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On the Development of Digital Twins for Spacecraft Operations: European Space Operation Centre (ESOC) Current Status and Vision

Federico Antonello[a]*, Daniele Segneri[b], James Eggleston[c], Klara Widegård[d]

[a] *European Space Operations Centre, European Space Agency, Robert-Bosch-Str. 5, 64293, Darmstadt, Germany,* *Federico.antonello@esa.int*
[b] *European Space Operations Centre, European Space Agency, Robert-Bosch-Str. 5, 64293, Darmstadt, Germany,* *Daniele.segneri@esa.int*
[c] *European Space Operations Centre, European Space Agency, Robert-Bosch-Str. 5, 64293, Darmstadt, Germany,* *James.eggleston@esa.int*
[d] *European Space Operations Centre, European Space Agency, Robert-Bosch-Str. 5, 64293, Darmstadt, Germany,* *Klara.widegardd@esa.int*
* Corresponding Author

Abstract

A Digital Twin (DT) is a self-evolving virtual replica of a physical asset, capturing its exact state at any moment. It enables bi-directional data exchange, offers enhanced insights into spacecraft health conditions, and serves as a foundation for automation, Artificial Intelligence (AI) applications, and decision-making. In this light, the development of DT solutions for spacecraft operations represents a pivotal step in the digital evolution of space systems, which has the potential to enable high-fidelity simulation capabilities, enhance mission situational awareness, facilitate validation of procedures, automate operational processes, and favour predictive maintenance, to mention a few.

This paper reflects on the needs and challenges for developing DTs for spacecraft operations, with a particular focus on the European Space Operation Centre (ESOC) current status and vision for future developments.

Keywords: Digital Twins, Spacecraft Operations, Advanced Simulations, Prognostics and Health Management, European Space Agency

1. Introduction

A Digital Twin (DT) is a self-updating virtual model of a physical asset, capturing its exact state in real-time. It enables two-way data exchange, provides insights into spacecraft health, and supports automation, AI applications, and decision-making. Developing DT solutions for spacecraft operations is crucial for the digital evolution of space systems. Benefits include high-fidelity simulation, improved mission awareness, procedure validation, automated processes, and predictive maintenance [1].

The concept of Digital Twins (DT) for asset operations has been thoroughly researched and implemented across various industries, leading to numerous use cases that demonstrate the potential benefits of this technology. The following sections offer an overview on DT application to various industries.

1.1. Digital Twins in Healthcare industry

Digital Twins for Healthcare are an emerging technology that offers opportunities for personalized healthcare, tailored to the individual characteristics, needs, and preferences of a patient [2]. Predictive interventions, based on simulations and predictions generated by the digital twin model, are designed to anticipate potential health issues before they become critical, thus allowing for tailored treatments [2-3]. Remote monitoring involves the continuous collection and analysis of a patient's health data from a distance, providing real-time insights and timely interventions. DTs for personalized medicine integrate features from each individual, such as digital phenotypes, with real-world data generated digitally via smartphones or other connected devices to form a deep digital phenotype. This comprehensive data may include information on individuals' lifestyles, psychological states, socio-demographics, and environmental factors, influencing the success or failure of therapeutic strategies. Furthermore, while some digital twins target specific organs or diseases, others offer general products that may enhance overall personalized health and wellness [2-3].

1.2. Digital Twins for asset management and maintenance

Asset management and maintenance are critically enhanced by Digital Twin (DT) technology, which facilitates real-time monitoring of physical assets, significantly reducing the likelihood of unexpected failures through predictive maintenance [4]. This technology has demonstrated substantial potential in improving maintenance planning accuracy, thereby enabling more efficient resource utilization and minimizing operational costs. Particularly in civil infrastructures such as bridges, dams, and buildings, DT technology proves invaluable [4]. Sensors deployed on these structures continuously collect data on vibrations, temperature, and structural movements. This data provides real-time insights, allowing for proactive measures like inspections, repairs, or reinforcements before issues escalate. Such continuous monitoring and timely interventions ensure the safety and longevity of civil infrastructures, preventing catastrophic failures and reducing repair costs.

