Applications of Digital Twins in Satellite Communications

Amogu J. Uduka

George Mason University

auduka@gmu.edu

***Abstract*- Satellite communications stand as a cornerstone in modern telecommunications infrastructure, facilitating global connectivity across diverse sectors. However, the dynamic and intricate nature of satellite systems presents significant challenges in terms of monitoring, maintenance, and optimization. The emergence of digital twin technology offers a promising solution to address these challenges by creating virtual replicas of physical satellite assets and their operational environment**

PART I

I. SYSTEM OVERVIEW

An IBM blog described Digital Twins (DTs) as virtual replicas constantly updated with real-time data to mirror real-world objects throughout their lifecycles, using simulation, machine learning, and reasoning to guide decision-making, highlighting their agility, and enabling rapid development and improvement of physical counterparts for better products [1]. Sedaro's CEO, Robertson, defined DTs as high-fidelity virtual portrayals persisting across the complete lifecycle until achieving perfect synchronization with the orbiting system [9]. Thiago and A. Reiner in [11] described DTs as ultra-realistic representations of a physical product, built on "multi-physics, multi-scale, probabilistic simulation" using the "best available physical models, sensor data, fleet history" to mimic its physical counterpart.

In addition to duplicating physical entities, DTs also gather live data to comprehend operational mechanisms. When interconnected, these digital counterparts form an "enterprise metaverse," a virtual realm that mirrors your entire organizational structure. This metaverse enables simulation, scenario planning, and informed decision-making [2]. DTs can enable corporate processes that foster automation, mass manufacturing of components, systems-driven approaches, re-usability, predictive maintenance, feedback loops, additive manufacturing and more. It combines modelling with analysis to identify the expected behavior and the impact of potential failures and risks associated with a design configuration in an objective, repeatable and traceable process [3].

II. PROBLEM STATEMENT

With the emergence of private players such as SpaceX and Blue Origin, the space industry has been rapidly democratized, and this has led to improved developments and increased funding from public agencies, governments, and private investors. From a market perspective, there are three main drivers for the use of digital twins: digitalization trends, space congestion and the growth of the sector in the US. However, it can be studied that with new technologies comes new problems, hence there is a need to develop a very robust model to take these new constraints into consideration.

As indicated by industry experts, the escalation of space congestion poses a significant concern if not effectively addressed. Yet, the issue extends beyond mere accumulation of 'space junk'; the proliferation of active satellites raises the potential for signal interferences. According to an Accenture survey, up to 74 percent of key stakeholders expressed feeling overwhelmed by the sheer volume of data emanating from products and services within today's interconnected environment. The study concluded that technologies like DTs could empower companies to harness data, yielding valuable insights, enhancing decision-making processes, and curbing manufacturing expenses.

Beyond the insights derived from digital twins, it's crucial to explore how their utilization impacts fundamental aspects of satellite communications. These encompass technical elements such as orbital challenges, modulation and coding techniques, link-budget design considerations, multiple access strategies, and network management issues. Addressing these critical concerns could mark a pivotal moment for the satellite communications sector [3] [7].

Another significant challenge that requires attention is the steep operational expenses resulting from flawed models and prototypes. DTs play a crucial role in offering more economical and effective testing approaches, along with early risk detection. Conducting tests within a secure virtual environment minimizes the expenses associated with failures, while early detection of risks prevents costly losses. Presently, live system testing has the potential to disrupt entire networks. Simulating satellite behavior in orbit, including its response to factors like radiation and extreme temperatures, serves to mitigate risks across the entire operation [7].

III. MOTIVATION AND CHALLENGES

From the outcomes of developing new technologies for the satellite communications industry, it can be observed that there exists a potential that is yet to be realized. By harnessing the power of cutting-edge technologies such as digital twins, artificial intelligence, machine learning, and quantum computing, we could revolutionize satellite operations and redefine the limits of our cosmic endeavors. The driving force behind adopting these key technologies could be narrowed down to the following motivations.

- Since the advent of private stakeholders, the competitive landscape of the space launch market has undergone a notable shift, fostering heightened innovation and cost-effectiveness within the industry. Companies are now compelled to pioneer novel technologies and methodologies to maintain a competitive edge. Consequently, the space launch sector has transformed into a dynamic and swiftly evolving realm, characterized by the continuous emergence of fresh players and technologies [3] [4].

