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Generating Realistic Failure Data for Predictive Maintenance: A Simulation and cGAN-based Methodology

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ABSTRACT

Absence of failure data is a common challenge for data-driven predictive maintenance, particularly in the context of new or highly reliable systems. This is especially problematic for system level failure prediction of analog electronics since failure characteristics depend on the actual system layout and thus might change with system upgrades. To address this challenge, this work pursues a novel simulation-assisted failure analysis methodology enabling automated and comprehensive evaluation of system level failure effects and failure detectability. While results obtained from simulations are suitable for comparative studies, they are confined to the simulation environment. To overcome this limitation, failure simulations are combined with generative models to generate realistic representations of missing failure data. Preliminary results demonstrate the capability of conditional generative adversarial networks (cGANs) to generate operational data of healthy systems, which accurately reflects correlations present in the source dataset. The proposed approach, using simulations as an additional source for generative models, not only targets the scarcity of failure data for highly reliable electronic systems but also ensures the adaptability of predictive maintenance algorithms to accommodate future system modifications and upgrades.

1. INTRODUCTION

Data-driven predictive maintenance of analog electronics requires algorithm-based detection of failure precursors in operational datasets containing voltage and/or current signals. However, obtaining sufficient historical failure data to train the algorithms, particularly for high-reliability or novel systems like safety instrumentation, is often a challenge. While manual studies of failure trajectories are feasible at the component level - such as examining discharge curves for capacitors - similar analyses at the system level involve studying numerous failure conditions, since failure characteristics not only depend on the components themselves, but also on their configuration in the system's layout. As a result, common failure trajectories may evolve with system upgrades or new generations, which would require validation or repetition of manual analyses. Hence, overcoming missing failure data requires a more automated approach, allowing exhaustive studies of failure characteristics while being adaptable to system upgrades.

The focus of this work is on developing a comprehensive simulation-assisted framework to establish a predictive maintenance algorithm for analog electronic systems in the absence of failure data. To illustrate this framework, a radiation monitoring electronics system, designed primarily for personnel safety, serves as demonstrator. It continuously monitors ambient dose rates and activates machine interlocks if defined radiation thresholds are exceeded. Given the system's critical role in ensuring safety, it is engineered to transition into a fail-safe mode upon detection of internal faults, initiating interlocks to mitigate risks. Thus, unforeseen failures triggering such interlocks can significantly impair the operational availability of downstream equipment. To address this conflict between safety and availability, the implementation of predictive maintenance based on data-driven failure prediction is proposed.

2. LITERATURE REVIEW AND RESEARCH CONTRIBUTIONS

Limited availability of failure data poses a challenge for failure prediction in industrial equipment, especially in systems with high reliability and preventive maintenance (Rombach, Michau, & Fink, 2023), making failures observed during operation rare. Common approaches to overcome the scarcity of failure data include laboratory experiments to reveal failure modes (Janeliukstis, Ručevskis, & Kaewunruen, 2019), physics-based models incorporating relevant failure processes (Sun, Fan, Qian, & Zhang, 2016), or simulations to evaluate the system's response to failures (Mosleh, Montenegro, Alves Costa, & Calçada, 2021). In contrast, data-driven approaches, typically employing generative methods, eliminate the need for intricate system modeling. (Xiong, Fink, Zhou, & Ma, 2023) use generative adversarial networks (GANs) to extend already available failure data to new, unseen operating conditions based on a physics-informed loss function. While simulations of analog circuits are commonly employed for studies of failure effects (Zhang, Hong, Gao, & Yin, 2021), using simulations as a data source for generative models is currently limited to mechanical systems. (Gao, Liu, & Xiang, 2020) exemplify simulation-assisted data generation in the field of roller bearings, using FEM simulations to generate missing failure data via GANs.

This work explores the potential benefits of incorporating simulation-assisted failure analysis and data generation into predictive maintenance algorithms for analog electronics in the absence of failure data. The key contributions are:

- Utilization of synthetic datasets obtained from simulations to inform decision-making in the development of predictive maintenance algorithms at an early stage
- Generation of missing failure data using simulation-assisted generative methods bridging the gap between the healthy and the faulty domain
- Automated and resource-efficient framework for system level failure prediction in the absence of real failure data

3. Methodology and Preliminary Findings

In the frame of a feasibility study (Waldhauser, Boukabache, Perrin, & Dazer, 2022), unsupervised anomaly detection algorithms were applied to operational datasets of the radiation monitoring electronics system. The study demonstrated the capability of these algorithms to detect unusual data events, such as rare spikes of the dose rate measurement. Although the detected data events are technically anomalies, they are not necessarily related to hardware degradation or faulty behavior. Instead, they may represent atypical yet normal operational behavior. This results in the requirement of introducing knowledge on the system's failure behavior to establish the link between detected anomalies and the system's condition.

