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INTEGRATION OF A RELIABILITY MODEL WITHIN A VIRTUAL ANALYSIS SYSTEM FOR PRINTED CIRCUIT BOARDS

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ABSTRACT

The field of modeling and simulation continues to grow and help reduce costs and increase development speed in the engineering community, but use of such capabilities has been minimal with respect to circuit board visualization and reliability. This work responds to this gap with a new simulation-based reliability model for electrical components and systems, integrated within a software platform for concurrent analysis. While statistics-based reliability analysis is common, this work presents the integration of such models in a comprehensive system. The results coupled with a user-friendly interface and display in a virtual environment combine to create a novel tool for the identification of problem areas and planning for future maintenance of electromechanical systems.

1. INTRODUCTION

Electromechanical systems essentially start to fail as soon as they are first implemented. As they age, they become more unreliable. They become increasingly unpredictable and difficult to maintain. Consequently, a significant amount of time and money is spent on the maintenance of large-scale systems, and there is a lack of analysis tools to assist with the maintenance process. To be sure, statistical analysis and reliability analysis are fertile areas of research, but the extension of these tools to complex electromechanical systems is rare, and integration with additional visualization and analysis capabilities is rarer still. In response to industry needs, The University of Iowa's Advanced Manufacturing Technology (AMTech) Group has developed a predictive environment for visualization of electromechanical virtual validation (PREVIEW). PREVIEW is an integrated platform that combines high fidelity 3D visualization with testing and analysis capabilities. Among the latest of these capabilities is the computation, prediction, and display of reliability, maintainability, and failure.

There are very few integrated tools that concurrently consider multiple aspects of an electrical system such as thermal analysis, electromagnetic (EM) analysis, or packaging studies. Mentor Graphics [1] has five different software packages to perform printed circuit board (PCB) design, thermal analysis, EM analysis, and packaging substrate analysis. CR-8000 by Zuken also provides EM analysis and packaging study capabilities [2]. Regarding system-level analysis, PREVIEW is integrated with CST Microwave Studio for thermal analysis and EMI/ EMF analysis, and with LTSPICE for circuit analysis.

There are even fewer software tools that predict reliability and failure. 217Plus by Quanterion Solutions has replaced MIL-HDBK-217 and PRISM as the most recent tool to be used by the government and industry [3]. It utilizes component-specific empirical data and stress coefficients to compute failure rate for individual components, and compiles them to compute system-level failure rate. The reliability model developed for PREVIEW differs from 217Plus by conducting a system simulation based on prediction of component failures.

Despite the advanced tools and ongoing research, there are currently no available tools that combine failure prediction with PCB visualization. Reliability information shown in a relevant context (i.e. a virtual representation of the PCB) is more easily understood and thus more useful.

PREVIEW is a unique physics-based toolkit for virtual modeling, simulation, and visualization, with a focus on increasing reliability and reducing costs. This toolkit includes a platform for coordinating 1) system visualization, 2) physics-based analysis capabilities, and 3) evaluation of system and component data. It provides a digital scratch pad for conducting upstream packaging studies with complex electromechanical systems. It provides capabilities for analyzing multi-board effects, conducting geometric analysis, visualizing component-based cost and reliability data, and integrating with virtual reality systems. Finally, it allows one to conduct electromagnetic interference/field (EMI/EMF) and thermal simulation and visualization, as well as virtual testing that typically have to be conducted with expensive and lengthy experiments. All of this is done in 3D.

The novelty of this toolkit is not only the ability to provide and coordinate a variety of new capabilities, but also a generalized approach to communication between a central model and external databases that house information regarding geometry, component specifications, and board specifications. This approach allows for integration with STEP AP203/210 protocols for mechanical, electrical, and connectivity information. In fact, the ability to conduct geometric analysis of mechanical and electrical systems concurrently is unique. In terms of data visualization, PREVIEW provides a generalized approach to selecting and highlighting components based on various search filters, as well as traces between components [4]. With the proposed work, PREVIEW is used to display results in a visual environment that gives the user the ability to predict the reliability, lifetime, and failure rate of a PCB under thermal stresses at any time. The following sections will discuss the underlying model, the challenges of implementation, and conclusions regarding implementation.