- Satellites can provide essential lifesaving broadband and VSAT (Very Small Aperture Services) data services to response and recovery agencies, hospitals and others in regions cut off from terrestrial internet and Wi-Fi services during a disaster. A very typical use was during Hurricane Maria. Satellite technology during Hurricane Maria in Puerto Rico provided crucial data for tracking the storm, enabling timely warnings and evacuation orders. It facilitated rapid damage assessment, guided emergency response efforts, and served as a vital communication lifeline for affected communities. Additionally, satellites aided search and rescue operations by identifying survivors' locations and supported infrastructure planning for long-term recovery [5] [6].

Even with the potential benefits of digital twins and the associated incentives, current and future satellite communications systems must remain vigilant regarding the security and integrity of their data, design, and critical infrastructure components. Misuse of digital twins could widen a company's attack surface, allowing malicious actors to exploit existing vulnerabilities and gain unauthorized access [8].

PART II

I. DIGITAL TWIN APPLICATIONS IN SATELLITE NETWORKS

Below is a brief discussion about key applications of the Digital Twin in Satellite Communications.

1.1 FAULT DIAGNOSIS AND HEALTH MONITORING

Data-driven methods like clustering and Neural Networks are used in satellite systems to extract implicit insights. NASA's Inductive Monitoring System employs clustering algorithms to analyze historical telemetry data for autonomous control and state monitoring of deep space probes. However, these methods face challenges with limited historical data or abrupt changes in the operating environment, resulting in high false alarm rates and inaccurate fault predictions. Additionally, they lack interpretability and expressibility.

S. Duansen et. al in [10] proposed a digital twin-driven FD-HM approach for the satellite systems. Their efforts amalgamate the physical comprehension of the system, offering a depiction of the satellite system's dynamic behavior. Moreover, they ensure real-time synchronization between virtual models and physical entities, thereby incorporating environmental interaction into the fault detection and diagnosis process.

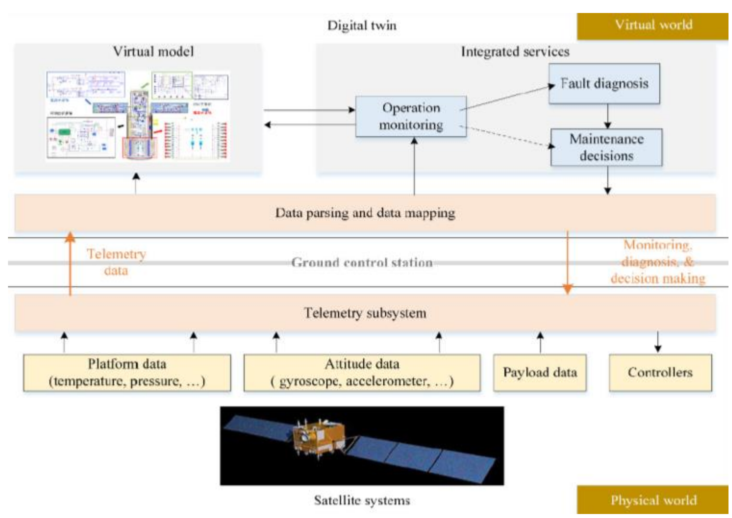

Figure 1: Block Diagram of Proposed Digital Twin by [9].

1.1.1 DATA DETECTION PROCESS

From the consolidation of the real-world data and the model data, we obtain twin data which is used to determine whether the satellite operating state meets the design expectations, and then discover faults or design flaws. Two matrices, X_{obs}, Y_{sim} serves as the observation matrix and evaluation matrix respectively, with respect to some specific operating conditions C. We also denote two vectors, X_i, Y_i to represent the states of the observed parameter and the virtual model over a period, $t_i - t_j$ respectively.

$$X_i = (x_{i1}, x_{i2}, \ldots, x_{im}), \qquad Y_i = (y_{i1}, y_{i2}, \ldots, y_{im})$$

$$X(t_j) = (x_{1j}, x_{2j}, .., x_{nj}), \; Y(t_j) = (y_{1j}, y_{2j}, \ldots, y_{nj})$$

Given a pre-defined threshold, T_p (operating state of the satellite), a fault is being diagnosed from the below relationship.

$$norm(X(t_j) - Y(t_j)) > \; T_p$$

1.1.2. SIMULATION AND RESULTS

In the plot below, setting $T_p = 2$, a simulation was performed using random data for both the observed and simulated data. Also, the historical data for the satellite was also taken into consideration. It can be observed that an abrupt fault occurred on the satellite. Hence, the need to perform fault diagnosis.