Since manual studies of the failure behavior are costly and not adaptable to design changes, alternative, more automated possibilities for acquiring comprehensive failure knowledge need to be explored. Here, simulations of the analog electronics using the SPICE simulation engine can be used to increase the understanding of the failure behavior. Specific failure scenarios are simulated by altering component characteristics, such as gradually reducing the capacitance of electrolytic capacitors. Hence, the impact of these failures on system-level outputs can be observed, facilitating the identification of failure patterns and assessing the detectability of component failures.

Additionally, simulation-derived datasets were used to identify the optimal source of failure knowledge for hybrid anomaly detection algorithms, which incorporate labeled failure data (Waldhauser, Boukabache, Dazer, Perrin, & Roesler, 2023). The results indicated that failure data derived from hardware tests, such as accelerated life tests, proved most beneficial in improving algorithm performance within this synthetic environment. Hence, the findings suggest prioritizing resources towards conducting hardware tests to gather failure data, as opposed to analysis of anomalous data events for failure identification by system experts.

4. Future Work and Research Strategy

The above mentioned studies emphasize the crucial need of understanding the system's failure behavior to refine failure prediction algorithms for identifying patterns indicative of hardware degradation. Failure simulations of analog electronics allowed detailed studies of failure detectability, common failure characteristics, and the generation of synthetic datasets. Although these simulations were suitable for comparative analyses, their utility is inherently limited to the simulation environment. Hence, future research endeavors will focus on bridging this gap between simulated and real datasets to ultimately compensate the missing failure data.

The subsequent phase of research therefore aims at manipulating operational datasets based on simulations to generate synthetic failure data. Here, one possible solution relies on generative artificial intelligence. Initially, a generative model is trained on data representing healthy system states with the objective of reproducing this baseline data. This methodology is then extended to address the generation of realistic failure data by fine-tuning the generative model with simulated failure scenarios without relying on real failure samples.

Preliminary studies with data of healthy states from radiation monitoring electronics containing measurements of internal voltages have demonstrated the capability of Wasserstein conditional generative adversarial networks (WCGANs) to generate synthetic data while preserving the correlations present in the training dataset. For example, WCGANs can accurately capture the relationship between temperature fluctuations and specific voltage signal characteristics. Figure 1 shows the comparison of real and WCGAN generated data for the kurtosis values of the 5 V signal.

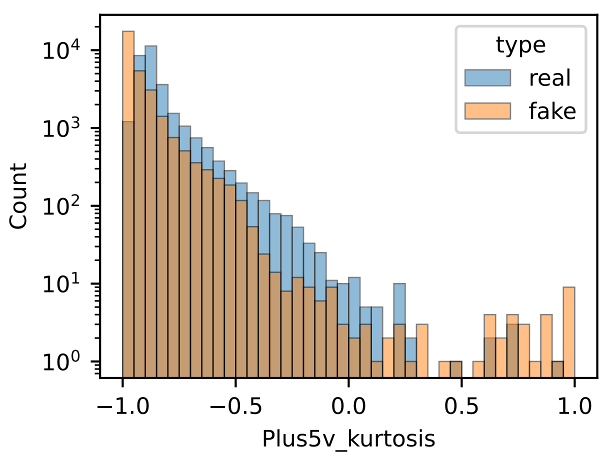

Figure 1. Histogram comparing the distributions of real and WCGAN generated (fake) data for the healthy system state on the basis of 30,000 samples per type. Plus5v_kurtosis is the kurtosis of the 5 V signal, with data normalized.

Ultimately, hardware tests of representative failure states will be required to validate the authenticity of the generated synthetic data. However, this necessitates accurate information regarding the health status of each component. Various options are being considered, including replacing components to replicate changes in their characteristics or inducing localized heat exposure to accelerate aging and confine failures to specific components.

5. Conclusion

The proposed methodology demonstrates a novel approach for developing predictive maintenance algorithms without relying on historical failure data. Simulations serve as additional knowledge source along the development process. This includes identifying detectable failures and generating synthetic failure data that is instrumental for training robust failure prediction algorithms. While hardware-based studies are still relevant, they are complemented by simulation results and limited to representative examples for validation purposes. Besides assisting the generation of missing failure data, comprehensive simulations of failure effects hold significant potential in automating analytical reliability assessments.

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