1.3. Digital Twins in Aerospace industry

Historically, the first example of DT is the application in aerospace operations. DTs offer numerous advantages, from enhanced performance monitoring, leading to improved forecasting, just-in-time inventory planning, and the ability to predict and control performance drift [5]. This process provides valuable feedback to operators, thereby optimizing overall performance. DT capabilities include also failure prediction and predictive maintenance, allowing for the detection of impending failures and the adaptation of operations to extend the lifespan of components [6]. This approach mitigates catastrophic failures through graceful degradation and reduces downtime by optimizing part availability. Furthermore, modelling and simulation of assets enable the assessment of current operating contexts and offer recommendations to minimize consumables usage while assuring and optimizing health status [5]. In-depth failure analysis, including root cause analysis based on detailed operational data, significantly reduces downtime and enhances reliability. End-of-life decision aids evaluate the conditions of parts and components, facilitating informed decisions regarding reuse, reconditioning, recycling, or disposal, taking into account historical operational environments. Operational trade-off analysis is another critical aspect, enabling the evaluation of the impact of different operational choices. This allows for the prioritization of performance versus endurance based on specific mission or market conditions. Finally, data integrity is maintained through the detection of anomalies in measured data, ensuring the operational integrity and resilience of systems against defects or tampering [6]. These capabilities collectively contribute to the advancement of aerospace operations through the integration of digital twin technology.

1.4. Digital Twins in Automotive and Autonomous Driving

The automotive industry is increasingly leveraging Digital Twin (DT) technology to revolutionize vehicle development and optimization processes [7-8]. Key benefits derived from DTs include increased productivity, reduced complexity, time savings, reduced costs, and improved quality. DTs generate valuable information that may not be readily available in real-world environments, thus enhancing the design and operational phases of automotive products. Once a physical counterpart exists, a DT offers i) functional representation of a vehicle based on model-based systems engineering; ii) efficient design and fault detection, contributing to enhanced vehicle reliability and performance; iii) a testbed for scenario simulations, significantly reducing time and costs during the testing phases and future design and development stage; iv) Virtual Reality Twins (VR twins) to provide visual aids for simulation, rendering, and optimization of manual assembly tasks on the vehicle, immersive visualization of complex assembly operations, improving accuracy and reducing errors; and v) a digital representation of the vehicle's end-of-life cycle [7-8]. Such capabilities have generated unprecedented opportunities for the design and testing of intelligent automobiles, testing under extreme conditions, leading to safer and more effective vehicles while reducing the cost of complex physical test setups. Additionally, continuous data processing allows for the quantitative evaluation of vehicle performance parameters. As artificial intelligence is further integrated into this framework, it will become feasible to assess current scenarios and accurately predict future electric vehicle performance metrics.

1.5. Considerations

The aforementioned overview has elucidated the benefits and use cases of digital twin technologies. The critical aspects present across all industry applications are:

1) simulations of scenarios for training and situational awareness, as well as validation of operations and planning, which are instrumental in preparing for unforeseen events and making informed decisions;

2) interaction with data and information through immersive environments, thereby revealing otherwise hidden knowledge and health insights and providing a more in-depth understanding of complex systems;

3) prognostics and health management, facilitating failure and anomaly detection, diagnostics, root cause analysis, and the prediction of future behaviors and anomalies, thus enhancing system reliability and mitigating the risk of unexpected failures;

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4) automation and assistance in operational processes, identifying corrective actions and recovery procedures from failures and anomalies, and formulating optimal plans to achieve set objectives, ultimately leading to more efficient and effective operations;

5) assessment of the remaining useful life of systems and components, along with the optimization of operations to prolong the lifespan of assets, ensuring maximum operational efficiency and sustainability.

This remaining of the paper reflects on the technological aspects, the needs and challenges for developing DTs for spacecraft operations, with a particular focus on the European Space Operation Centre (ESOC) current status and vision for future developments.