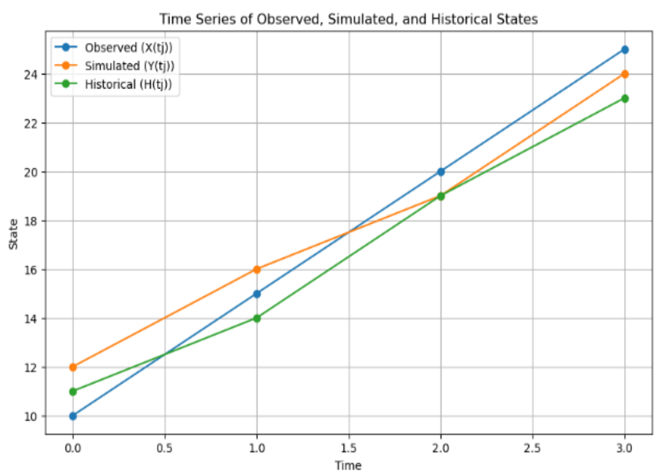

Figure 2: Time series plot.

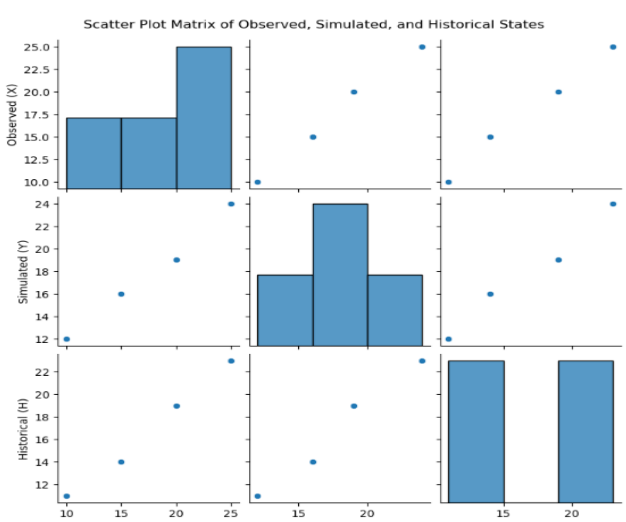

Figure 3: Scatter plots.

Nevertheless, the construction of multi-domain integrated satellite system models, the consolidation of twin data, and the implementation of integrated services emerge as the most formidable hurdles in realizing digital twin-based FD-HM applications. Addressing the effectiveness of mutual coupling across various disciplines like mechanics, electronics, control, thermology, and information, as well as establishing a robust mapping relationship between model data and telemetry data, remains pivotal for the successful implementation of this technology. The general idea was to construct a physical–virtual convergence digital twin system to integrate simulation data, real telemetry data, and fused data. The goal was to realize real-time monitoring as well as the maintenance of the on-orbit satellites using data-driven and model-based algorithms [10].

1.2 QoS MECHANISMS

Bandwidth in satellite systems is precious and expensive. To optimize efficiency and manage costs, bandwidth on demand (BoD) mechanisms are commonly employed. It's essential to implement the right Quality of Service (QoS) approach for optimal performance of TCP/IP applications while working closely with BoD mechanisms. The current inter-satellite routing algorithm encounters challenges in managing a multi-layer satellite network with complex hierarchical relationships. These challenges stem from the high density and dynamic topology changes within the satellite network, leading to frequent disconnections and switching of inter-satellite links (ISL). Additionally, the uneven distribution of global traffic results in congestion on certain ISLs. Without an effective routing strategy to address these issues, resource utilization remains low, and the service quality of service (QoS) requirements cannot be met [11] [12].

In [12], X. Jiang, T. Zhang, and L. Liu designed and proposed a three-layer, three-loop digital twin system architecture for satellite networks. This architecture aims to sense and deduce the operational state of the physical satellite network, providing necessary data and algorithms to support the entire lifecycle of the digital twin system for satellite networks. frequency link switching in satellite networks were mitigated. The diagram below shows the Three-layers Digital Twin Satellite Network (DTSN) architecture.

