A VIRTUAL RELIABILITY TOOL FOR CIRCUIT BOARDS

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Abstract

In nuclear power plants, circuit board malfunctions and failures can result in power reductions and other plant challenges, causing losses of up to a million dollars per day. Therefore, having a predictive lifetime and reliability model reduces the time and cost associated with maintaining and planning for both in-service and new circuit board. In this research, a predictive remaining lifetime, reliability and maintainability analysis model of circuit boards for nuclear power electronics is developed for both the component level and the system level. Methodology and criteria are integrated within an immersive and interactive 3D visual environment, the Predictive Environment for Visualization of Electromechanical Virtual Validation (PREVIEW), which is a software package that displays the developed model and offers a versatile environment that accepts modifications.

Keywords: circuit boards, reliability, maintainability, virtual manufacturing.

1. Introduction:

Equipment related problems such as component failure have become very critical issues in nuclear power plants, as the reduction in plant performance is due to part and equipment failure and system performance degradation. Design for reliability in circuit boards has been accomplished with the introduction of reliability prediction tools in 1960s. The most widely used tool is Mil-HDBK- 217 [1]. However, the lack of accuracy and slow pace of updating the databases have limited the usage of this method. Moreover, Circuit boards used in nuclear power plants are facing failures due to aging. As a consequence, many of those plants adopt approaches of running to failure or doing a periodic replacement without solid technical basis, where this can be very costly [2]. Although a plethora of research has been conducted to improve circuit board reliability in the context of solder joint reliability and its fatigue life, limited research has been performed at the board level [3, 4]. That, a demand for tools that specifically simulate component and system reliability in the power industry, and predict remaining time to failure were the contributing factors which led to this research.

In this research, a predictive remaining lifetime, reliability and maintainability analysis model of circuit boards for nuclear power electronics was developed, for both component and system level. The criteria to determine the position of the failed component on the board layout and its effect on entire board operation are presented and incorporated in our circuit board’s reliability model to predict the life time and reliability of circuit boards. Furthermore, thermal stressor effect on the reliability of circuit board is discussed and sensitivity of reliability to thermal stress is incorporated.

The proposed methodologies were integrated within an immersive and interactive 3D visual environment called Predictive Environment for Visualization of Electromechanical Virtual Validation (PREVIEW) [5]. PREVIEW is an interactive 3D environment that includes predictive physics based on capabilities to support virtual testing of PCBs. It enables product designers to assess potential design shortcomings based on virtual physics-based test capabilities, thus reducing the time and cost associated with developing and testing several iterations of prototypes prior to production [5, 6]. This gives the benefit of flexibility and capability to perform a large number of “what-if” computations for early evaluation of the occurrences and analysis of the causes, minimizing the risk of the flight test activities, simulating hazardous conditions, evaluating the manufacturing process, and performing capacity analysis
In our research, PREVIEW is used as a software package that displays the developed model and offers a versatile environment that accepts modifications. This will enable new applications and interfaces with tiered solutions that can be easily implemented and eventually provides significant improvement in the reliability, maintainability, and lifetime of the PCB and its components.

This research provides effective methodologies for determining where corrective action may be particularly helpful, and it helps predict the overall system failure characteristics for any given configuration. It helps in identifying components that contribute the most to downtime and in determining the effect of design alternatives on system performance in a cost-effective manner.

2. System and Component Level Lifetime Using Simulation Methodology

Given the need at power plants to predict the performance and remaining lifetime of circuit boards, the feasibility of simulating the lifetime of nuclear electronics at both the circuit card and component scale are investigated. The component time to fail (TTF) data is used to predict the circuit lifetime. The collected time to fail (TTF) data is fitted in the cumulative distribution function (CDF) $F(t)$ to find its best fit distribution using the Kolmogorov Simonov (KS) test as a goodness-of-fit approach [6-8]. (KS) test as a goodness-of-fit approach was preferred to be used due to the following reasons [7,8]: first, it is among the best distance tests for a small number of data points; second, it can be easily computerized and thirdly, it is very versatile; where any continuous distribution can be fit with it.

In this approach, the TTF data for each PCB component is sorted in ascending order, and the empirical cumulative distribution function ($F_n$) is found for each PCB component. Then, Weibull, exponential, normal, and lognormal distribution parameters are estimated in order to find the theoretical cumulative distribution function ($F_0$) for each PCB component [6]. The maximum absolute distance between the theoretical and empirical distributions $|F_0 - F_n|$ is found using one of the mentioned distributions. Depending on the KS logic, the component TTF data set was likely to follow the assumed distribution if the maximum absolute distance between the theoretical and empirical distributions $|F_0 - F_n|$ of that distribution is less than other distributions’ maximum absolute distance $|F_0 - F_n|$. As a result, it represents the best fit distribution of that component TTF data.

After obtaining the best fit distribution, a random number (between 0 and 1) was generated using a Monte Carlo simulation. This number was used as a cumulative probability under a component best fit assumed distribution, to find a new TTF (using inverse CDF) that represents the PCB components’ upcoming time to fail. This methodology for obtaining a new TTF which was presented in our previous work [6] is illustrated in Figure 1.

