Design Of Digital Twins for In-Service Support and Maintenance

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ABSTRACT

This research aims to examine the challenges in developing Prognostics and Health Management (PHM) analytics for Digital Twin (DT) use cases in industrial applications, with a particular focus on Multi-Component Degradation (MCD) scenarios. A hybrid methodology, integrating physics-informed and data-driven models, is employed, using limited asset degradation data for model development. Preliminary work includes an analysis of the impact of data quality on Fault Detection and Isolation (FDI) algorithm performance, as well as the proposal of a weighted ensemble hybrid approach for assets experiencing MCD scenarios Preliminary results indicate enhanced diagnostics in asset health management through the use of Physics-Informed models for FDI in MCD scenarios with limited prior degradation data. Expected contributions for this research are the development of physics-informed PHM analytics for DT applications in MCD scenarios, adaptive PHM analytics for evolving asset lifecycles in DT applications, and interpretable DT model analytics for PHM in systems facing Multi-Component Degradation.

1. Background And Problem Statement

Many high-value complex systems rely on advanced technologies, particularly the Industrial Internet of Things (IIoT), to monitor assets and carry out maintenance activities. Many stakeholders are increasingly turning to data-driven methods to monitor the condition of their assets, with Original Equipment Manufacturers (OEMs) offering various service packages in this regard (Barimah, Niculita, McGlinchey & Babakalli, 2021). These services leverage digital technology, particularly the concept of the digital twin (DT), to enable Prognostics and Health Management (PHM) applications. Digital twins serve as virtual replicas of physical assets (Grieves & Vickers, 2017), enabling operators to monitor, analyse, and predict asset states effectively. According to the Digital Twin consortium, the key capabilities required for digital twin use cases are data services, integration, user experience, intelligence, management and trustworthiness. This provides a framework for tailoring the capabilities of a digital twin for a particular industrial asset. The intelligence capability of a digital twin provides the requirements for enabling prognostic and health management applications. The analytics that drive intelligence in digital twins are constituted by either data-driven or knowledge-based models that provide insights for detection, diagnostics and prognostics for enhanced system reliability and support (Mihai, Yaqoob, Hung, Davis, Towakel, Raza, Karamanoglu, Barn, Shetve, Prasad, & Venkataraman, 2022).

However, developing the analytics that enable intelligence in digital twins (DT) for the full suite of PHM applications ─ detection, diagnostics and prognostics ─ is dogged with a lot of challenges which Compare, Baraldi and Zio (2019) describe in their work. One key challenge is the development of robust analytics for PHM applications, particularly with limited training data and in scenarios where assets are undergoing multi-component degradation (MCD) as part of a larger system. Bayesian approaches have been explored by Lin, Zakwan, and Jennions (2017) where the probability of two components in a fluid system was determined using a Bayesian probabilistic approach. However, there are limitations of this approach especially when compared with data-driven approaches in the MCD scenarios.

Another challenge in developing the analytics for PHM applications for Digital Twins is the evolution of the virtual replica of an asset throughout the asset's lifetime after commissioning and subsequent maintenance actions (Pires, Cachada, Barbosa, Moreira & Leitão, 2019), as various operating factors change the operating state of the asset, whether in a healthy or faulty condition. The complexity that the evolution of an asset throughout its lifecycle introduces in the DT development process presents model performance challenges for the PHM analytics embedded in the DT. Investigating how different DT model frameworks optimize analytics for PHM applications for an asset undergoing MCD scenarios will aid in identifying optimal DT model frameworks in the context of an evolving asset.

Lastly, the adoption of DTs has been increasing steadily in recent times, with data streaming and enhanced visualisation being some of the key selling points. However, the inadequate explainability in the outputs of the analytics capabilities limits the widespread adoption of DT analytics for critical assets (Presciuttini, Cantini, Costa & Portioli-Staudacher, 2024). In most DT applications, data-driven models that support the performance of DTs often train and perform as black boxes relying on the development of model weights which often become less intelligible (Kobayashi & Alam, 2024). Addressing the explainability of DT actions will facilitate the adoption of DTs for PHM applications, particularly for safety-critical systems.

