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# Digital Twin for Satellite Operations

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## Abstract

In the rapidly advancing field of satellite technology, ensuring the reliability and efficiency of satellite missions remains a paramount objective. This paper presents EnduroSat's innovative development of a satellite digital twin, a high-fidelity virtual replica of satellite systems designed to aid mission analysis, validation of procedures and anomaly investigations. The concept behind the digital twin is to mirror the satellite's physical counterpart, offering an integrated service that simulates its behaviour and responses to various scenarios.

One of the primary functionalities of the EnduroSat digital twin is the validation of upcoming satellite operations. By inputting the current state and planned mission operations into the digital twin, the operations team can comprehensively assess the feasibility and potential outcomes of these operations before they are executed. This is especially useful in the case of contingency operations, where circumstances such as a collision warning may mean that the primary mission must be interrupted.

In addition to operational validation, the digital twin plays a crucial role in anomaly management. When the satellite encounters unexpected events or deviations from nominal behaviour, the digital twin provides a virtual testing environment where these anomalies can be replicated and analyzed. This allows engineers to trace the root causes, evaluate the impact, and develop corrective actions swiftly and efficiently. Consequently, the digital twin enhances the diagnostics process and shortens the response time to anomalies, leading to increased mission resilience and reduced downtime.

The digital twin's capability to consistently provide an up-to-date status of the satellite and planned operations facilitates a more dynamic and informed decision-making process. This paper discusses the architectural framework of EnduroSat's digital twin, detailing the core components and technologies leveraged to achieve high fidelity and real-time synchronization. We also highlight case studies where the digital twin has been deployed in operational scenarios and how this can aid the automation of satellite operations in doing so.

In summary, EnduroSat's satellite digital twin represents a groundbreaking advancement in satellite operations and anomaly management. Its predictive analytics and real-time simulation provide a robust tool for ensuring mission success and safeguarding satellite investments. With this paper, we aim to contribute to the space operations community by sharing valuable insights and advancements in digital twin technology, promoting its adoption and further development across the industry.

**Keywords:** (Digital Twin, Automation, Anomaly Detection, Simulation, Cloud Architecture)

## 1. Introduction

As software plays a greater role in the space industry, automating many of the processes that would previously have been done manually, there is a great opportunity to extend this automation to spacecraft performance analysis.

Within this context, digital twins have become an increasingly popular concept. A digital twin—often described as a high-fidelity virtual replica of a physical system—enables engineers and operators to assess performance, validate scenarios, and diagnose anomalies using real or simulated data without risking physical hardware.

The concept of digital twins originated in advanced manufacturing and the automotive sector, where virtual replicas provided critical insights for product lifecycle management. [1] Over time, the aerospace sector recognized the significant cost and risk associated with space missions and began adopting digital twin techniques to simulate and validate spacecraft design, operations, and maintenance.

This paper presents EnduroSat’s satellite digital twin: a near-real-time virtual representation of a satellite’s hardware and software systems. By accurately mirroring the satellite’s physical and functional characteristics, the digital twin enables a more dynamic, informed, and efficient approach to operational validation and anomaly management. Through predictive analytics, the digital twin anticipates potential issues and streamlines contingency procedures. Furthermore, this virtual environment allows engineers to replicate anomalies and evaluate solutions rapidly, reducing satellite downtime while safeguarding mission investments.

## *2.* Use cases

### *2.1 Operational Validation*

High-fidelity simulators have historically been used in space operations to refine procedures before deployment. Operators can test maneuvers, command sequences, or firmware updates in the virtual environment, then commit only when the simulation demonstrates safe and reliable behaviour. However, these have often required a large amount of configuration and preparation, with specialist operations engineers needed to correctly operate the simulator. The EnduroSat Digital twin allows for the simulation to automatically populate the run with contextual information from the operations environment and permit multiple simulation runs with different scenarios to be run in parallel.

