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An Industrial PHM Framework Aimed at Condition-Based Maintenance and Fleet Management of Advanced Jet Trainers

By

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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The integration of equipment operational data into decision-making processes is transforming asset management, laying the foundation for smarter and optimized operations. Prognostics and Health Management (PHM) strategies combine operational monitoring and historical data within a unified framework to assess system behavior and predict future health status leveraging advanced data processing techniques. This approach benefits Original Equipment Manufacturers (OEMs), operators, and maintenance technicians by enabling tailored maintenance planning and increased fleet status awareness. In particular, the implementation of optimized scheduling strategies for maintenance operations facilitates improved asset availability and operational readiness, thereby reducing total operational expenditures and increasing system performance.

The possibility of the integration and development of PHM approaches on historical databases or datasets derived from already operational equipment is one of PHM many selling points. In fact, in this case, the operation of legacy equipment can be enhanced without the need to incorporate new sensors, utilizing the signals already monitored and thus eliminating the need of long and expensive certification phases. The main challenge when dealing with operational equipment is to envision a PHM system able to infer, extract, and interpret operational multimodal data which was not originally and systematically recorded for PHM purposes but that was instead captured for a diverse array of applications, such as Structural Health Monitoring (SHM), control loops, diagnostic purposes, etc. It is then essential to approach the analysis of these sources from an completely different point of view, trying to extract prognostic value from an existing set of signals to analyze prognosable failures. In fact, when a system is prognosable, PHM strategies can be built on existing monitored signals, enabling new capabilities without equipment modification.

However, the effective utilization of PHM strategies on operational industrial data faces considerable challenges, especially in terms of data quality and representativeness. Often, the needed signals are not monitored, sampling frequencies are

insufficient, and data sources are inconsistent or isolated in different siloed databases. Due to the limited coverage of these areas in existing literature, this thesis encounters several challenges stemming from the innovative nature of the questions posed and the lack of comparable studies available. Within this high-risk, high-reward context, this thesis develops a PHM framework utilizing operational, historical, and logistic data from a fleet of Advanced Jet Trainers (AJTs). The study focuses on the Horizontal Tail (HT) Electro-Hydraulic flight control Actuator (EHA) of the AJT, which underwent comprehensive analysis to collect and analyze all relevant data sources.

The research methodology involved an extensive data collection campaign, culminating in an Extraction-Transformation-Load (ETL) pipeline, followed by detailed Exploratory Data Analysis (EDA) to identify data-specific strategies. Algorithms were developed and tested to identify influential features created during feature engineering. In this context, flight clustering was performed to enable mission-informed trend propagation in the future. The features were projected into the future using Monte Carlo simulations and compared against a dynamic probabilistic hazard distribution. This process generated a Probability of Failure (PoF) distribution over time, which was integrated to create a risk trend. This risk trend ultimately drove the maintenance optimization framework, divided between short-term and long-term predictions within an explainable pipeline.

In summary, this thesis positions itself at the interface between industrial challenges and academic advances in PHM for EHAs, with the aim of bridging the gap between deployable solutions and state-of-the-art research. Beyond the methodological contributions, it highlights how a structured PHM framework can provide the foundation for concrete operational benefits, from improved situational awareness to more informed maintenance planning. The concepts and tools developed here provide a foundation for future developments that will further exploit operational outputs, enabling their progressive integration into routine maintenance workflows and flight operations, and their adaptation to different customers, fleets, and mission profiles.