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Digital Twin Technology in the Full Life Cycle Maintenance and Overhaul of Aviation Engines

Ziyu Zhang

Brunel London School, North China University of Technology, Beijing, China
2379531@brunel.ac.uk

Abstract. With the rapid development of the information industry, technologies such as high-precision scanning and multi-physics field simulation have made continuous breakthroughs, driving the maintenance mode of aero-engines to upgrade from "repair after failure" to "predictive maintenance". Digital twin technology, with its main advantages of virtual-real mapping and real-time interaction, has become an ideal solution in this field. Leading enterprises and airlines at home and abroad have actively carried out related research and applications. Mainstream engine manufacturers and some airlines have achieved mature practical results. The "Full Life Cycle Management" operation and maintenance project jointly developed by China Eastern Airlines and Rolls-Royce is a model of digital twin technology in the full life cycle management of engines. This technology relies on three core enabling technologies: data collection, modeling and simulation, and real-time monitoring, effectively supporting the entire process control of engine design, manufacturing, operation, maintenance, and retirement. However, it also has some drawbacks such as high modeling costs and insufficient data interaction, which can be improved through technical optimization and standard unification. In addition, it also plays an important supporting role in engine supply chain collaboration, precise spare parts management, and the digital transformation of aviation enterprises.

Keywords: Digital twin, Aero-engine, Predictive maintenance, Full life cycle management.

1. Introduction

In recent years, the continuous growth in transportation demand has led to an expansion of the scale of civil aviation transportation. As the core component of aircraft engines, their safety, reliability, and operational costs directly affect the operational efficiency of airlines. Therefore, engine maintenance has attracted much attention in the industry. The traditional engine maintenance model has significant flaws. Regular maintenance can lead to excessive maintenance or maintenance oversights, which can cause irreversible damage to the engine. Post-event maintenance may cause flight delays or even safety accidents, exacerbating the economic losses of the enterprises. The industry urgently needs a maintenance alternative solution that is stable, reliable, economical, and efficient. With the development of information technology, the application of scanning and simulation technologies in the aviation field has driven the iteration of engine maintenance technology. Digital twin technology, leveraging the advantages of the integration of the physical and

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virtual worlds, full lifecycle data connection, and multi-scenario simulation, has become the preferred solution for aircraft engine maintenance. Currently, many aviation engine manufacturers and airlines around the world are conducting related research. This technology establishes data cycles through scanning, integrates measurement and simulation data to accurately identify faults, and has outstanding cost-effectiveness, enabling rapid promotion. The integration of aircraft engines and digital twin technology has achieved remarkable results. Rolls-Royce has accumulated rich experience over three decades, resolving thousands of technical deviations, analyzing over 19 million reports annually, and ensuring the reliability of the Trent 700 series operating engines at 99.9%, with a cumulative safe flight time of over 200 million hours [1]; large airlines such as Lufthansa and Delta Air Lines have also independently carried out related research, and domestic enterprises such as China Aviation Industry Group have also released development plans and held simulation exchange activities [2]. Currently, the integrated application of this technology is increasingly mature, and its importance is becoming more prominent. However, there are still significant limitations. The high investment cost makes it difficult for most small and medium-sized airlines to bear it. Airlines with low profits and small fleet sizes are unable to support long-term high-investment projects and technology leasing. Airlines operating old aircraft cannot obtain corresponding digital services due to engines being close to or already obsolete. In the future, the development direction of this technology in the maintenance of the entire life cycle of aircraft engines may shift to a low-cost and high-safety model.

This article focuses on digital twin technology in aircraft engine full-life-cycle maintenance, covering its theoretical foundation, system architecture, application scenarios, a turbine blade application case, existing challenges, and a summary of achievements, deficiencies and future research ideas.

2. An overview of digital twin and maintenance and overhaul of aero engines

2.1. The foundation of digital twin technology

Digital twin builds a virtual twin model for physical entities via digital means, realizing real-time mapping [3,4], dynamic interaction and full-lifecycle simulation through data connection to monitor, diagnose, predict, optimize and control physical entities. Physical entities are the foundation [5], virtual entities are their precise digital mapping, connection technology bridges the two, data provides core support, and services drive its development for physical entities' full-lifecycle management.