### *2.2 Predictive Maintenance and Anomaly Detection*

Detecting hardware or software malfunctions early is paramount for satellites. Digital twins enable predictive maintenance through continuous comparison of simulated states with real-world telemetry. [2] With the rise of Artificial Intelligence Applications both on-board and ground, there is a huge potential in providing large amounts of simulated data for training data and for real-time anomaly detection.

### *2.3 Operations Preparation*

To evaluate system budgets that have been created from the mission analysis tools, the digital twin can be used to run multiple scenarios to identify suitable limits to parameter in the automation sequences. These could be identifying duty cycle constraints or evaluating satellite performance during contingency situations. The ability to identify the systems budgets in both an analytical and statistical way using accurate propagation of detailed subsystem interaction can help by making sure that certain edge-cases are captured before operations.

## *3.* EnduroSat’s Digital Twin Architecture

EnduroSat’s digital twin framework focuses on three major components (Fig. 1):

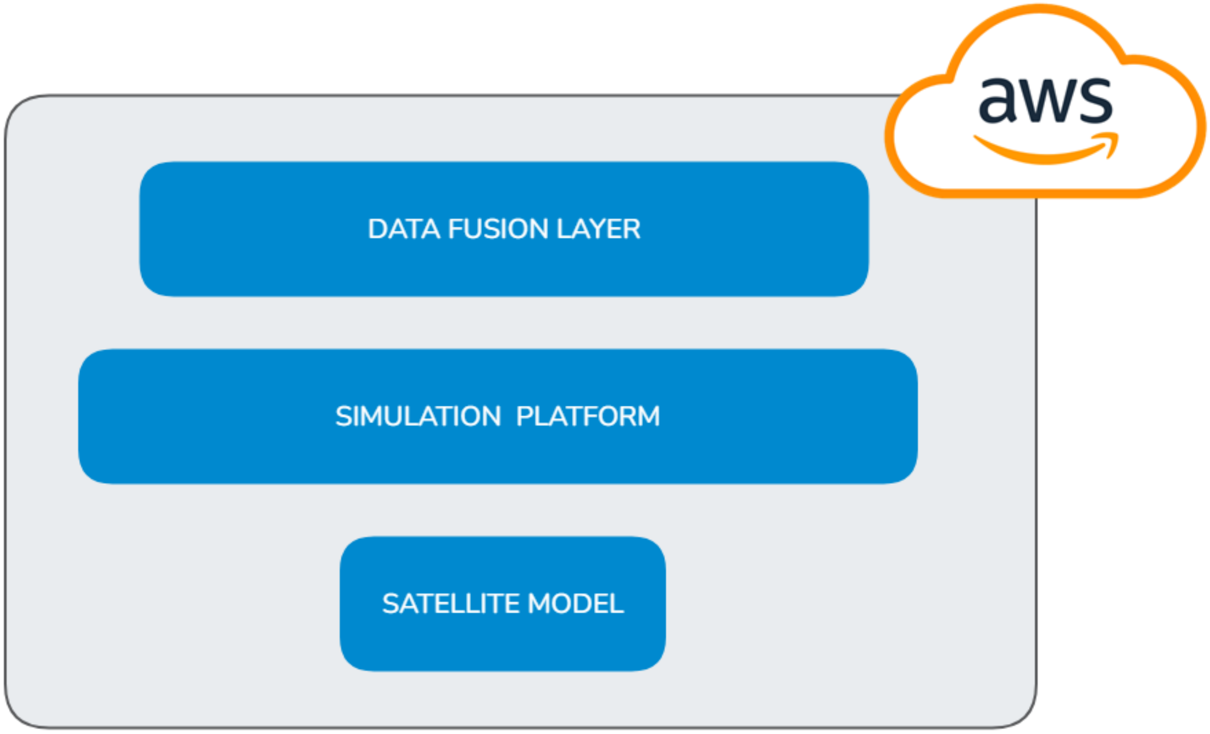

Fig. 1. EnduroSat's Digital Twin Architecture

### *3.1 Cloud-Based Simulation Platform*

The cloud-based simulation platform is the basis for developing and maintaining a sophisticated satellite digital twin, offering the scalability and integration required to handle complex, real-time operations. Scalability is a fundamental requirement, enabling the platform to support numerous concurrent simulations simultaneously. This capability ensures that multiple scenarios can be tested and analyzed in parallel, facilitating rapid iteration and validation of various operational strategies without performance bottlenecks. By leveraging cloud infrastructure, the platform can dynamically allocate resources based on demand, ensuring seamless scalability as simulation needs grow.