2. LIFETIME, RELIABILITY AND MAINTAINABILITY MODEL

Although an abundance of research has been conducted to improve mechanical reliability in the physical world, the potential application of computer modeling and simulation to PCB reliability has been largely untapped. This section summarizes the work by Dababneh *et al*, 2013 [5] in developing a model for predicting remaining lifetime, reliability and maintainability. The subsequent sections discussed the integration of this model with PREVIEW.

2.1 Component Analysis

In order to accurately compute system-level lifetime, the system's components must first be analyzed. Each component's behavior is estimated by finding the approximate best-fit distribution of a sampling of past time to fail (TTF) data. The Kolmogorov-Simonov (KS) test is used to determine whether the sampling is best fitted to a Weibull, exponential, normal, or a lognormal distribution. A random number between 0 and 1 can then be used as a probability under this cumulative distribution function (CDF) to find the estimated time to the next failure for the component. The maximum and minimum lifetime for each component is determined by the mean TTF of its data sample plus or minus 1.5 times the standard deviation, respectively.

Component reliability is a measure of non-failure calculated using the best cumulative distribution function (CDF) based on the TTF sample data. In this research, PCB components are assumed to have non-zero age. Thus, reliability is calculated beyond the age of each component, not after time zero. The reliability of a non-new component is a conditional reliability and uses Bayes' rule with a component's CDF: P [no failure (x, x+t) |no failure (0, x)]. A component's CDF represents its *unreliability*. Therefore, the reliability is computed as 1 minus the CDF [6].

2.2 System Analysis

In order to use the above mentioned component analysis and provide a system-level analysis, a new simulation methodology has been developed. This approach computes lifetime, reliability, and maintainability of the entire circuit. Once the simulation starts, the component with the smallest TTF fails first, and its position on the circuit card is checked. Series, parallel, series-parallel, parallel-series, and bridge configurations are considered during this simulation. If the component is part of a parallel cluster or bridge configuration, then its failure does not stop the operation of the entire card. It does not result in system failure. If, however, the failed component is in a series configuration, and not in any parallel cluster, then the entire PCB fails.

A "time to repair" or "time to replace" value is assigned to that component. Then, a new TTF value and new "time to repair" or "time to replace" values are assigned for that component, and the entire circuit resumes operation. While the circuit is in failure mode, the TTF values of other components freeze at the time when the failed component stopped operating. Once the circuit resumes operation, the functioning components that were stalled continue operating from the same point where the failed component stopped.

Since one of the simulation outputs is the next failure time of the circuit card, the reliability probability property [5,6,7] is used to compute reliability for the entire PCB. The empirical distribution function is used to calculate the reliability. We count card failures occurring at a desired time (or higher) among all replications, and divide the outcome by the number of replications. The result represents the card level reliability at the specific time.

The maintenance of failing PCBs and their components is crucial in expensive and complicated systems. Maintainability is the probability that a failed component can be repaired within a given time frame. Similar to component reliability, component maintainability can be computed using a best CDF from a sampling of time to repair (TTR) data. For the entire PCB, the maintainability probabilistic feature [5,6,7] is used. Each run of the simulation executes a number of replications to increase the accuracy of the results. Since one of the simulation outputs is "time to repair" (for those components in which their failure leads to the entire PCB failure), we count "time to repair" values, which are equal to or lower than a desired time from all replications, and then divide the outcome over the number of replications. The result represents the maintainability at that desired time.

Thermal stress is the primary cause of lifetime and reliability decay in PCBs. Thus, component physics-based thermal models are coupled with system-level reliability analysis. The Arrhenius life-stress model is used in this research, as it is the most common relationship utilized in accelerated life testing. It is especially useful when the acceleration variable is temperature. This model is used to calculate adjusted lifetime and reliability data for a user-specified stress temperature or for a temperature provided by component-based thermal models [5,8,9,10]. The simulation is then re-run with new component TTF (under thermal stress) in order to determine the effects of this stress temperature on the entire PCB lifetime and reliability as well as on each of its components lifetime and reliability.

2.3 Sub-system Analysis

A new method has also been developed to calculate reliability between two user-specified PCB nodes, by determining the least reliable path between the nodes. This is done by finding all paths between the two nodes and calculating each path's combined reliability at a specific time. The final sub-system reliability is the minimum reliability of all of the connecting paths. A virtual multi-meter is used in the PREVIEW user-interface to select nodes and compute reliability between them at a specific time.

