The Future of Aircraft Maintenance: Goals and Challenges of Digital Twins for In-flight Operations

PHD FORUM SUBMISSION

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***Abstract*—The aviation industry is undergoing a digital transformation driven by Artificial Intelligence (AI), cloud computing, and cybersecurity. Digital twins are a key component of this transformation, but their implementation on resource-constrained in-service aircraft is challenging. This research focuses on developing a power-efficient digital twin framework specifically for predictive maintenance. The process involves (1) building a high-fidelity model, (2) simulating fault data, (3) developing a machine-learning algorithm, and (4) deploying the algorithm. The goal is to improve aircraft maintenance by accurately predicting component failures using a resource-efficient digital twin.**

***Index Terms*—Digital Twin, Predictive Maintenance, Aircraft.**

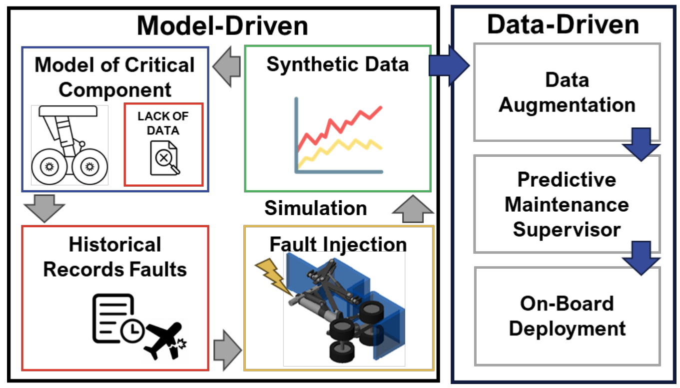

Figure 1: An overview of the proposed framework for the implementation and deployment of an In-flight digital twin for predictive maintenance.

I. Introduction

Digital twins are increasingly gaining traction across various industries, notably in the aerospace sector [1]. A digital twin is a virtual model designed to accurately reflect a physical system, whether natural, engineered, or social. This model is continuously updated with data from its real-world counterpart. It possesses the ability to predict outcomes and supports decision-making that enhances value. A key feature of a digital twin is the two-way interaction between the virtual model and its physical version [2]. The advantages of utilizing digital twins in aerospace applications are numerous, including shortened design cycles, less frequent overhauls, and lower maintenance costs compared to traditional modeling and simulation approaches [3]. The maintenance aspect is especially important due to the extremely long period of the aerospace product life cycle. Incorrect maintenance can seriously jeopardize safety. Despite the significant potential of this technology, it is still largely unexplored, and many challenges must be addressed [2], [4], [5]:

- **Lack of formal definition of digital twin**: At the time of writing, many different definitions of digital twins exist; however, there is no standardized methodology to effectively create a digital twin for Predictive Maintenance in the aircraft domain.
- **Models and Data Availability**: One of the biggest challenges is the lack of publicly available models and datasets due to proprietary restrictions limiting research advancements.
- **Data Imbalance and Quality**: Available datasets used to train and benchmark the proposed machine learning models are commonly imbalanced, skewed towards normal operations with insufficient failure data. This affects the model's ability to learn from and predict rare failure events.
- **Explainability and Uncertainty Quantification**: The increased use of artificial intelligence and empirical modeling in engineering highlights two significant issues. First, there is no standardized method for reporting on model verification, validation, and uncertainty quantification. Second, there is often a lack of focus on how confident we can be in the results these models produce.

These challenges are at the base of the two primary approaches for building a digital twin: the Model-Based approach and the Data-Driven approach. Both have their strengths and weaknesses, and recent trends aim to combine these approaches into a hybrid model to leverage their respective advantages [3]. Starting from these assumptions, the thesis wants to tackle these challenges by developing a hybrid digital twin framework (see Figure 1) delineated as follows:

1) **Develop a high-fidelity model and robust methodology for faulty data simulation**: Creating a model of a critical component of an aircraft to simulate various fault conditions.
2) **Develop a tool for data augmentation**: Facilitate the use of data augmentation techniques to enhance the quality and balance of the dataset, making it accessible

to engineers with strong domain expertise but limited AI knowledge.

3) **Develop and evaluate a Predictive Maintenance supervisor**: Design a predictive maintenance supervisor leveraging state-of-the-art machine learning algorithms, focusing on the explainability and reliability of the proposed solution.
4) **Deployment on Hardware with Limited Computational Power**: Optimize the proposed solution to minimize space and resource requirements during in-flight operations without compromising efficiency and reliability.

By combining these two approaches, we can leverage the decades-long experience of the aeronautical industry with model-based design and high-fidelity software tools such as ANSYS, Autodesk, and Simulink. This integration will facilitate the generation of analytically created and deterministic fault data. Consequently, the deterministic faulty and healthy data will be used to generate data through Generative AI, thereby enhancing the overall quality and reliability of the synthetic datasets.

II. Preliminary Results

Our preliminary work has focused on validating system failure modes through fault simulation as a foundational step toward developing an effective digital twin framework for predictive maintenance. Fault simulation has recently gained attention for its potential to enhance predictive maintenance strategies. However, the field is still in its early stages, and comprehensive fault libraries and standardized methodologies are not yet fully developed. A generic methodology, applicable to different aircraft parts, has been proposed [6]. For our case study, we selected a Landing Gear System. The first step involved selecting this critical component. Following this, we gathered data on common failure modes by reviewing the literature. Additionally, we identified the sensors available on the system to monitor its health. subsequently, given the early state of fault simulation research, we developed specialized fault blocks within Simscape to simulate conditions such as actuator leaks, pipeline wear, and hydraulic supply issues. This custom approach was essential for generating synthetic fault data that emulate real-world scenarios. We collected extensive data through these simulations, meticulously analyzing it to identify patterns and correlations in system behavior under different fault conditions. Our analysis indicated that the framework could effectively simulate fault conditions across multiple domains—mechanical, hydraulic, and control systems—providing a comprehensive understanding of the system's behavior under fault conditions. This multi-domain approach is crucial for accurately representing the complexities of real-world systems. The initial results from these models demonstrated promising accuracy and reliability, suggesting their potential application in real-world scenarios. The fault simulation framework successfully replicated various failure modes, offering valuable insights into the system's resilience and identifying potential areas for improvement.

III. Future Work

Our future work will evaluate how Generative AI, specifically diffusion models, can enhance data quality from past simulations. By leveraging the simulations conducted using the proposed methodology, we aim to generate high-quality and balanced datasets covering major faults in the chosen system. AI-generated data will be based on model-driven equation distributions to ensure accuracy and explainability. This approach will fully exploit the advantages of Model-Based Design, which has a long history and wide acceptance in engineering. The first step will involve generating explainable and reliable data. We will develop a pipeline that engineers with limited AI knowledge but strong domain expertise can easily use, bridging the gap between model-driven and data-driven approaches. Subsequent efforts will focus on creating an explainable predictive maintenance algorithm to monitor the health state. This algorithm will aim to minimize failures and maintenance costs, thereby enhancing the overall reliability of aircraft operations. Finally, we will deploy the proposed solution on hardware with limited computational capabilities. We will explore edge and split computing techniques to minimize space and energy requirements during in-flight operations. For scenarios where the solution needs to operate locally without in-flight connectivity, data gathered during flight can be securely transferred using a secure transfer protocol at the end of the mission [7]. Ensuring robust security against potential threats.

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