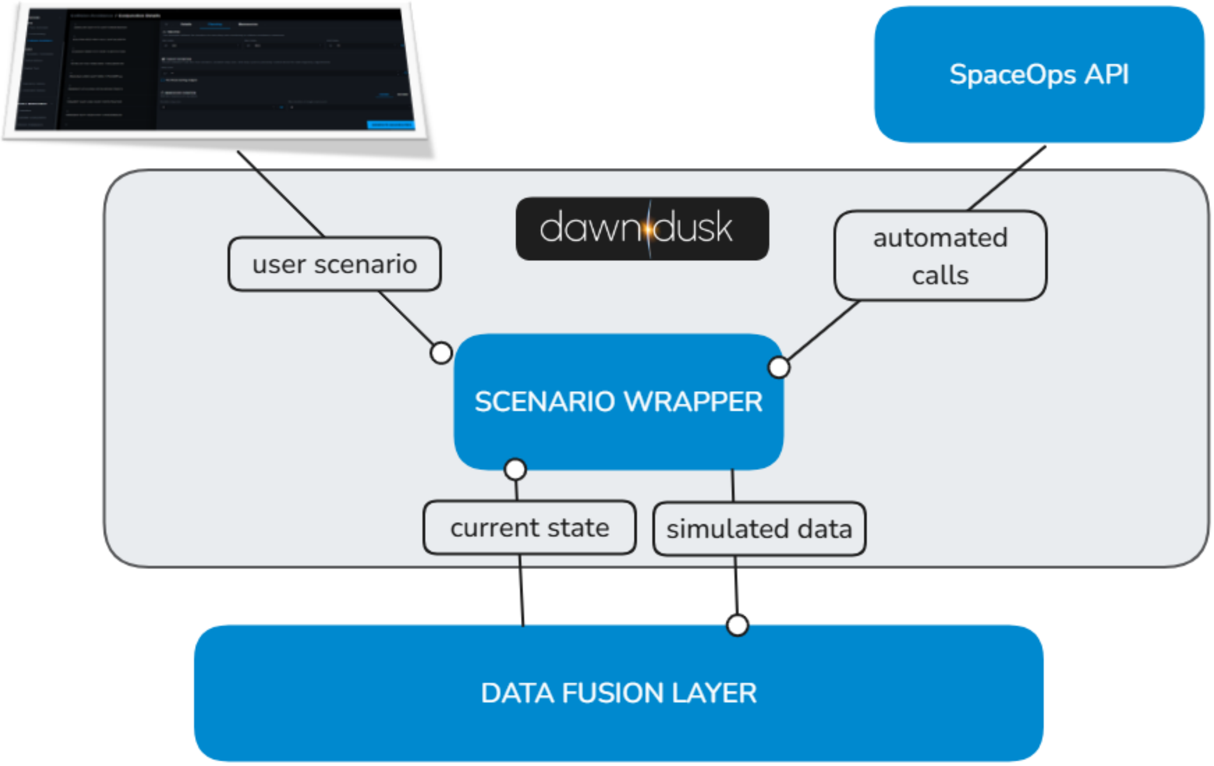

Fig. 2. Digital Twin Simulation Platform

Integration with existing cloud-based products, particularly EnduroSat’s mission operations solution SpaceOps [3], is pivotal for automation and streamlined workflows. By interfacing with SpaceOps, the simulation platform can automatically trigger simulations based on predefined operational events or schedules, reducing the need for manual intervention and enhancing operational efficiency. This integration allows for the seamless flow of data and commands between systems, ensuring that the digital twin remains synchronized with the broader mission control environment. Automated processes not only speed up response times but also minimize the risk of human error, thereby increasing the reliability and robustness of satellite operations.

