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Digital Twin-Based Health Management for Complex Aircraft Systems: Case Studies and Applications

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***Abstract*—*Digital Twin technology, initially conceptualized during the NASA's Apollo program, has evolved into a transformative tool for system health management, particularly in aviation. By integrating high-fidelity simulations, real-time sensor data, and predictive analytics, DTs enable significant innovation in Prognostics and Health Management methods. This paper explores the application of DTs in health management for complex aircraft systems, focusing on two critical subsystems: Flight Control Electrical Actuators and Main Landing Gear. Leveraging MATLAB Simscape, modular DT frameworks were developed to simulate these systems under nominal, degraded, and fault conditions. The inclusion of fault injection models enables the generation of realistic datasets to support predictive maintenance, alleviating difficulties in data availability. Two case studies are presented to illustrate the potential of DT-based approaches to reduce downtime, optimizing performance, and enhancing system reliability. This paper provides a comparative analysis of existing DT tools, highlighting their capabilities and limitations in aerospace contexts. While platforms such as MATLAB Simulink and ANSYS Twin Builder offer robust modeling capabilities, operational tools like AVIATAR and IBM Maximo excel in fleet management and predictive analytics. This comparison highlights the need for tailored DT solutions that balance real-time capabilities, scalability, and configurability. This study contributes to the growing body of knowledge on DT technology, offering insights into its role in enhancing aviation safety, efficiency, and sustainability. It serves as a guide for applying DT-based health management, paving the way for broader adoption in next-generation aerospace systems.*

Keywords—Digital Twin, Prognostics Health Management, Aircraft Management.

I. INTRODUCTION

Digital Twin (DT) technology, rooted in NASA's Apollo space program, was initially conceived as a way to mirror and simulate conditions of a space vehicle by using an identical "twin" on Earth [1]. This twin could simulate and predict the state of the mission vehicle in space. Later, in 2002, Michael Grieves formally introduced the concept of DT as a method for Product Lifecycle Management (PLM), envisioning it as a tool for visualizing and managing asset information over its entire lifecycle. Originally, DTs functioned as information systems that visually represent a physical asset's data, and by 2012, NASA redefined DT as a complex, high-fidelity, multi-physics model that leverages historical data, real-time sensor inputs, and physical models to accurately represent the state of its physical counterpart.

DTs have evolved to become integral to Prognostics and Health Management (PHM) systems [2]. They offer significant advantages over traditional PHM techniques by combining data from real-time sensors, expert knowledge, and system history to form a virtual replica of an asset. This replica can forecast the health of systems, estimate Remaining Useful Life (RUL), and support maintenance decisions. DT-driven PHM surpasses conventional PHM by incorporating multiple modelling dimensions, such as behavioral and rules-based modelling, which improve precision and adaptability.

Key DT types include Data-Driven Digital Twins (DDDT) and Model-Based Digital Twins (MBDT) [3]. DDDTs use real-time sensor data to dynamically update the virtual model, making it ideal for real-time monitoring, optimization, and predictive analysis. MBDTs, on the other hand, rely on mathematical and physical models grounded in scientific principles, which simulate a system's performance based on underlying laws of physics. The choice between DDDT and MBDT often depends on the complexity of the system and the specific requirements for predictive accuracy and real-time responsiveness.

Despite their advantages in decision-making, predictive maintenance, safety, and customer experience, DTs face challenges, including data quality, integration issues, and high upfront costs. Achieving accurate and actionable insights requires reliable data and standardized integration across systems. Furthermore, substantial investment in hardware, software, and data analytics is necessary, which can be a barrier for organizations with limited resources. Nonetheless, the potential of DTs to enhance the efficiency, safety, and reliability of mission-critical aerospace systems continues to drive research and application in this field.

This paper aims at providing a fundamental understanding of technical paths of applying DT technologies to distinct aspects of aviation and related solutions. The author includes two potential pathways of DT-based solutions for two complex aircraft systems health management, Electrical Actuator (EA) in Flight Control (FC), and Main Landing Gear (MLG) systems, respectively. The Evaluation on commercial software and customized applications with use case and application circumstances contributes to start-up acceleration of research and development circle.