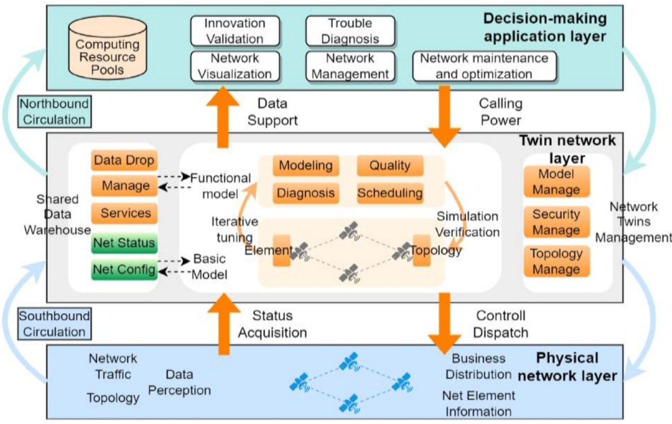

Figure 4: Three-layers digital twin satellite network architecture [12]

The three-loop system enhances the twin network's ability to accurately perceive and analyze the operational status of the satellite physical network. This transformation from a "black box" to a "white box" enables the provision of data and algorithms crucial for supporting the entire life cycle of the satellite network's digital twin system within the framework of DTSN.

The system collects information from the real satellite network, models it to construct the twin network, and conducts inference and prediction. Subsequently, the decision layer's computing power is being utilized to solve the digital twin satellite routing algorithm. Finally, routing control commands are transmitted back to the real satellite network. By establishing the inter-satellite link switching and congestion prediction model in the twin network, it is observed that issues such as load imbalance and frequency link switching in satellite network were being mitigated.

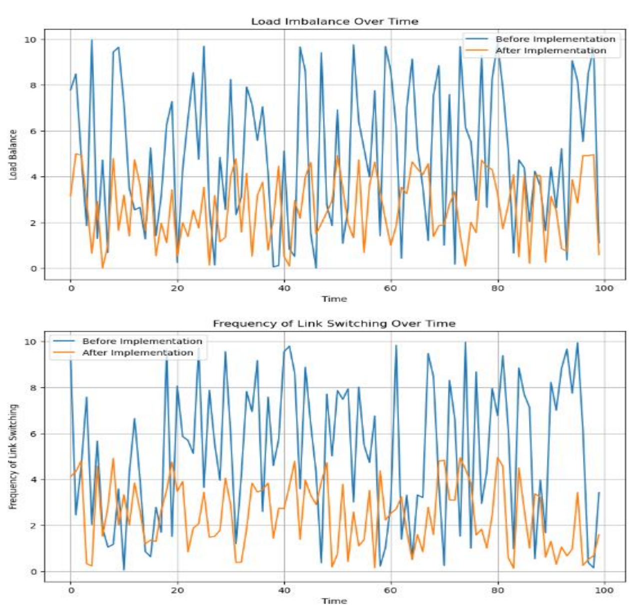

Figure 5: Implementation of Three-layers DTSN

II. COMMERCIAL PRODUCTS

Some Commercial Digital Twin Products includes;

- **Simcenter and Xcelerator by Siemens**: Simcenter offers an integrated digital risk twin strategy enabling engineers to consistently assess the reliability, availability, maintainability, and safety (RAMS) of spacecraft designs in relation to cost and operational efficiency, right from the inception of the design phase.
- **Sedaro**: It is a cloud-native platform for space system digital twins. It is exceptionally interoperable and produces high-fidelity virtual representations of the physical systems that space missions depend on.

III. FUTURE DIRECTIONS

Intriguingly, ongoing research endeavors and pioneering advancements persist in the domain of Digital Twins (DTs), aimed at augmenting the efficacy of satellite communications. The following areas would be worth taking advantage of for future applications in satellite communications.

1. Resilient Secure Communication: Develop resilience strategies and contingency plans to mitigate the impact of cyber-attacks, jamming, and signal interference on satellite operations.
2. Dynamic Spectrum Management: Explore dynamic spectrum management techniques within DTs to optimize spectrum utilization and mitigate interference in satellite communication bands.
3. Resilient Network Architectures: Investigate resilient network architectures and redundancy strategies within DTs to enhance the fault tolerance and survivability of satellite communication networks.

IV. CONCLUSION

In conclusion, the ongoing advancements in DT technology present a compelling opportunity to revolutionize satellite communications, offering unprecedented capabilities for real-time monitoring, predictive analytics, and proactive management of space-based communication systems. As researchers continue to push the boundaries of knowledge and innovation in this field, the future holds immense promise for leveraging digital twins to enhance the performance, reliability, and resilience of satellite networks. By embracing emerging technologies and fostering collaboration across disciplines, we can unlock new frontiers in space-based communication, driving progress towards a future where satellite communications are more efficient, secure, and accessible than ever before.

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