The simulation framework is built on CubeSpace’s DawnDusk [4] simulation product, utilizing C# to deliver significant performance benefits necessary for large-scale simulations. C# offers high execution speed and efficient memory management, which are critical for handling the extensive computational demands of environment modelling and real-time data processing. This framework ensures that the digital twin can faithfully replicate the satellite’s operational environment, enhancing the precision and reliability of simulation results.

Furthermore, the platform generates a substantial volume of simulated telemetry data, which is stored alongside real telemetry from the satellite. This vast repository of data enables comparative analysis, allowing operators to identify discrepancies, predict potential issues, and optimize performance based on both simulated and actual operational data. By maintaining a comprehensive dataset, the cloud-based simulation platform supports advanced analytics and machine learning applications, driving continuous improvement and innovation in satellite operations.

### *3.2 Environment Models*

Creating a robust and accurate satellite digital twin requires the integration of comprehensive environment models that replicate the myriad factors influencing a satellite’s operations in space. DawnDusk includes a comprehensive suite of environment models, such as Orbital Dynamics, Solar flux modelling and RF propagation, providing a solid foundation for accurate and realistic simulations.

Orbital propagation is the cornerstone of any satellite digital twin, as it predicts the satellite's trajectory and position over time. This model encompasses the laws of celestial mechanics and accounts for various perturbative forces that can alter a satellite’s orbit. These forces include gravitational influences from the Earth, Moon, Sun, and other celestial bodies, as well as non-gravitational forces such as atmospheric drag, solar radiation pressure, and Earth's oblateness. The digital twin will not be required to provide high fidelity propagation as a separate flight dynamics component will be used for this for satellite operations. However, being able to model the relative effect of maneuvers on the satellite trajectory will be needed to validate operational behaviour.

There are then multiple environmental factors that are necessary to correctly calculate the satellite subsystem performance. The environment must also propagate the satellite attitude by simulating correctly the external forces and the interaction with the satellite ADCS subsystem. To account for power and thermal simulation, the environment must account for variations in solar irradiance, such as those caused by the satellite's orientation relative to the Sun, Earth albedo affects and the occurrence of eclipses both due to celestial bodies and parts of the satellite structure. This environment must also simulate the transmission and reception of radio frequency signals between satellites and ground stations or other satellites. RF propagation models account for factors such as signal attenuation, atmospheric effects and antenna configurations.

Beyond individual environment models, integrating these components into a cohesive framework is essential for the digital twin's accuracy and utility. Orbital propagation, power systems, thermal dynamics, and RF propagation are interdependent, with changes in one aspect often affecting others. For example, orbital adjustments can influence solar exposure, impacting power generation and thermal conditions, which in turn can affect RF communication capabilities. The subsystem interactions need to be pragmatically implemented in the simulation as the low levelling modelling of the mechanical, electrical and thermal interactions should be left to specialist design tools to not over burden the twin leading to performance issues. It is therefore critical to select only the interactions that will most effect satellite operational performance.

An integrated approach allows the digital twin to simulate complex interactions and dependencies, providing a more realistic and comprehensive representation of the satellite's operational environment. This holistic modelling enables operators to conduct multi-faceted analyses, such as assessing the impact of a power system failure on thermal management and communication capabilities. It also supports advanced functionalities like scenario planning, where multiple environmental variables can be manipulated to evaluate their combined effects on satellite performance.

### *3.2 Satellite Components*

As EnduroSat manufactures many subsystems for the satellite in-house, this allows us to have access to large amounts of design, test and operational detail of the components to build the digital twin components.