The lifetime range, including mean, maximum and minimum TTF, is calculated for each component based on the new distribution [9].

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**Figure 1:** Component new TTF: A new time to fail value is assigned to each component of a circuit card based on its data best fit distribution as the predicted lifetime of that component.
A new simulation methodology, which was presented in our recent work [6], is used to predict the life time of circuit boards (see Fig. 2), where the simulation starts with the age of each component. As the time for the next failure for each component equals to any time between the maximum TTF of that component and its current age. If the maximum TTF is less than the age, a new TTF is generated by a random number generator. Once the simulation timer starts, the component with the smallest TTF fails first, resulting in a reduction in the time needed for other components to fail sequentially. After the component with the smallest TTF fails, its position on the card is checked, where connectivity configurations including series, parallel, series-parallel, parallel-series, and bridge configurations are considered. As if the component is a part of a parallel cluster or bridge configuration, then its failure does not stop the operation of the entire card. Connectivity information of a PCB is obtained by directly reading the Standard for Exchange of Product (STEP) model data.

3. System and Component Level Reliability

TTF \( t \) represents the lifetime of the component, where it takes values in the interval \([0, \infty)\) and its probability distribution function is \( F(t) \). \( F(t) \) at a specific time for each component in the circuit board is used; reliability is calculated and assigned for all components as follows [6, 9]:

\[
R_t = 1 - F_t
\]

Components are assumed to have a non-zero age. Thus, the reliability of a component is a conditional reliability based on Bayes’s rule: \( P \) [no failure \((x, x+t)\) | no failure \((0, x)\)]. That is, the reliability after time \( t \) can be determined as follows [6, 9]:

\[
R_{x+t} / R_x
\]
Since one of the simulation outputs is the time of next failure, the reliability probability feature (the empirical distribution function) is used to calculate the reliability of the entire card. Given $N$ data points in ascending order, the failures that occurred at a desired time (or higher) are counted among all replications, and the outcome is divided by the number of replications using the below equation:

$$E_N = \frac{n(i)}{N}$$ (3)

where $n(i)$ is the number of next fail times values that are equal to or greater than the desired time. Figure 3 shows the example card-level reliability for 10 different runs (with 100 replications in each). As shown in the figure, there is a high correlation and small deviation between runs due to the probabilistic nature of our approach, which reflects the validity and precision of the simulation model.

![Card Level Reliability (10 Runs)](image)

**Figure 3**: Card-level reliability over time for 10 different runs

### 4. Sensitivity Analysis

In order to demonstrate the effectiveness of the proposed methodology, sensitivity analysis was performed on a case study example with 133 components and 248 networks (see Fig. 4) to understand the effect of changes in input TTF data on the next fail time of the card.

![The card configuration for the case study in PREVIEW](image)

**Figure 4**: The card configuration for the case study in PREVIEW
Using the developed simulation tool, a deviation in the value of each datum in TTF data was analyzed; where a deviation up to 10% in the TTF input data resulted in approximately 12% deviation in the entire circuit lifetime. Similarly, up to 20% deviation in TTF input data resulted in approximately 23% deviation in the entire circuit lifetime (see Fig. 5).

![Next Fail Range (years)](image)

Figure 5: Sensitivity analysis of the card model: effect of change in the TTF input data on system minimum, mean, and maximum TTF.

In addition to the above analysis results, additional sensitivity analysis on the case study example was also conducted to understand the effect of variability in component ages on the next fail time of the card. Using the developed simulation tool, a deviation in the value of each component age was introduced. A deviation of up to 10% in the components’ age input resulted in an approximately 11% deviation in system TTF. Similarly, an up to 20% deviation in the components’ ages brought an approximately 22% deviation in the output as depicted in Figure 6.

![Next Fail Range (years)](image)

Figure 6: Sensitivity analysis of the card model: effect of change in the ages input data on system minimum, mean, and maximum TTF.

On the other hand, sensitivity analysis was also performed to understand the effect of changes component TTF on system level reliability. Using the simulation methodology, a deviation in the value of each datum in TTF data was analyzed; where a deviation up to 10% in the TTF input data, resulted in approximately 12% deviation in system reliability. Similarly, up to 20% deviation in TTF input data resulted in approximately 23% deviation in system reliability as depicted in Fig. 7.
The results show that error in the components’ condition does not cause significant deviation in the lifetime and reliability of the components or the card, indicating that the simulation tool is a powerful tool for accurate prediction of card failure behavior.

5. Conclusion
In this work, the criteria and methodology of the development of an immersive and high-fidelity virtual environment for lifetime and reliability prognostics for nuclear power electronics were demonstrated. This technology of virtual testing and predictive remaining lifetime and reliability analysis of circuit cards provides support to maintenance engineers in nuclear power plants worldwide.

This research provides a better understanding of prediction of overall system failure characteristics for any given configuration. A new approach to determining component position in the circuit card was illustrated, and the entire circuit lifetime and reliability were found using new simulation failure criteria.

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References

Figure 7: Card-level reliability changes based on changes in the input TTF.