Bridging Gaps in Distributed Space Systems: A Digital Twin Solution

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Abstract: This paper presents a conceptual design for an advanced simulator leveraging digital twins, focusing on the subsystems of small satellites and their interdependencies. Existing simulators face challenges due to computational intensity, lack of flexibility, and inability to adapt to dynamic satellite missions. The proposed digital twin-based simulator offers a lightweight, computationally efficient alternative, enabling detailed analysis of mission requirements, iterative design processes, and comprehensive operational assessments. A review of existing Distributed Space Systems (DSS) applications highlights ongoing efforts and completed missions involving small satellites, identifying significant gaps in imaging and surface analysis. These gaps arise from increased complexity in coordination, data synchronization issues, and higher maintenance costs, which currently outweigh the advantages of DSS. To address these gaps, the study proposes developing adaptable digital twins for all satellite subsystems, accurately modeling interdependencies and interactions to establish a robust DSS framework.

1. INTRODUCTION

In recent years, the concept of Distributed Space Systems (DSS) has emerged as a revolutionary approach in space technology. These systems involve multiple spacecraft working in a coordinated manner to achieve a common objective, offering enhanced capabilities compared to a single satellite. This technique is particularly significant for Earth observation, as it allows for more comprehensive data collection and improved spatial and temporal resolution [1]. Consequently, DSS are crucial for a myriad of applications, including environmental monitoring, disaster management, urban planning, and climate change studies.

The advent of small satellites has further transformed the landscape of space exploration and observation. As the NewSpace paradigm emphasizes cost-effective, rapid, and innovative approaches to space missions [2], small satellites have become enablers and have democratized access to space, enabling a broader range of entities, including universities, startups, and developing countries, to participate in space activities.

This article will delve into the current state of DSS and, in particular, DSS of small satellites. The missions and concepts found in this review aim to enhance the ability to monitor and understand our planet with greater precision and frequency. This capability is essential for making informed decisions that impact both local and global scales.

2. LITERATURE REVIEW

According to reviews by Saptarshi Bandyopadhyay et al. [3, 4], there is a significant focus on Earth observation within the area of DSS of small satellites. These missions have proven to be invaluable for various applications, including ionosphere measurements [5-8], multi-spectral imaging [9, 10], electrical field sensing [11], magnetosphere studies [12-15], aeronomy and geodesy measurements [16, 17], extreme weather prediction [18], Low Earth Orbit (LEO) radiation environment [19-21], Fourier Transform spectrometer for long-term weather forecast [22], lower thermosphere and re-entry research [23-25], space situational awareness [26, 27], and geophysical monitoring [28-30].

A review of ongoing missions and conceptual studies highlights the innovative approaches and technological advancements in the field of DSS of small satellites. The matrix presented in Figure 1 provides a comprehensive review and categorizes the reviewed works based on their applications and the satellite subsystems they focus on. Novel studies are also included and categorized as technology demonstrators, to provide further knowledge of the current research scopes. Additionally, the status of the mission is highlighted, as they can be completed, ongoing, failed, conceptual or uninitiated missions. This structured approach to the review not only facilitates a clearer understanding of the current state of DSS but also identifies potential areas for future research and development.