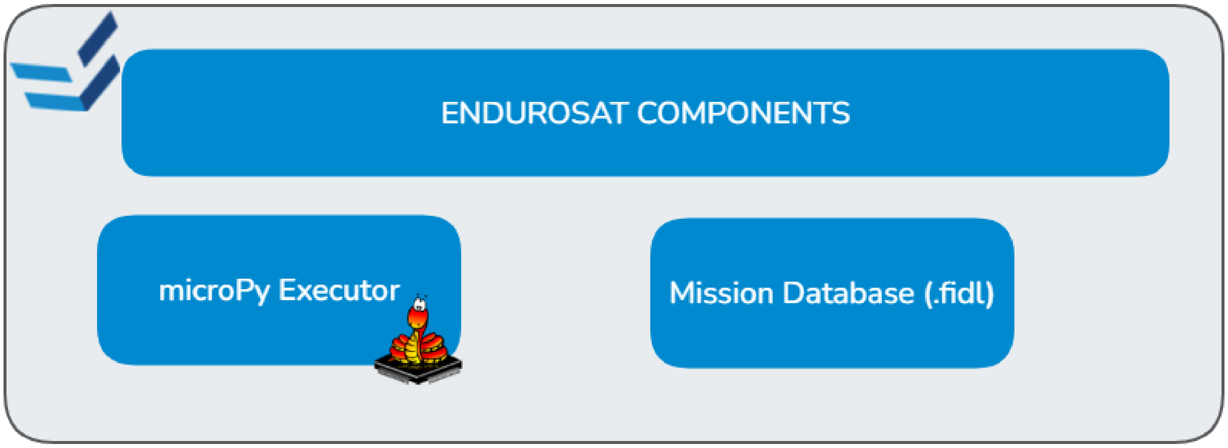

Fig. 3. Digital Twin Satellite Components

Central to the digital twin is the On-Board Computer (OBC), the most critical component controlling satellite behaviour. The OBC model includes the emulation of satellite Concept of Operations (ConOps) and Fault Detection, Isolation, and Recovery (FDIR) mechanisms, ensuring that the satellite can execute mission-specific tasks and respond to anomalies effectively. It incorporates a MicroPython (upy) interpreter and Franca interface definition language [5] (Franca IDL) databases, mapping operational commands to the simulation framework. This integration allows for the direct testing of operational procedures, enabling operators to develop and refine command sequences and mission scripts within the simulation environment. By leveraging tools like Desksat for software validation, the digital twin remains streamlined, focusing on real-time behaviour and operational scenarios without overcomplicating the model with full software validation processes.

The Attitude Determination and Control Systems (ADCS) are fundamental for maintaining the satellite's orientation and stability in space. Utilizing platforms like Cubespace D2S2, the digital twin incorporates high-fidelity simulations of ADCS commands, closely mirroring the actual control loops employed by the CubeComputer. This includes simulating a full catalogue of sensors and actuators, including third-party components, which allows for accurate prediction and testing of the ADCS's behaviour under diverse conditions. By doing so, operators can ensure precise attitude control, critical for tasks such as maintaining communication links and optimizing solar panel orientation for power generation.

Communication systems are equally vital, as they enable data transmission between satellites and ground stations. The digital twin models radio frequency (RF) performance, antenna beam patterns, and data rates to ensure that communication systems operate within desired specifications. By simulating antenna beam patterns, engineers can optimize the directional behaviour of antennas to maximize coverage and minimize interference. Additionally, modelling data rates helps in identifying and addressing potential communication bottlenecks, ensuring efficient and reliable data transmission is essential for mission operations.

Power management is another crucial subsystem modelled within the digital twin. This includes detailed simulations of battery performance, solar panel efficiency, and various power modes. The battery performance model accounts for charge and discharge cycles, degradation over time, and responses to varying power demands, ensuring a reliable energy supply. Solar panel performance is simulated by considering factors such as solar irradiance, panel orientation, and efficiency losses, which are critical for maintaining adequate power generation under different environmental conditions. Additionally, the digital twin can simulate different power modes, allowing operators to optimize power allocation strategies for different mission phases or operational scenarios, thereby extending the satellite's operational lifespan and optimizing energy usage.