2.2. Aerospace engine maintenance, repair and overhaul - full life cycle analysis

The maintenance, repair and modification (MRO) process of an aircraft engine consists of six steps: health monitoring, fault diagnosis [6], maintenance decision-making, disassembly inspection, component repair and replacement, and assembly testing. This includes real-time parameter monitoring [7], fault location, maintenance planning, component repair or replacement, assembly, test bench testing, and airworthiness release. The maintenance mode includes regular maintenance, condition-based maintenance and predictive maintenance. The combination of these three modes can maximize the service life of the wing [8], reduce the total life cycle cost, and ensure safety [9].

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3. The architecture of the full life cycle maintenance system for aircraft engines based on digital twin technology

3.1. Overall architecture design

The maintenance and support system for the entire life cycle of an aircraft engine based on digital twin can be divided into four layers: the physical layer covers the engine body, sensors, and ground simulation and testing equipment; the data layer is responsible for multi-source data collection, classification processing, integration and storage; the model layer includes geometric, physical, rule and integrated modeling; the application layer realizes health detection and fault diagnosis, remaining life and risk prediction, maintenance decision support, scheme optimization and full life cycle traceability.

3.2. Key enabling technology

The application of digital twin technology in aero-engines relies on three core supporting technologies: multi-source heterogeneous data collection and fusion technology, high-fidelity virtual entity modeling technology [10], and virtual and real-world interaction and data mapping technology. The former integrates and processes diverse data into standardized ones, storing the engine's full-lifecycle data to support its upgrades and maintenance and reduce resource investment [11]. The second achieves 1:1 digital replication of physical entities with high accuracy, integrating multiple physical simulation models to identify potential engine damage early. The third realizes real-time dynamic mapping between physical and virtual entities, ensuring their consistency to enhance simulation accuracy and support full-lifecycle engine management.

4. The specific application of digital twin technology in the entire life cycle of engine maintenance and repair

4.1. In wing maintenance and condition-based maintenance

The operational phase of an aircraft engine refers to the complete cycle from when it is installed and put into use until it is first disassembled for major overhaul. This is the stage with the longest time span and the highest usage intensity during the entire lifecycle, directly determining the operational efficiency of the airline. During this stage, the maintenance and servicing of the engine mainly focuses on maintenance, and there is no need to disassemble the engine. It can be completed on-site at the airport, featuring high convenience, fast response, and minimal impact on flights. The overall cost of this stage is relatively low, mainly consisting of single inspections, parts replacements, troubleshooting, etc., but with high frequency and a large proportion of total expenditure. The core tasks of MRO (Maintenance, Repair and Overhaul) include pre-flight inspection, post-flight inspection, in-flight inspection [12], oil and vibration monitoring, cylinder body inspection, parameter monitoring of the Full Authority Digital Engine Control System, replacement of small components, and rapid fault detection [13]. These ensure that the engine remains in an airworthy condition. The value of this stage lies in maximizing the service life of the engine, reducing unplanned downtime [14], ensuring flight punctuality, and being a key part in controlling the total life cycle cost of the engine.

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4.2. Return for repair and upgrade

Aircraft engine upgrade is conducted after multiple major overhauls and near the end of design lifespan, extending service life through technological improvements and structural reinforcements as a value-enhancing MRO operation. It requires certification from the original manufacturer or authoritative institution, featuring rigorous processes, customized plans, moderate implementation ease, a cycle synchronized with major overhauls without extra time, and a cost between regular overhaul and new engine purchase with outstanding cost-performance. The core maintenance and repair tasks include fatigue life assessment, material upgrading, critical component reinforcement [15], control software upgrade, performance optimization and airworthiness certification. These measures can enhance the durability and economy of the engine, extend the design life [16], postpone the purchase of new engines, alleviate the pressure of fleet renewal, and improve fuel efficiency and reliability. However, the number of service life extensions and upgrade cycles is strictly regulated and not unlimited. Generally, civil aviation engines can undergo 1 to 3 extensions, depending on engine model, manufacturer's technical strategy and operational economic boundaries; most mainstream engines complete the first extension during the second to third major overhauls, significantly increasing in-wing lifespan. A few high-end wide-body engine models can have a second extension to further extend lifespan, requiring dual certification. The third extension is extremely rare, only considered for a few high-value, long-life models when economically feasible, with significantly increased technical risks and costs and irreversible structural fatigue. The number of extensions is limited by thermal end component metal fatigue physical limit, incremental certification and renovation costs per extension, and manufacturer's commercial strategy, making more than three extensions unfeasible in practice.

