Operational Digital Twins: A Vector Toward the Next Generation of Aerospace Systems

Jack Thompson
President & CEO, JTE Systems, LLC., Madison, AL, USA

Dr. Alex Bendoyro
Space Nuclear Systems Engineer, JTE Systems, LLC., Madison, AL, USA

R. Paul Lewis
Systems Architecture Director, JTE Systems, LLC., Madison, AL, USA

Abstract

On 28 January 2025, an F-35A aircraft operating out of Eielson Air Force Base experienced a catastrophic failure following a series of in-flight troubleshooting efforts. The aircraft, miscued by faulty Weight on Wheels (WoW) sensor inputs caused by frozen hydraulic struts, transitioned into an "on-ground" flight control law while airborne. This rendered the aircraft uncontrollable, forcing the pilot to eject. While no lives were lost, the incident resulted in the destruction of a $196.5 million aircraft and highlighted a critical vulnerability in modern flight control systems: the aircraft's inability to reliably determine its own operational state. Or more simply, the incident aircraft did not know it was flying.

This incident is not isolated, and is emblematic of a broader, systemic issue in aerospace systems—one that has persisted across generations of aircraft. The reliance on brittle sensor fusion architectures and increasingly complex control logic has led to systems that are difficult to diagnose, expensive to modify, and prone to cascading failures. As aircraft become more software-defined, the complexity of integrating new sensors and validating control laws grows exponentially, often outpacing the ability of maintainers and designers to keep up.

To address this, we propose an evolutionary shift in flight control system architecture: the integration of a real-time Digital Twin onboard the aircraft. This digital twin would simulate the aircraft's physical state, mission context, and environmental conditions in parallel with reality, enabling the aircraft to "understand" its operational status beyond raw sensor inputs. Rather than relying solely on sensor fusion, the digital twin would provide a model-informed validation layer that cross-checks sensor data against expected behavior, physics-based models, and mission parameters. This approach would provide a robust solution to an otherwise brittle sensor fusion methodology that lacks comprehensive and repeatable awareness of the system's true state.

This onboard architecture would be built using a Modular Open Systems Approach (MOSA), enabling interoperability with existing and emerging standards such as the Sensor Open Systems Architecture (SOSA) and other compatible frameworks. MOSA ensures that the digital twin can be integrated with legacy systems, upgraded incrementally, and extended across platforms without proprietary lock-in. By leveraging open standards, the architecture supports plug-and-play sensor modules, scalable computing environments, and secure data exchange protocols.

A ground-based digital twin architecture would concurrently mirror the onboard system, ingesting real-time telemetry and operational data to inform a range of downstream applications. This land-based twin would serve as a feedback mechanism for manufacturers and designers, enabling predictive maintenance, accelerated design iteration, and enhanced fleet planning. In a military context, it could support mission operational planning, pre-positioning of aircraft and maintenance assets, and dynamic risk assessment. The integration of these concurrent Digital Twin systems would create a continuous digital thread from design to deployment, operation, sustainment, and retirement.

The F-35 incident illustrates the consequences of a system that lacks self-awareness. A digital twin architecture, informed by MOSA principles and supported by compatible open standards, offers a path forward. It shifts the paradigm from reactive troubleshooting to proactive system intelligence. It reduces reliance on brittle sensor fusion and mitigates the risks of software complexity. Most importantly, it enables aircraft to not only know what it is doing, but to understand as well.