II. DT-BASED HEALTH MANAGEMENT FRAMEWORK

DT technology has transformed health management for complex systems by enabling real-time, data-driven insights and predictive maintenance capabilities. In the aerospace industry, DTs allow for enhanced monitoring and management of critical systems, reducing unplanned downtime and improving safety.

A. *Opportunities for DT in Health Management*

DT technology holds transformative potential for aircraft system health management by addressing many of the inherent challenges in monitoring and maintaining complex systems.

- **System complexity management:** Aircraft systems are naturally complex, involving numerous interdependent components. Traditional health monitoring methods face limitations in assessing the entire system from individual component data alone. DTs overcome this by integrating data across multiple domains (mechanical, electrical, software) to present a unified, holistic view of system health.
- **Real-Time monitoring and predictive Analysis:** Effective health management for aircraft requires real-time monitoring and analysis to detect anomalies or predict failures before they occur. DTs facilitate this by enabling continuous data collection and processing, using advanced algorithms to predict faults and optimize maintenance schedules. Although computationally demanding, DTs improve responsiveness to potential issues by providing near-instant insights into system conditions.
- **Enhanced data utilization and quality:** DTs address the need for high-quality, accessible data by leveraging historical operational records and real-time sensor input. This ensures that predictive models are built on reliable data, enhancing their accuracy. For systems without substantial operational history, DTs can simulate potential scenarios, providing valuable data for training algorithms even in data-scarce contexts.
- **Improved data security and privacy:** The secure handling of operational data is crucial given the cybersecurity risks associated with data transmission in health management systems. DT platforms are often designed with security protocols that protect sensitive information, ensuring data privacy and security while maintaining the fidelity of health monitoring.
- **Adaptation to environmental stressors:** DTs provide a robust way to account for the harsh environmental conditions aircraft systems endure, such as extreme temperatures, high altitudes, and constant vibrations. By simulating these environmental factors, DTs help in predicting the wear and performance of components over time, thereby enhancing reliability.
- **Compliance with safety and certification standards:** Any health management technology used in aviation must meet stringent safety standards, requiring extensive validation and certification. DTs can accelerate this process by simulating failure modes and maintenance scenarios, providing valuable insights into safety margins without needing repeated physical tests.
- **Cost-effectiveness through proactive maintenance:** While advanced health management technologies can be costly, DTs offer significant returns on investment by optimizing maintenance schedules, reducing unplanned downtime, and extending component life. This balance between cost and benefit is critical in the resource-intensive aviation industry.
- **Interoperability and standardization:** DTs provide a promising solution to the challenge of interoperability, allowing integration with various systems and platforms in aviation. As the industry moves toward standardized health management technologies, DTs offer flexibility and adaptability across different aircraft systems, supporting compatibility.
- **Enhanced training and expertise:** Effective implementation of health management systems relies on the skill and training of operators and maintenance staff. DTs offer valuable tools for training, simulating real-life scenarios that personnel can use to develop diagnostic and problem-solving skills in a virtual environment.

By addressing these challenges, DT technology has the potential to represent a major advancement in aircraft system health management, enhancing the safety, reliability, and efficiency of aviation operations. This multidisciplinary approach, combining technology, data security, environmental adaptation, and regulatory compliance, is essential for modernizing and streamlining maintenance and operational practices in the aerospace industry.

B. *System Architecture*

The DT framework shown in Fig. 1 comprises three primary layers: data acquisition (Raw Cycle), modelling and simulation (Simulation Cycle), and fault diagnosis and prediction (Ready Cycle). Data integration is key activation to the DT framework. By collecting and merging data from diverse sources, including sensor readings, maintenance logs, and operational parameters, the DT can generate a holistic view of system health.

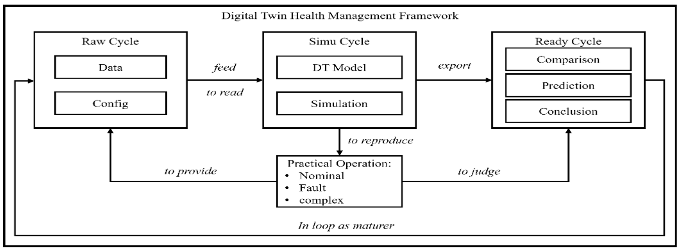


Fig. 1. DT Framework structure with three key cycles.