4.3. Supply chain and spare parts management

Digital twin technology builds high-precision virtual models of the entire aircraft engine and its key components, enabling real-time two-way interaction between physical entities and the digital space. It integrates data from the entire process of design, manufacturing, logistics, and maintenance, providing key support for the intelligent upgrade of supply chain and spare parts management. This technology can promote the pre-collaboration of R&D design and supply chain, and Rolls-Royce, in the Trent XWB engine development, used digital twin to reproduce the thermal stress distribution of the combustion chamber and combined with fiber optic sensors to collect key parameters, effectively shortening the R&D cycle [17]. Meanwhile, digital twins can optimize intelligent manufacturing and supply chain management. Airbus has established a digital twin visualization system for the supply chain, integrating all link data to optimize logistics and inventory, resulting in a 3.2-fold increase in inventory turnover rate. In terms of spare parts management, this technology can accurately predict demand and achieve intelligent inventory scheduling. Rolls-Royce relies on related systems to issue early warnings for component failures. The State Energy Group combines 3D printing to complete on-demand production of spare parts, effectively reducing operating costs. After acquiring the A220 project, Airbus collaborated with IBM to complete a hybrid cloud migration. Without any production interruption, it migrated massive data and virtual machines, promoting the monthly production capacity of A220 from 6 aircraft to 10 aircraft, and optimizing the performance of the core system by 30% [18]. Subsequently, Airbus deployed a globally unified digital twin platform to achieve cross-base data collaboration, and jointly with suppliers, established a virtual supply chain. By 2024, the on-time delivery rate of suppliers was increased to 97%, the inventory turnover rate was raised by 45%, and the new product introduction cycle was shortened by 30% [19].

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5. Case analysis and verification

Rolls-Royce has entered into a long-term TotalCare Life operation and maintenance service partnership with China Eastern Airlines, providing full lifecycle operation and maintenance support for the Trent 700 engines installed on the A330 passenger aircraft of China Eastern Airlines. This service integrates the onboard health monitoring terminal and digital twin model, achieving real-time mapping of the physical engine and its virtual counterpart. Through data collection on operating conditions, performance degradation analysis, and fault prediction, it transforms traditional passive maintenance into predictive condition-based maintenance [20]. By applying this model, the service life of the engines in the wings has been effectively extended, the operational availability and flight dispatch reliability have been improved, and the unexpected maintenance costs and operational risks have been transferred to the engine manufacturer. This has helped airlines establish a cost-controlled, efficient and low-risk asset management system. The A330 operated by China Eastern Airlines has demonstrated through practice that this service has significantly reduced unplanned downtime, optimized the allocation of maintenance personnel and spare parts, and enhanced the operational efficiency of the entire fleet.

Practice has shown that digital twin technology can cover the entire process of engine condition monitoring, fault diagnosis, targeted maintenance, and full life cycle asset management. It is a key technology for promoting the upgrade of the aviation power equipment maintenance support system to be intelligent and lean.

6. Conclusion

The deep integration of digital twins with aircraft engine maintenance and overhaul brings significant advantages. It can promote the transformation of maintenance from reactive and condition-based to predictive and condition-based, integrate all-link data to achieve full life-cycle management, reduce operation and maintenance costs, help extend engine lifespan, and improve operation efficiency and safety. However, it also has some limitations. The initial investment is high, the return period is long, the model reusability is poor, there are safety risks and data confidentiality issues, and the human-machine collaboration is unbalanced. Overall, it is the core support for the intelligent transformation of maintenance. Optimization measures are needed to improve its application.

Digital twin technology has prominent drawbacks in aircraft engine applications: economically, high upfront investment in modeling, sensors and computing power is unaffordable for small airlines, with continuous long-term investment, long return period and insignificant short-term benefits; in scalability, models are mostly single-aircraft customized with poor cross-model reusability; in security, single point failure easily breaks virtual-real mapping, causing insufficient fault identification and false/missed alarms; in confidentiality, core engine data faces cyber-attack risks, imperfect full-chain protection and additional cross-border sharing compliance costs. Corresponding optimizations include hierarchical lightweight modeling, AI-simplified non-critical part modeling and benefit traceability to shorten return period; modular design for cross-model reusability; full-chain encryption, permission levels and operation traceability for confidentiality; and clear human-machine decision-making rights, experience integration and fault-tolerant closed-loop mechanism to optimize model iteration.

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