. Six subsystems were identified in this study, as indicated in the Figure 7.

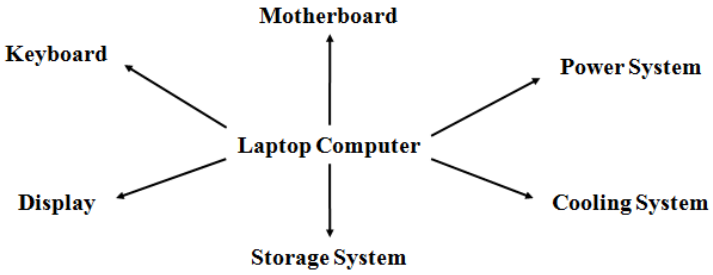


Figure 7: System divisions in MADe.

The laptop was then modeled based on the above described divisions using the MADe software tool (Figure 8). A functional model was created in the software for each subsystem by further dividing each subsystem into its constituent parts. For example, the display system was modeled as consisting of an LCD panel (liquid crystal sandwiched between a lower polarizer and a color filter), a driver circuit, a backlight system (cold cathode fluorescent lamp (CCFL) tubes along with a diffuser), an inverter board, and cables. The driver circuit is the electronic control that is responsible for all operations of the screen. The electric current passing through each liquid crystal make the molecules tilt to suitable angles so that the polarized light can be rotated to the desired polarization. The operation of the CCFL tubes requires a high voltage provided by an inverter. The inverter feeds a high voltage to the backlights via a ribbon cable. Each subsystem was then defined in a similar manner and a system level model for each of the subsystems was developed.

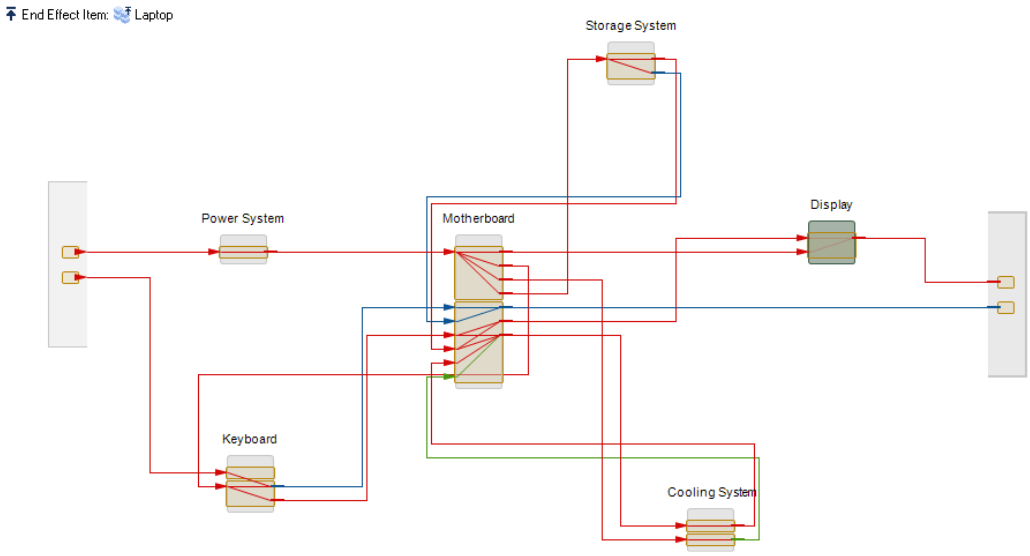


Figure 8: System model in MADe.

Once the system modeling was complete, the failure diagrams were created for each level in the hierarchy, and the causal connections between the faults at the various hierarchical levels of the system were made, depicting the propagation of the fault through the system. An example of the failure diagram definition is shown in the Figure 9.

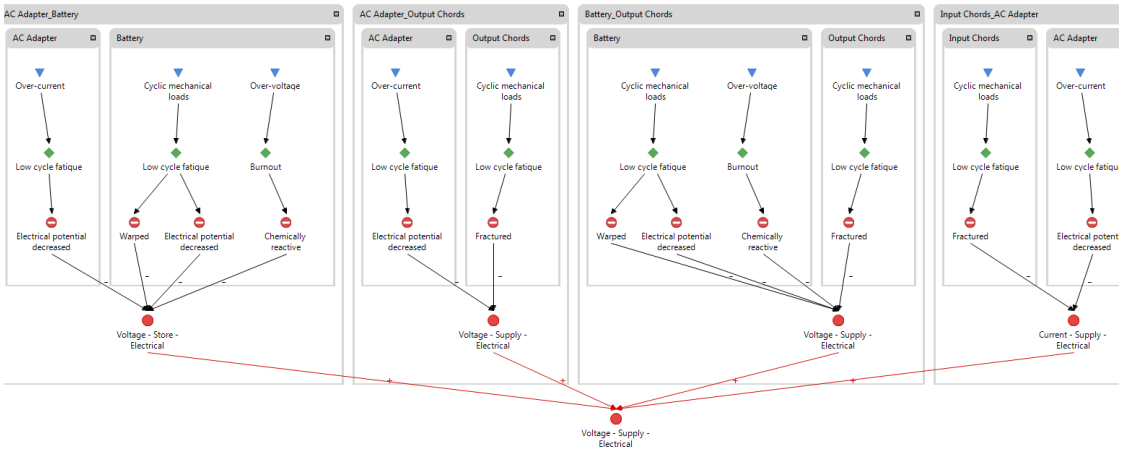


Figure 9: Failure diagram example (power system).

Once the failure diagrams were defined at each level, failure was propagated through the system to obtain a failure propagation table. The failure propagation table provides the system-wide responses for each of the failure mechanisms. The results indicated that the laptop computers are susceptible to failures caused by factors such as contaminants in the atmosphere, cyclic loading including thermal loading and mechanical loading, drops or impacts and the printed circuit board (PCB) failures in the control electronics. The failures that ranked the top in terms of risk priority number were the failure in the motherboard and failure in the controller circuit board for the storage system. Multiple failure mechanisms including thermal fatigue, electrical overstress and electro-static discharge contributed to failures in both these subsystems. The results of the failure propagation are then used to detect and differentiate between failure mechanisms, and an optimized sensor set is obtained for the system-level monitoring. The present detail in modeling allows for 100% failure coverage. This means that with the available sensors in the library, 100% of all the defined failure mechanisms are clearly distinguishable in the system.

One drawback with the MADe software is that the failure database at present does not include all possible mechanisms that may occur in electronic assemblies. This results in incomplete definition of the failure diagram at each level. However the failure database is currently being updated to include possible electronic failures. The work is a joint effort between the Center for Advanced Life Cycle Engineering (CALCE) at the University of Maryland, and PHM Technology Pty. Ltd.

Discussion and Conclusions

This paper addresses the need for optimizing a prognostic solution to predict reliability for electronic assemblies. Identification of the critical failure mechanisms contributing to the failure using an FMMEA based approach is suggested. An outline of the basic procedure to develop an FMMEA approach to PHM for electronics using the software package MADe is provided in this paper. The software-based approach for FMMEA reduces the time and resources needed to carry out system level FMMEA for complex electronic systems. It forces designers to use similar taxonomy for FMMEA analysis, which creates less confusion between the layers at which the FMMEA is carried out, such as the design level, process level, and assembly level. The sensor analysis technique, which is a part of the software, allows the designer to design sensor sets based on the trade-offs between the number of sensors, the weight, and the desired failure coverage. This methodology can be used to create a rapid solution for PHM in electronics.

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