The data acquisition as Raw Cycle includes and not limited to:

- real-time sensor data from physical systems/architecture
- exist historical recordings
- parameter values from engineering understanding
- processed data from Ready Cycle during initial loops

, which serves as the foundation for accurate digital replicas. After packing database and outline configuration information, the package is proactively fed to or read by Simulation Cycle. In this Cycle, practical operations are reproduced to evaluate operations in static, fundamental, dynamic, complex, and with/without interference situations. The reproduction contributes to generating processed data to support decisioning in Ready Cycle as well as verify the representability of the Simulation Cycle under specified configuration in the Raw Cycle. By harmonizing the three cycles, the accuracy and maturity of the DT can be assessed and improved.

III. EXISTING DIGITAL TOOLS

DT technology has seen the development of several toolboxes and software platforms that support research and development in many disciplines such as aviation, civil, automation and manufacturing. This section provides an overview of widely used tools, including their fundamentals, capabilities, data source and typical use cases, and compares them with the developed models in this study.

TABLE I. categorizes the several types of DTs based on their functional and modeling specifications, offering a comprehensive overview of their diverse applications in monitoring, simulating, and managing complex systems across various domains. Each category reflects a unique approach to system representation, focusing on capturing critical aspects such as structural integrity, dynamic behaviors, and system interactions. This categorization serves as a foundation for understanding how DTs can be tailored to meet the operational requirements and challenges of specific applications, especially in safety-critical systems like those in aerospace.

TABLE I. DT TYPES IN A SUMMARY

Type of DT	*Specification*	*Use Case*
Geometric Model	Kinetic Motion Fluid Power transmission	Single & complex machinery operation monitoring
System Model	Schematic e.g., electrical, mechanical, thermal	System status monitoring and health management
Organization	Finance Human resource Supply chain Relationship	Virtual corporation
Finance	Revenue Expense management Cash flow Budgeting	Finance management

TABLE II. SUMMARY OF SPECIFICATIONS OF DT-RELATED SOFTWARE

Software	*Owner*	*Use Case*	*Industry*	*Type*	*Language*	*HCI*	*Ref*
MATLAB DT/Simulink	MathWorks	Predictive Maintenance	Aviation, Automation	System	MATLAB, Simulink	GUI (Simulink), Scripting Interface	[4][5]
AVIATAR	Lufthansa Technik	Fleet management, Condition monitoring, MRO management, Predictive health analytics	Aviation	System, Organization, Finance	Cloud-Native (Python, Java)	Cloud platform, API Integration	[6]
Digital FinTwin	Keepflying	Fleet management, MRO management	Aviation	Organization, Finance	Cloud-Native (Python, Java)	Cloud platform	[7]
Ansys TwinAI	Ansys	Automation system, Management, Condition monitoring	Aviation, Automation	Geometric, System	C#	CAD Integration	[8]
AMESIM	Siemens	Mechatronic System, Simulation	Aviation, Industrial assets	Geometric, System	C#, Python	CAD Integration	[9][10]
IBM Maximo	IBM	Asset management	Aviation, Industrial assets	Organization	Python, Java, SQL	Web interface, Mobile apps	[11]
Predix	GE Digital	Asset performance, management	Industrial assets	Organization, Finance	Python, Java	Cloud API, Web interface	[12]
Insights Hub	Siemens	IoT Application	Industrial assets	Organization	Java, Node.js, Cloud APIs	Wed interface, Mobile apps	[13]
Unity Reflect	Unity Technologies	AEC Visualization	Civil engineering	Geometric, System	C#, Unity Engine	3D Visualization, VR/AR interface	[14]
iTwin Platform	Bentley Systems	Infrastructural Digital Twins	Civil engineering	Geometric, System	Java, Python, C++	Web interface, Collaborative tools	[15]
DELMIA	Dassault Systemes	Manufacturing operations management	Automation	System, Organization	Python, Java, C++	Cloud platform, CAD Integration	[16]

As summarized in TABLE II. , DT technologies span a range of industries, supported by diverse software platforms tailored for specific use cases and requirements. Each software platform illustrates the expanding role of DTs.

TABLE III. provides a structured overview of the primary tools used for DT modeling, accompanied by representative examples and the foundational skills necessary for their effective use. This classification emphasizes the multidisciplinary expertise required to design and implement.