2. Expected Contributions

This research aims to design a scalable online Hybrid-Digital Twin model architecture for IIoT-enabled PHM strategies for in-service support and maintenance applications. The expected contributions for this PhD research are presented below:

1. Development of physics-informed PHM analytics using limited training data for instantiating DT applications in Multi-Component Degradation scenarios.

2. Development of adaptive PHM analytics for evolving asset lifecycles in Digital Twin (DT) applications.

3. Development of interpretable DT model analytics for PHM applications in systems undergoing Multi-Component Degradation scenarios.

3. Proposed Research Plan

The research plan seeks to advance the field of Hybrid-Digital Twins (H-DT) by defining an optimal physics-enabled model architecture for detecting and isolating Multiple Component Degradation (MCD) phenomena in complex systems. The research is based on a well-established testbed (see Appendix) to analyse the dynamic behaviour of a fuel system undergoing MCD scenarios. This hydraulic system comprises critical components, including a main supply tank, and an external gear pump driven by an induction motor. The rotational speed of the motor is regulated by a Variable Speed Drive (VSD). The system also features a solenoid shut-off valve (SHV) and five direct proportional valves (DPV1 to DPV5) for fluid flow control and fault emulation, respectively. Data collection is facilitated by pressure transmitters (P1, P2, P3, P4, and P5), turbine flow meters (F1 and F2), and a laser sensor to measure the pump's speed.

System components are connected using PVC tubing, and a finger valve is used for tank isolation when needed. In the context of fault simulation, specific control valves were manipulated to emulate fault conditions. For instance, DPV1 represented a clogged suction filter, fully open at 0% fault severity, while DPV2 simulated pump discharge side leakage and was fully closed at 0% fault severity. The SHV solenoid valve remained open, and DPV3, emulating a blocked or degraded shut-off valve, was fully open at 0% fault severity. DPV4 represented a clogged fuel nozzle, also fully open at 0% fault severity, while DPV5, simulating downstream pipe leakage, was fully closed with 0% fault severity. The healthy condition operating state of the system's control valves and their associated fault codes, as well as the test degradation scenarios for FDI Model Testing, are shown in the appendix.

The research will address several key objectives and research questions across four main areas:

1. Definition of a Hybrid-Digital Twin (H-DT): The research seeks to define an optimal architecture for H-DT models that meet diverse industry requirements and address MCD phenomena. This involves examining current trends and insights from literature via a systemic literature review.

2. Hybrid-Digital Twin Model Development: This phase involves the development of an online H-DT model tailored for MCD detection in complex systems. Key focus areas include data quality assessment, AI-enabled Fault Detection & Isolation (FDI), selection of hybrid model frameworks, and practical implementation considerations within Industrial Internet of Things (IIoT) systems.

3. System Reliability & Maintenance: The research will investigate the impact of employing an H-DT model architecture on different maintenance approaches, considering various technical, operational, and platform-specific requirements. The economic benefits of using H-DT models for different maintenance strategies will be analyzed.

4. Business Development: Finally, the research will focus on developing API-enabled services using a DevOps approach for the end-to-end implementation of the H-DT model architecture on IIoT platforms. It will explore the technical and business services enabled by an H-DT model architecture for cross-platform applications.

4. Proposed Methodology

The project will use the agile framework to plan various aspects of the digital twin development. A DevOps methodology will be adopted to facilitate the seamless integration and continuous deployment of physics-informed Prognostics and Health Management (PHM) analytics for the hybrid Digital Twin, focusing on components within the designated testbed. The industrial Internet of Things (IoT) platform Thingworx™ will be utilized to craft a user-centric experience (UX) for the digital twin, integrating the physics-informed PHM analytics for each asset through an Application Programming Interface (API) hosted on a remote server. Different physics-informed PHM analytics approaches will then be benchmarked on their performance in predicting multi-component degradation (MCD) scenarios in the context of challenges presented in the background of this report. Bayesian approaches will then be used to develop a trustworthiness framework to address the physics-informed PHM model uncertainty in predicting MCD phenomena. The Hybrid DT model testing and validation will be done using real-time data from the existing testbed and another testbed (proposed) which contains the same assets but in a different configuration. This will help in determining the scalability of the intelligence that underpins the predictive capabilities of the hybrid digital twin.