2. Digital Twin for Spacecraft Operations: Features and Vision

Figure 1 reports four key features envisioned for the Digital Twins for Spacecraft Operations:

1) Enhanced simulation engine for procedure test and validation, scenarios investigation and planning. This feature allows connecting the digital twin to the mission operation infrastructure and allow users to leverage the advanced simulation capabilities of the digital twin for the preparation of a mission.
2) Enhanced situational awareness. This feature makes use of monitoring data from telemetries and telecommands to align simulation models to actual spacecraft conditions, augmenting representativeness of the simulations and proving health insights of components condition, degradation and on the status of consumables (e.g., battery state of change and capacity, fuel level, thermal budget, etc.).
3) Enhance visualization and XR representation. This feature provides immersive interaction with data and information, allowing users to easily retrieve information, locate health insights and out-of-limits and simplifies the identification of representative telemetries describing undergoing systems behavior.
4) Enhanced analytics, health management and prognostics. This feature takes advantage of situational awareness, data, knowledge and simulation capabilities provided by the above features and uses AI and computational models to allow for failure and anomaly detection, diagnostics, root cause analysis, and the prediction of future behaviours, identifying corrective actions and recovery procedures from failures and anomalies, and formulating optimal plans, assessment of the remaining useful life of systems and components, along with the optimization of operations to prolong the lifespan of assets.

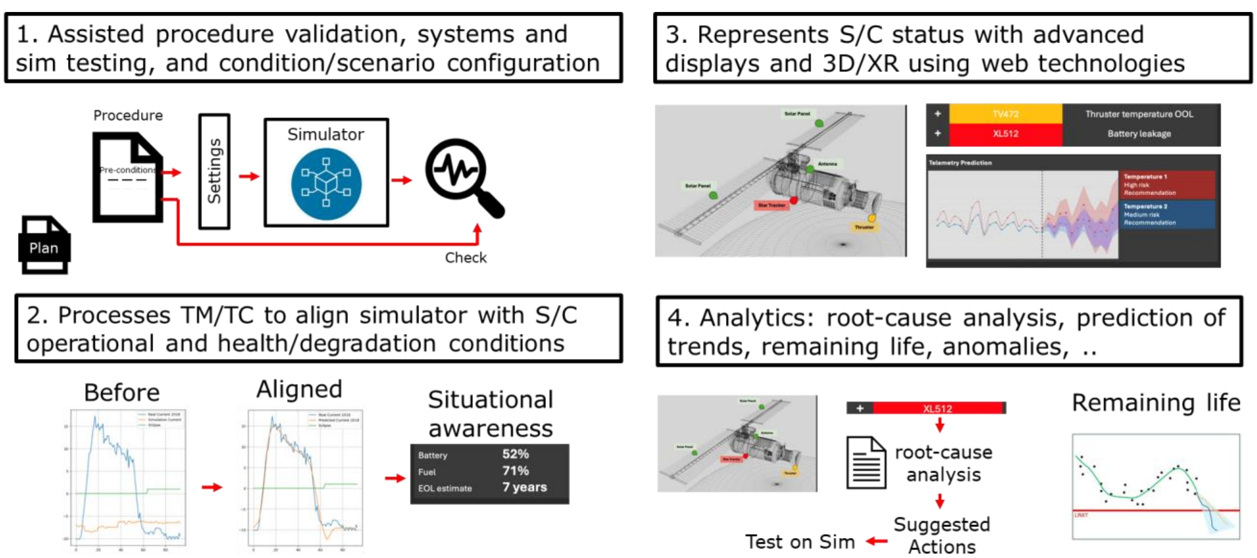

Fig. 1. Key features envisioned for the Digital Twins for Spacecraft Operations

3. Digital Twin for Spacecraft Operations: Architectural Components

To achieve the aforementioned objectives and features, the following architectural components have been identified and are illustrated in Figure 2. It includes *i*) Digital Twin Architecture, which consists of all the features needed to support the architecture, the digital continuity and the links with the mission operation infrastructure; *ii*) Digital Twin

Simulation Engine, which includes the advanced simulation and modelling features to enable DT capabilities; and *iii*) Suite of applications for advanced analytics, health monitoring and planning, which consist of the set of AI and computational tools to support operations.