DT frameworks, particularly for complex applications like aircraft health management. By aligning tools with their respective domains and associated skillsets, the table highlights the constructive collaboration between technical proficiency and tool functionality in achieving robust DT solutions.

Besides the lists, data, as discussed in the previous section, also triggers the thought that despite types of DT, data source and quality should always be key parts when develop and validate DT models.

TABLE III. DT MODELLING TOOL AND ITS WORKING BASIS

DT Modelling Tool	*Example*	*Basic Skills*
Processing Language	Python C# C++ JavaScript	Coding logic
CAD Model	UG NX CATIA SolidWorks	Mechanical engineering
Mathematical Model	MATLAB Mathematics	Mathematics logic
Simulation	AnyLogic Witness	System engineering

IV. DT CASE ILLUSTRATION

This section presents two case studies leveraging Digital Twin (DT) principles to address critical challenges in aircraft systems. Each application underscores the importance of data accessibility, acquisition, and configurability, highlighting the potential for predictive maintenance and system optimization.

A. *Flight Control Electrical Actuator DT*

This section provides practical insights into the development of a DT framework adapted for EMAs in aircraft FC shown in Fig. 2 [17]. Due to the lack of historical data and restricted access to real-time data for non-safety-critical systems, this framework offers a solution to produce reliable simulation data. This data effectively represents EMA operations across various conditions, including nominal, degraded, and faulty states. The work leverages MATLAB SimScape to create a modular, multi-domain representation of the FC EMA on an Airbus A350-900 aircraft. The proposed framework operates by combining high-fidelity simulations with fault injection models, creating datasets that mimic real-world behavior with high-freedom configurability. This approach is applicable for predictive maintenance, where understanding failure patterns is key to optimizing performance and reducing downtime.

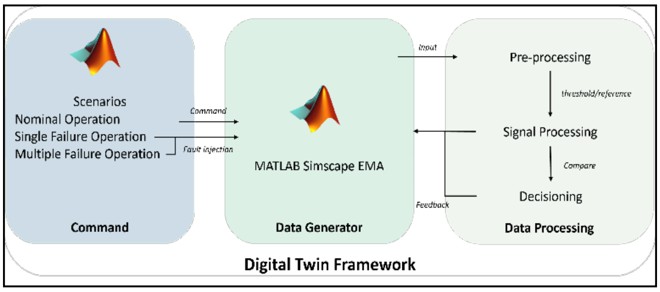
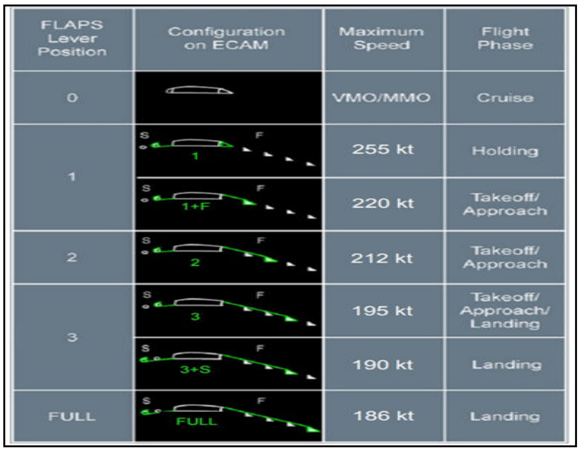


Fig. 2. DT Framework for FC EMA health management

The study defines realistic operational scenarios based on flight phases shown in Fig. 3, such as pre-flight check, take-off, and landing. These scenarios provide an outline for simulating how EMAs behave under varying loads and fault conditions. Faults like unstable voltage supply, mechanical jamming, and electric cable wear are represented through parameterized inputs:

- **F1:** Voltage instability modeled as a multi-step voltage variation below the nominal value, reaching up to 10% below the operational safety threshold of the motor
- **F2:** Mechanical jamming and resistance represented by interconnected reverse torque applied to mechanical transmission circuit of an EMA
- **F3:** Electric cable wear represented by multi-step resistor value above 5 to 10%.

In the Simulation Cycle of the DT model, different scenarios were conducted to represent practical working condition. The scenarios including nominal condition, singular fault condition, dual faults condition, and complex conditions. The model effectively captures EMA performance under nominal conditions, showing a compelling correlation between input and output signals for parameters such as load profile, voltage like in Fig. 4, and leadscrew displacement. This highlights the model's capability to accurately simulate EMA behavior in response to flight control commands.