Propulsion systems are essential for executing maneuvers such as orbit adjustments and attitude control. The digital twin models maneuver propagation, predicting how the satellite's trajectory changes in response to thrust commands. It incorporates Concepts of Operations (ConOps) to simulate the strategic execution of these maneuvers, ensuring operational procedures are effective and efficient. Moreover, the digital twin accounts for torques generated from thruster uncertainty, providing insights into potential deviations and their impact on the satellite's orientation. This detailed propulsion modelling ensures precise orbit maintenance and enhances the reliability of attitude control maneuvers, which are crucial for mission success.

For imaging payloads, the digital twin simulates camera and sensor performance, ensuring optimal image quality and coverage. Communication payloads are modelled to verify data transmission capabilities, ensuring efficient and reliable communication links.

### *3.2 Data Integration and Real-Time Updates*

Integration with the operational environment ensures that the digital twin operates within the broader mission framework, providing real-time support and enhancing decision-making processes. A critical aspect of this integration is the sophisticated mapping between simulated telemetry and real telemetry data. By accurately correlating simulated data with the actual telemetry received from the satellite, the digital twin maintains a high level of fidelity, ensuring that simulations reflect the true operational state of the satellite. This alignment allows operators to trust the digital twin's outputs and use them confidently for operational planning and troubleshooting.

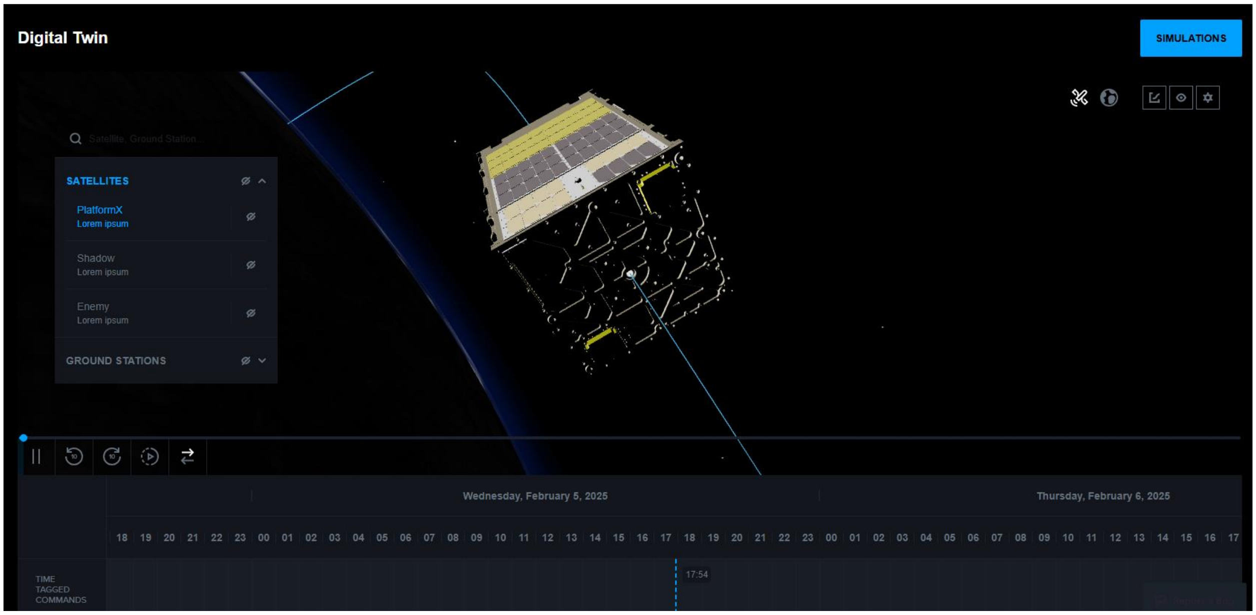

Fig. 4. Digital Twin User Interface Integrated into SpaceOps

Moreover, the digital twin offers the capability to define simulations based on the current state of the satellite as calculated from real-time telemetry. This means that the digital twin can dynamically adjust its simulations to mirror the satellite's actual conditions, providing a precise and up-to-date virtual representation. For instance, if telemetry data indicates a change in the satellite's orbit or a shift in power consumption, the digital twin can immediately update its models to reflect these changes, enabling accurate predictions and responses.