3. IMPLEMENTATION

3.1 Lifetime, Reliability and Maintainability

An often neglected challenge with analysis tools that generate large amounts of data is organizing and presenting such data. Thus, with this work, significant effort went into implementation of the above-mentioned capabilities within a software platform, as well as the actual interface development. Ultimately, for component analysis, a user can provide age, time-to-repair, and time-to-replace; and then see as output average lifetime, minimum and maximum time to fail, a plot of reliability vs. time, and a plot of maintainability vs. time. For system analysis, using the output from component analysis, one can determine the average time to next failure, the failure rate, and a list of system failures with associated component-based causes.

As a foundation, the proposed software platform leverages advances with gaming technology, which continuously pushes forward the fields of graphics and visualization. The infusion of these technologies with engineering has advanced the development of analysis tools. Thus, PREVIEW has been developed using a game-prototyping rendering engine called Virtools. With this engine, PCBs as well as printed circuit assemblies (PCAs) can be displayed in high-resolution 3D for detailed visual analysis and testing, as shown in Figure 1.

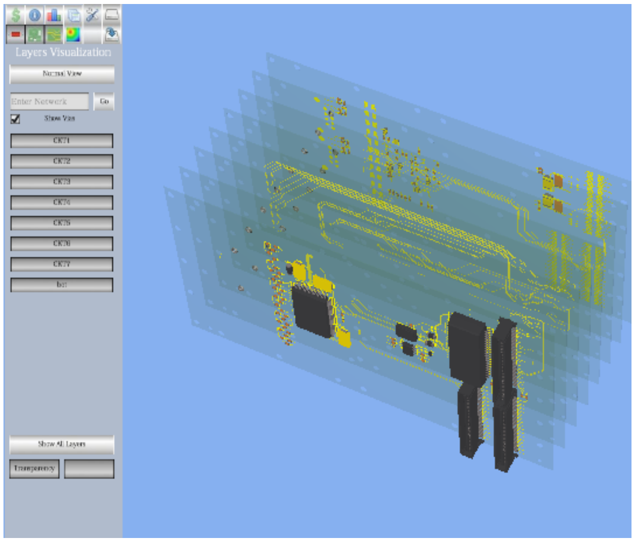

Fig. 1: 3D view of PCB in PREVIEW with expanded and transparent layers

Before actually interacting with a PCB or PCA, it is necessary to import mechanical and electrical models. Thus, a module has been developed to read the Standard for Exchange of Product model data (STEP). STEP files provide a standardized method of representing product model data and are utilized in PREVIEW. Each STEP file contains a multitude of information about the PCBs and the assemblies it refers to, often reaching 50,000 or more lines of data. A method for automated interpretation of these files, called a STEP post-processor, consists of a parser and an object-oriented database (OODB) object creator [11]. For PREVIEW, the STEP-OODB objects that represent geometric objects are retrieved and translated into Open Computer Aided Software for Computer Aided Design and Engineering (Open CASCADE) objects, and then converted to Virtools objects, so that they can be displayed within the Virtools environment.

PREVIEW has many capabilities that make it unique among STEP visualizers. These include the ability to store objects in a database for concurrent engineering [12], while still taking advantage of the capabilities of Open CASCADE for rendering; the ability to view each layer of the board separately while being able to rotate and zoom in; and the ability to trace connectivity through the product structure tree in a multi-board context. Most significantly, PREVIEW allows one to view mechanical and electrical design, which can often be mismatched as a result of uncoupled design processes.

Despite its advantages for quickly developing and testing CAD capabilities, Virtools presents some challenges. It is not ideal for developing Graphical User Interfaces (GUIs). Virtools also does not support parallel development for projects with multiple team members. Finally, there is no explicit functionality for creating graphs in Virtools, so external tools for displaying reliability data had to be explored and tested. Various tools were investigated including Mathematica, Boost, MathGL, and GNUplot. MATLAB was selected due to the ability to write code in C++ that calls the MATLAB engine in order to graph data externally.