FLAPS Lever Position	Configuration on ECAM	Maximum Speed	Flight Phase
0		VMO/MMO	Cruise
1	S F 1	255 kt	Holding
	S F 1+F	220 kt	Takeoff/ Approach
2	S F 2	212 kt	Takeoff/ Approach
3	S F 3	195 kt	Takeoff/ Approach/ Landing
	S F 3+S	190 kt	Landing
FULL	S F FULL	186 kt	Landing

Fig. 3. Slats and flaps configuration on Airbus A350-900 [18]

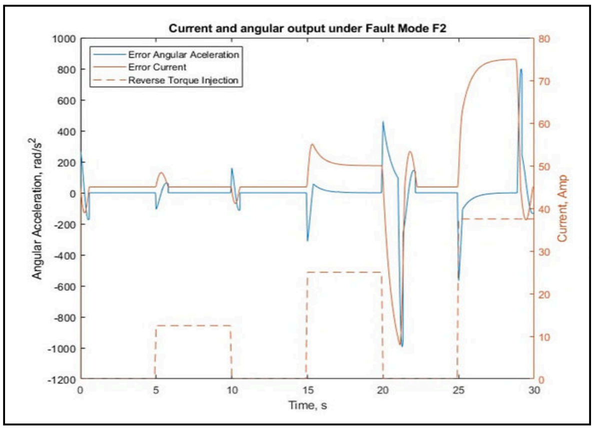


Fig. 4. Current and angular velocity output under fault mode F2 as an example

For readers exploring DT applications in fault diagnostics and system prognostics, the work offers a compelling case study in integrating advanced simulation tools and real-world fault scenarios.

B. Main Landing Gear Force and Torque DT

This section briefly introduces the development towards a robust and optimized sensing simulation model for a representative A320-family MLG System in static condition. This approach aims to consolidate the base of development α version simulator shown as Fig. 5 in the next stage, improving efficiency and accuracy in data acquisition to support landing gear load prediction performance.

The model bases on the geometry configuration referring to the placement of physical strain gauges (SGs) attached to the instrumented MLG. The placement was optimized with FEA analysis to ensure good acquisition performance. The model consists of two independent input elements, a customizable column for inserting a load of aircraft and adjustable roller for Actual Take-Off Weight (ATOW), and six pair output elements for strain gauges labelled from SG01 to SG 12 for individual sub-structural elements. Standard experiment date and Time columns are also created for data stamping and labelling purposes.

LH MLG Ground Loads DT Version α

Input Load of Aircraft

TFW 67.4 68.9 70.4 71.9 73.4 74.9 76.4 77.9 79

Output

Lower Side Stay
SG01 sigma01
SG02 sigma02

Lower Torque Link - shear
SG03 m03
SG04 m04

Lower Torque Link - path
SG05 sigma05
SG06 sigma06

Main Fitting
SG07 sigma07
SG08 sigma08

Sliding Pistion
SG09 sigma09
SG10 sigma10

Centre Wheel Axs
SG11 sigma11
SG12 sigma12

Experiment Date mm/dd/yyyy
Time e.g., 0900

Fig. 5. MLG ground loads (force and torque) DT version α interface

The future plan involves several key steps. First, a detailed test plan will be developed to encompass a range of operational scenarios, including various aircraft weights and center-of-gravity (CG) locations between 25% and 40% of the reference chord, focusing on static conditions. Next, a series of controlled laboratory experiments will be conducted to simulate different load conditions and measure the resulting stresses and deflections. The data obtained from these tests will be used to calibrate the model, ensuring it accurately represents the physical behavior of the landing gear. Finally, the model will undergo validation by comparing its predictions with real-world data, such as flight test results from actual A320 ground operations, which will include data from onboard sensors and ground-based measurement systems.