Furthermore, the digital twin is designed to automatically initiate simulations in response to specific operational events. For example, in the event of collision avoidance warnings or when telemetry data falls outside predefined limits, the digital twin can promptly trigger relevant simulations. This automation ensures that potential issues are analyzed and addressed swiftly, minimizing the risk of mission-critical events. By responding to real-time events with appropriate simulations, the digital twin enhances the satellite's resilience and operational reliability. Overall, tight integration with mission operations, precise telemetry mapping, dynamic state-based simulations, and automated responses to operational events collectively ensure that the digital twin serves as a powerful tool for maintaining and optimizing satellite performance throughout its mission lifecycle.

## 4. Challenges and Future Work

One significant challenge lies in the development of comprehensive simulation and space systems frameworks. Currently, there is a need to meticulously describe the architecture and behavior of all satellite components to be integrated into the digital twin. This involves defining how each subsystem interacts within the overall system, ensuring accurate replication of real-world operations. However, the existing frameworks lack straightforward methods for incorporating third-party equipment, which limits the flexibility and extensibility of the digital twin models. To mitigate this, the adoption of modeling languages such as Systems Modeling Language [6] (SysML) could be explored, providing a standardized approach to describe complex system architectures and behaviors. Nevertheless, a prevailing issue is that systems engineering teams are often more proficient in languages like Python, which are widely used for scripting and automation. Bridging this knowledge gap by developing interfaces or translation layers between SysML and Python could facilitate the integration of diverse components, enhancing the digital twin's versatility and ease of use.

Another critical area requiring attention is the increased automation of satellite operations. Automation can significantly enhance the efficiency and reliability of satellite missions by streamlining various operational processes. For instance, automating system validation before launch, including conducting regular non-regression tests, ensures that all subsystems function correctly and consistently over time. This continuous validation is crucial for detecting and rectifying issues early, thereby reducing the risk of mission failures. Additionally, automating satellite commissioning processes can expedite the transition from deployment to operational status, minimizing downtime and ensuring that the satellite is fully functional as quickly as possible. Furthermore, digital twins enable the training of decision-making algorithms using simulated data [7], allowing these algorithms to learn and optimize their performance in a controlled environment before being deployed in real missions. This approach enhances the robustness and adaptability of the algorithms, making them better equipped to handle real-time challenges.

Moreover, the ability to model errors within the digital twin environment is invaluable for developing effective contingency procedures. By simulating potential failures and anomalies, engineers can design and test strategies to mitigate these issues, ensuring that the satellite can maintain operational integrity even under adverse conditions. This proactive error modeling fosters resilience, enabling the satellite to recover from unexpected disruptions with minimal impact on mission objectives. Future work should focus on enhancing the integration of these automated processes within the digital twin framework, leveraging advanced machine learning techniques and real-time data analytics to further improve decision-making capabilities and operational reliability.

## 5. Conclusions

EnduroSat's satellite digital twin signals a paradigm shift toward proactive, data-driven mission operations. Rather than waiting for anomalies to occur, operators can rely on the twin's predictive analytics to mitigate risk. The platform's seamless workflow—from telemetry ingestion to model-based decision-making—demonstrates how digital twins can unify operational validation, diagnostics, and continuous improvement. This approach promotes safer, more efficient, and ultimately more cost-effective space missions.

As the space industry embraces a new wave of commercial services and constellations, digital twins are poised to become standard practice for mission assurance and anomaly management.

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