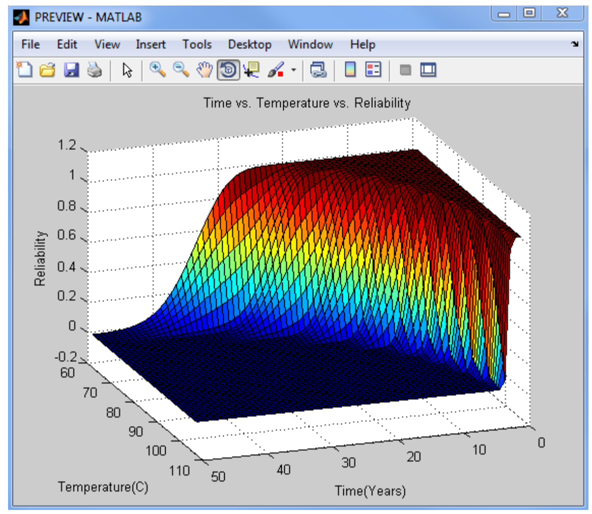

Fig. 2: Seamless MATLAB plotting from PREVIEW

Given the ability to import various electromechanical systems and visualize them, a new interface was developed for the proposed reliability-analysis capabilities (Figure 3). Note that the numerical feedback has been expanded in this figure for clearer illustration. Once a PCB and its components have been rendered, the user can click 'Compute Reliability' to run the reliability simulation and 'Compute Maintainability' for further output. All results discussed with respect to the reliability model are displayed for the system as well as any selected component. System and component reliability and maintainability plots are provided with the graphing feature (Figure 2).

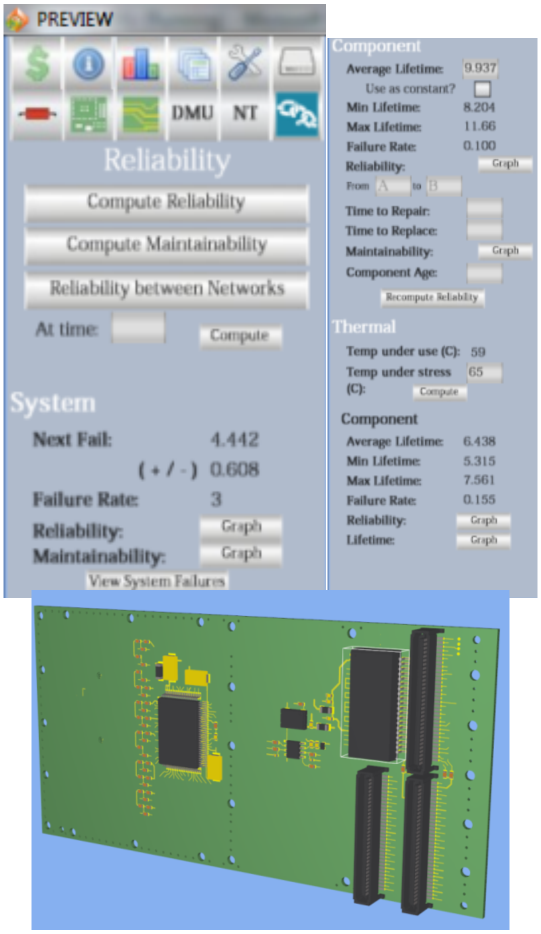

Fig. 3: Reliability user-interface in PREVIEW

One of the advantages of the newly developed capabilities is the ability to study cause-and-effect relationships in real time. Any component's average lifetime, time to repair, time to replace, age, or thermal stress temperature can manipulated in order to see the resulting effects on the reliability data for the components and the system, as well as in plots displaying the effect of thermal stress on reliability and lifetime. In this way, the effects of potential replacements or stresses can be tested quickly in a risk-free environment.

3.2 Component Thermal Analysis

In addition to visualizing reliability data, it can be useful to see the results of the component-based thermal analysis, which provides input to the reliability model as a common stressor. A significant amount of useful information can be ascertained using PREVIEW's component-based thermal analysis feature. For any thermally modeled component, temperature-distribution data are obtainable. Each type of circuit card component is unique in its construction, so they all have different material properties and internal geometries. The components that are shown with PREVIEW interface are cylindrical resistors, cylindrical diodes, cylindrical capacitors, and a specific integrated circuit.

Nonetheless, there were several challenges in the integration of the component thermal analysis formulation with PREVIEW, the foremost being the visualization of point clouds within the Virtools rendering environment. In Virtools, the data points within a point cloud are opaque, which means that when all points are displayed, only the outermost layer can actually be seen. To overcome this, a method called *point cloud segmentation* was used. Point cloud segmentation involves a sorting algorithm used to represent one large point cloud as a series of smaller point clouds. It was implemented slightly differently for each of two method for visualizing temperature distribution. For the first method, the data points were segmented by temperature. With the second method, the data points were segmented by the coordinates.