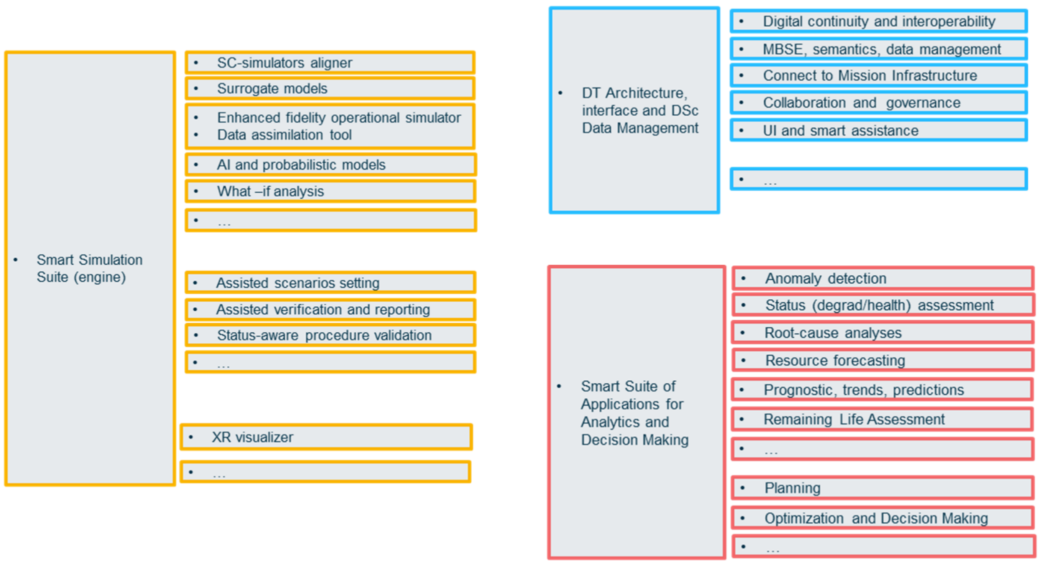

Fig. 1. Architectural Components of Digital Twins for Spacecraft Operations

4. ESOC current status

The European Space Operations Centre (ESOC) is currently in the process of defining the architectural components for its Digital Twin (DT) development. This includes the prototyping of advanced features to be integrated into existing operational simulators, aiming to enhance their fidelity and situational awareness. Enhanced synchronization and calibration techniques have been implemented within simulation models, leveraging state-of-the-art methods such as optimization based and Bayesian calibration with model discrepancy reduction to better represent in-flight conditions with accurate simulations and confidence intervals.

Additionally, ESOC has been at the forefront of prototyping tools for health management and prognostics. Noteworthy examples include a tool designed for assessing solar arrays degradation and predicting future system performance using Machine Learning algorithms and predictive analytics. This tool has proven instrumental in operations, providing insightful predictions of power production drops up to two years in advance using time-series analysis. Furthermore, tools for estimating the remaining useful life (RUL) of systems have been developed, utilizing physics-based models and data-driven approaches, enabling more informed decision-making and the optimization of spacecraft operations through predictive maintenance and anomaly detection.

5. Conclusion

In conclusion, the development of Digital Twins (DTs) for spacecraft operations represents a significant advancement in the digital evolution of space systems. The integration of DT technology offers numerous benefits, including enhanced simulation capabilities, improved situational awareness, and advanced health management and prognostics. These features collectively contribute to more efficient and effective spacecraft operations, enabling high-fidelity simulations, predictive maintenance, and automated operational processes.

The European Space Operation Centre (ESOC) has made substantial progress in this domain, reflecting a strong commitment to leveraging DT technology for future developments. The current status and vision outlined in this paper highlight the potential of DTs to revolutionize spacecraft operations, providing a robust foundation for automation, Artificial Intelligence (AI) applications, and informed decision-making.

As the technology continues to evolve, it is essential to address the challenges and needs identified in this paper to fully realize the potential of DTs in spacecraft operations. Continued research and development, along with collaboration across the industry, will be crucial in overcoming these challenges and achieving the envisioned advancements.

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