5. Research Work Done And Preliminary Results

5.1. Data Quality and FDI Model Performance

The relationship between data and predictive analytics was investigated in a recently published paper by Barimah, Niculita, McGlinchey and Cowell (2023). The analysis in this paper used data generated on the testbed described above as well as synthetic data to demonstrate high repeatability by the measurement system of the testbed. In the development of analytics for PHM applications, a lot of emphasis has been placed on data transformation for optimal model development without enough consideration for the repeatability of the measurement systems producing the data. This paper explored the relationship between data quality, defined as the measurement system analysis (MSA) process, and the performance of fault detection and isolation (FDI) algorithms within smart infrastructure systems using components of the testbed described above. The methodology employed starts with an MSA process for data quality evaluation and leads to the development and evaluation of fault detection and isolation (FDI) algorithms.

During the MSA phase, the repeatability of a water distribution system's measurement system was examined to characterize variations within the system. A data-quality process was defined to gauge data quality from the measurement system of the water distribution system. Synthetic data with varying data levels of quality levels was also used to investigate their impact on FDI algorithm development. Key findings reveal the complex relationship between data quality and FDI algorithm performance. The work carried out showed that synthetic data, even with lower quality, can improve the performance of a statistical process control (SPC) model, whereas data-driven approaches benefit from high-quality datasets. The study underscored the importance of customizing FDI algorithms based on data quality and a framework for instantiating the MSA process for IIoT applications, was also proposed for edge analytics which would be considered as part of future work.

5.2. Physics-Informed PHM for MCD scenarios

Optimizing PHM analytics for a system undergoing MCD scenarios using limited data was also investigated in the paper by (Barimah, Niculita, McGlinchey, Cowell and Milligan) and submitted to the PHME2024 conference which is currently under review. This study addresses the challenge of limited degradation data in developing Fault Detection and Isolation (FDI) models for multi-component degradation (MCD) scenarios. Utilizing a small fraction (1%) of the water distribution testbed dataset analyzed in the previous publication, a weighted ensemble hybrid approach was proposed and evaluated against more established modelling approaches. The proposed approach combines heuristic approximation and Physics-Informed Neural Network (Cai, Mao, Wang, Yin & Karniadakis, 2021) methods with a neural network model to enhance diagnostic performance.

The hybrid model generally outperforms other algorithms when tested on an MCD dataset, demonstrating improved diagnostic accuracy in such scenarios. This study contributes to the application of physics-informed FDI models for PHM applications in MCD scenarios, ultimately advancing asset health management. The paper also presents an ensemble FDI approach with the capability of addressing the limitations of integrating both data-driven and physics-based FDI models in multi-component degradation scenarios. Additional research will focus on dynamically optimizing ensemble hybrid model weights, leveraging prediction and model uncertainty to further enhance model performance for PHM applications.

6. Conclusion

In conclusion, this research endeavours to push the boundaries of Hybrid-Digital Twin (H-DT) technology, specifically targeting the challenges posed by Multiple Component Degradation (MCD) phenomena within complex systems. By researching issues of data quality assessment, fault detection and isolation (FDI) algorithm development, and the optimization of Predictive Health Management (PHM) analytics, some strides have been made. By studying data-driven and physics-based models, this research aims to propose a hybrid approach that optimizes diagnostic accuracy in MCD scenarios for PHM applications. The physics-informed PHM analytics developed from this research will improve on the current status quo by developing DT analytics models for PHM applications based on limited degradation data, adaptable in evolving asset lifecycles and intelligible. This will provide a new approach for addressing MCD scenarios aside from the use of classic Bayesian approaches for MCD prediction in the context of limited degradation data. This project will be relevant to industry because it will reduce the requirement for acquiring a lot of degradation data to train their degradation models ultimately reducing the cost of the FDI model development process for complex cases such as MCD scenario.

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