The first method involves viewing each temperature range as a colored point cloud (a 3D mapping of data points) and overlaying all of the point clouds on top of each other. This formulation allows the user to view individual temperature ranges simply by selecting the corresponding check boxes on a sidebar. Displayed next to each check box is the value of the temperature range it represents (Figure 4). This can be useful in situations where it is important to know if the component, or even an element within the component, has reached a certain temperature.

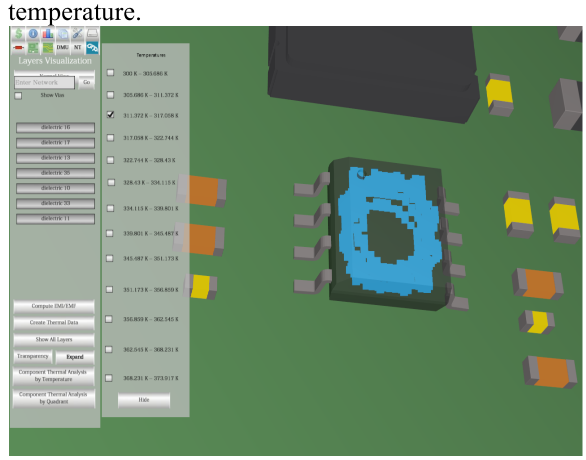

Fig. 4: First method for component-based thermal analysis: temperature ranges

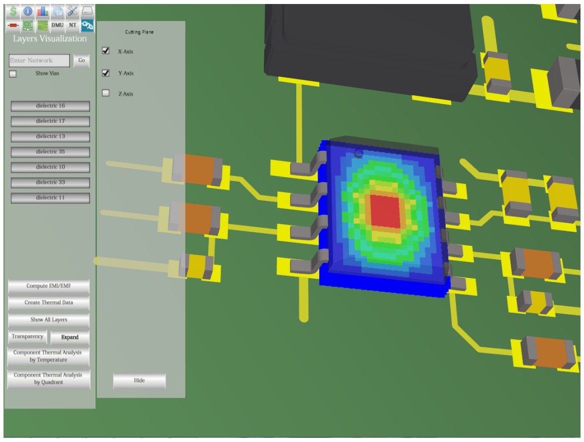

Fig. 5: Second method for component-based thermal analysis: XYZ plane cutting

The second method of visualization involves splitting the temperature data into point clouds organized by location (Figure 5). In this case, the check boxes on the sidebar allow the user to select which quadrant of the point cloud they wish to view. The advantage of this method is that it allows the user to create geometric slices through the part.

4. CONCLUSION

The latest additions to the PREVIEW platform predict the future of complicated electromechanical systems in order to facilitate maintenance. Reliability is computed based on empirical component failure and maintenance data. The system is then simulated using connection information and statistical failure models for individual components. The results of the computations and simulations are integrated within PREVIEW, a comprehensive system-analysis tool. To this end, a new reliability user-interface is developed in the form of text, plots, and colorized point clouds. Perhaps the most unique and significant aspect of this work is the system integration. The PREVIEW system not only allows one to couple a suite of visualization and analysis tools but also explore the linking of data-based analysis with physics-based analysis (i.e. the component-level thermal models). These capabilities will ultimately save time and money with maintenance process.

With respect to practical application in the manufacturing arena, these tools can help move virtual testing and analysis upstream *and* far downstream onto the plant/factory floor, allowing a maintenance department to identify and resolve PCB failure issues quickly. This project's automatic interconnectivity with MATLAB should be used as a model for other software engineering analysis tools in early stages of development. When conducting feasibility studies that require heavy computation or detailed plots, there is no need to re-develop tools that already exist.

Despite the newly developed capabilities, there is potential for future work on the reliability user-interface in PREVIEW. In order to help present large amounts of data, the PREVIEW interface will be addressed systematically from a human-factors perspective. Colorizing components based on various characteristics such as failure rate or reliability would help make extensive analysis results more palatable. In addition, a slider to control the time coupled with colorization could also be used to investigate component and systems characteristics during specific time intervals.

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