While this paper focuses on FC EAs and MLG systems, the proposed DT framework has the potential to be extended to other critical aircraft systems, such as propulsion systems, avionics, and environmental control systems. Each of these systems presents unique challenges for DT implementation, including varying failure modes, operational conditions, and data requirements. For instance, propulsion systems, which are critical for both commercial and military aircraft, require robust DT models to predict engine performance degradation and optimize maintenance schedules. Similarly, avionics systems, which are sensitive to environmental stressors, could benefit from DT-based health monitoring to ensure reliable operation in extreme conditions. Furthermore, the adaptability of the proposed DT framework to different types of aircraft, such as fixed-wing, rotary-wing, and UAVs, should be explored. Each aircraft type operates under distinct conditions and constraints, necessitating tailored DT solutions. For example, UAVs, which often operate in dynamic and unpredictable environments, may require DT models that can rapidly adapt to changing conditions. By extending the scope of the DT framework to these systems and aircraft types, the aviation industry can achieve more comprehensive health management solutions, enhancing safety, reliability, and operational efficiency. For different aircraft types, key characteristics remain the similar categories while dominant parameters and values depend on specific type and operational situations.

C. DT Contributions to Health Monitoring

With the development of DT methods, it has the benefit of accelerating the overall Research & Development process in a cycle. Looking back to the NASA Apollo project, establishing a digital twin besides/replace the physical twin could save test rig build-up time, be flexible on setting key parameter acquisition ports, and be secured in data generation, transmission and recording. To evaluate the effectiveness of the proposed DT framework in health monitoring, several key health metrics should be analyzed:

- **Remaining Useful Life (RUL)**: The RUL of critical components, such as the FC EAs and MLG, was estimated based on the simulated fault conditions. The results indicate that the DT framework can accurately predict RUL, enabling Proactive Maintenance and reducing unplanned downtime.

- **Fault Detection Rate**: The DT framework demonstrated a high fault detection rate, accurately identifying faults such as voltage instability, mechanical jamming, and electric cable wear. This capability is crucial for ensuring the reliability and safety of aircraft systems.

- **Mean Time Between Failures (MTBF)**: The MTBF for the simulated systems was calculated, showing a significant improvement in system reliability when the DT framework was used for predictive maintenance.

- **Maintenance Cost Reduction**: By optimizing maintenance schedules and reducing unplanned downtime, the DT framework contributed to a significant reduction in maintenance costs.

These health metrics highlight the potential of the proposed DT framework to enhance the safety, reliability, and efficiency of aircraft systems, providing valuable insights for both academia and industry.

V. CONCLUSION

This paper presents a detailed investigation into the application of Digital Twin technology for the health management of complex aircraft systems. By leveraging modular, high-fidelity frameworks developed in MATLAB Simscape, the study contributes to:

- Development of a Modular DT Framework: This paper presents a modular, high-fidelity DT framework for health management of complex aircraft systems, specifically focusing on Flight Control Electrical Actuators and Main Landing Gear systems.

- Fault Injection Models: The proposed framework incorporates fault injection models to simulate realistic failure scenarios, enabling the generation of datasets that support predictive maintenance and fault diagnostics.
- Comparative Analysis of DT Tools: A comprehensive comparison of existing DT tools is provided, highlighting their capabilities and limitations in the context of aerospace applications.

Despite the promising results, several challenges remain, including the computational intensity of high-fidelity simulations and the need for seamless integration with existing operational workflows. Future research should focus on enhancing real-time capabilities, optimizing computational efficiency, and developing standardized frameworks to facilitate broader adoption across the aerospace industry.

While the proposed DT framework offers significant advantages in terms of predictive maintenance and fault diagnostics, it is important to acknowledge the high computational demands associated with high-fidelity simulations. To mitigate these challenges, future research should focus on optimizing the computational efficiency of DT models. One potential approach is the use of reduced-order models (ROMs) that simplify the system dynamics while maintaining sufficient accuracy for health monitoring purposes. Additionally, leveraging cloud-based computing resources and distributed computing architectures can help alleviate the computational burden, enabling real-time processing of large datasets. Furthermore, the integration of machine learning algorithms, such as neural networks, can enhance the predictive capabilities of DT models while reducing the computational load. By addressing these computational challenges, the proposed DT framework can be more effectively integrated into operational workflows, ensuring scalability and real-time responsiveness.

The findings contribute to advancing the state of the art in DT-based health management, providing a roadmap for integrating this transformative technology into next-generation aerospace systems. The work emphasizes the critical role of DTs in enabling Proactive Maintenance, reducing downtime, and ensuring the safety and reliability of mission-critical operations.

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