RADemics

Digital Twin Models of Aircraft Systems for Real Time Fault Diagnosis and Post Accident Analysis

Krishna Kumar L, I. Parvin Begum, Asha A
INDEPENDENT RESEARCHER, B. S. ABDUR RAHMAN CRESCENT INSTITUTE OF SCIENCE AND TECHNOLOGY, ST JOSEPH'S INSTITUTE OF TECHNOLOGY

Digital Twin Models of Aircraft Systems for Real Time Fault Diagnosis and Post Accident Analysis

[1]Krishna Kumar L, AI Architect, Artificial Intelligence, Independent Researcher.krishnakumarme@gmail.com

[2]I. Parvin Begum, Assistant Professor, Computer Applications, B. S. Abdur Rahman Crescent Institute of science and Technology, Vandalur, Chennai- 600048 parvinnadiya@gmail.com

[3]Asha A, Assistant Professor, physics, St Joseph's Institute of Technology, OMR, Chennai, asha.nov17@gmail.com

Abstract

Digital Twin technology has transformed intelligent aircraft health management by establishing continuously synchronized virtual representations of physical aircraft systems capable of supporting real-time monitoring, predictive diagnostics, and lifecycle optimization. Increasing aircraft complexity, extensive sensor deployment, and rapidly evolving operational environments demand advanced analytical frameworks capable of integrating heterogeneous data sources into reliable decision-support systems. This chapter presents a comprehensive review of Digital Twin models for aircraft systems with particular emphasis on real-time fault diagnosis and post-accident analysis. The discussion examines the architectural foundations of Digital Twin technology, aircraft system modeling methodologies, sensor networks, IoT-enabled data synchronization, multi-fidelity modeling strategies, and artificial intelligence techniques for adaptive diagnostics. Particular attention is devoted to reinforcement learning, explainable artificial intelligence, predictive maintenance, and prognostics to demonstrate their contribution toward intelligent fault detection, degradation assessment, and remaining useful life estimation. The chapter also explores Digital Twin applications in accident reconstruction through integration of Flight Data Recorder information, avionics data, structural health monitoring records, and engineering simulations for accurate failure sequence analysis and root cause identification. Emerging developments involving cloud-edge computing, cyber-physical systems, secure data communication, and autonomous analytics are critically examined to highlight future research opportunities. The presented framework establishes Digital Twin technology as a fundamental enabler for resilient aviation systems by improving operational safety, maintenance efficiency, diagnostic accuracy, and post-accident forensic investigation across next-generation intelligent aircraft platforms.

Keywords: Digital Twin, Aircraft Health Monitoring, Real-Time Fault Diagnosis, Predictive Maintenance, Reinforcement Learning, Post-Accident Analysis.

Introduction

The aviation industry has experienced a profound technological transformation driven by rapid advancements in digital engineering, intelligent automation, artificial intelligence, and cyber-physical systems [1]. Modern aircraft represent highly sophisticated engineering platforms comprising interconnected mechanical, electrical, hydraulic, structural, propulsion, and avionics subsystems that operate under continuously changing environmental and operational conditions. Every flight generates an enormous volume of heterogeneous data through embedded sensors, flight control computers, navigation systems, engine monitoring devices, communication networks, and maintenance management platforms [2]. This continuous flow of operational information provides valuable insight into aircraft performance, component degradation, system interactions, and environmental influences throughout the aircraft lifecycle. Conventional maintenance approaches have historically relied on predetermined inspection intervals, scheduled servicing, and post-failure corrective actions to ensure operational reliability [3]. Such approaches often fail to capture subtle degradation patterns that gradually evolve during service, resulting in unnecessary maintenance activities or delayed identification of critical failures. Increasing aircraft complexity, stringent aviation safety regulations, and growing demand for operational efficiency have accelerated the transition toward intelligent monitoring systems capable of continuously assessing aircraft health under real operating conditions [4]. Digital Twin technology has emerged as a transformative solution capable of addressing these challenges through synchronized virtual representations that accurately mirror physical aircraft behavior. Continuous interaction between physical assets and computational models enables comprehensive assessment of system performance while supporting predictive maintenance, intelligent diagnostics, operational optimization, and lifecycle management. This technological evolution has fundamentally redefined aircraft health management by shifting maintenance strategies from reactive interventions toward predictive, data-driven, and autonomous decision-making processes capable of improving aircraft reliability, reducing operational costs, and strengthening aviation safety across increasingly complex aerospace environments [5].

Digital Twin technology represents a significant advancement beyond traditional simulation and computer-aided engineering methodologies because it establishes a living digital representation that evolves continuously alongside its physical counterpart [6]. Unlike static engineering models developed primarily for design validation or offline analysis, digital twins integrate real-time operational data, engineering knowledge, mathematical models, historical maintenance records, environmental observations, and intelligent analytical algorithms into a unified computational framework. Continuous synchronization enables virtual aircraft models to accurately reproduce current operational conditions while simultaneously predicting future system behavior under varying flight scenarios [7]. Such capabilities provide maintenance engineers, system designers, and operational analysts with unprecedented visibility into aircraft performance, structural integrity, subsystem interactions, and degradation mechanisms. High-fidelity computational models combined with real-time sensor information facilitate comprehensive understanding of aircraft dynamics across multiple operational stages including taxiing, takeoff, climb, cruise, descent, landing, and post-flight maintenance inspections [8]. Integration of artificial intelligence with Digital Twin technology significantly enhances analytical capabilities by identifying hidden operational patterns, recognizing emerging anomalies, estimating remaining useful life, and recommending optimized maintenance strategies according to continuously changing operational conditions [9]. Increasing adoption of cloud computing, edge intelligence, Internet of Things architectures, high-speed communication networks, and advanced sensing technologies has substantially expanded the practical implementation of Digital Twin platforms within commercial aviation, military aviation, unmanned aerial systems, and aerospace manufacturing. Such developments have positioned Digital Twin technology as a cornerstone of intelligent aviation infrastructure supporting enhanced operational resilience and sustainable aircraft lifecycle management [10].