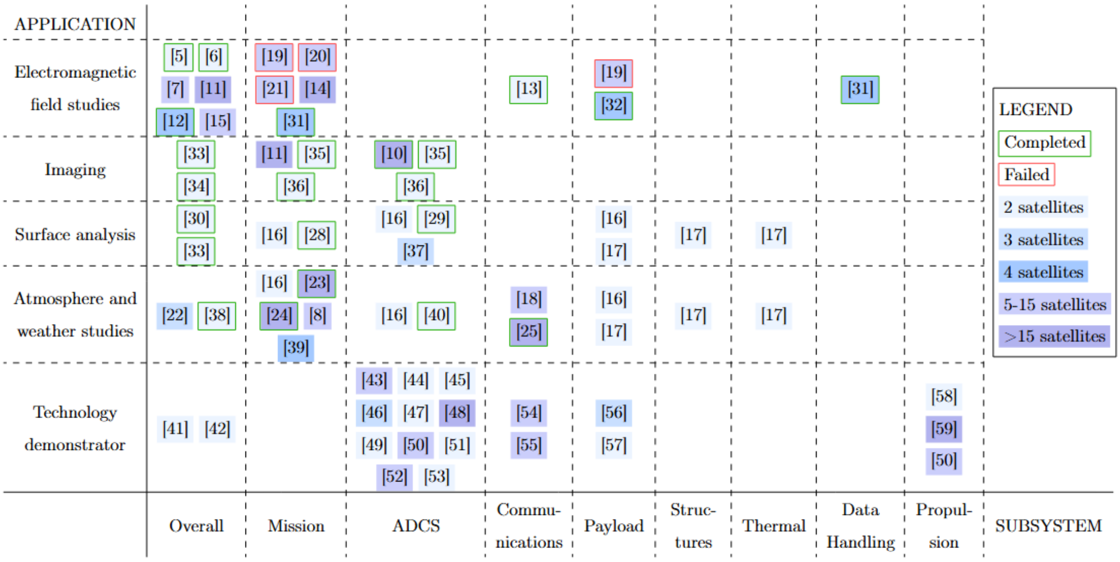

Figure 1: DSS literature review matrix. Rows represent different applications, including novel studies as technology demonstrators in the last row. Columns represent the satellite subsystem of focus. Border colors highlight the status of the mission: green for completed and ongoing, red for failed, no border for conceptual or uninitiated.

The matrix reveals a significant number of missions dedicated to electromagnetic field studies, indicating a strong interest in this application, and this trend is evident across the overall subsystems. Interest in DSS for electromagnetic field studies can be attributed to several advantages offered by DSS [60], mainly the spatial distribution, which enhances the ability to study complex and dynamic processes that would be difficult to capture with a single satellite.

Another area with a significant focus is atmosphere and weather studies, with interest across various satellite subsystems. This can be explained by the ability to achieve high temporal and spatial resolution when using DSS, which is one of their primary benefits. By deploying multiple satellites, researchers can obtain simultaneous measurements from different locations, providing a more detailed and dynamic picture of atmospheric conditions for accurately modeling weather patterns and predicting changes [61]. Furthermore, the redundancy offered by DSS ensures continuous data collection, even if one satellite encounters an issue. This reliability is essential for long-term atmospheric monitoring, where consistent and uninterrupted data is necessary for accurate analysis and forecasting.

While the matrix highlights several applications with a significant number of missions, it also reveals areas with fewer missions, such as imaging, surface analysis, and space debris. Understanding the reasons behind this disparity can provide valuable insights into the challenges and emerging trends in these fields. For imaging and surface analysis, the relatively lower number of missions can be attributed to the specific requirements and complex operational challenges. High-resolution imaging and detailed surface analysis often demand advanced sensors and precise calibration, which can be more challenging to achieve with DSS [62]. Additionally, the need for stable and synchronized positioning of multiple satellites to capture coherent images can complicate mission design and execution, due to the need of accurate post-processing [63].

It is noteworthy that the majority of these missions are designed for systems of two satellites, although some involve three or four. Nonetheless, only a few missions involve larger formations. Moreover, it is noticeable that almost all missions involving more than four satellites remain conceptual, indicating a lack of further development and implementation for large satellite formations. This highlights the need for continued research and innovation to advance the practical deployment of extensive satellite constellations.

Regarding the technology demonstrators, remarkable advancements are driven by these innovative concepts aimed at enhancing their performance and capabilities. Among these missions, the ADCS stands out as a pivotal domain of focus. This subsystem is crucial for maintaining the precise orientation and positioning of satellites, which is essential for successful DSS mission outcomes, there are currently a vast array of methodologies for this purpose.

5. DIGITAL TWIN CONCEPT

A digital twin is a highly sophisticated virtual replica of a physical system that mirrors its characteristics, behaviors, and dynamics. The key to this technology consists in the continuous assimilation of real-time data from its physical counterpart. Digital twins have become an advantageous tool for predictive maintenance, real-time monitoring, and process optimization in industries such as manufacturing, energy, and aerospace in the industry of today. Through the process of continuously updating real-time information, digital twins enable engineers and decision-makers to simulate operations, experiment with scenarios, and predict failures before they occur.

Consequently, these high-fidelity models offer numerous benefits due to their data-driven approach. By integrating real-time sensor information, digital twins provide robust predictive maintenance functionalities, enabling systems to respond quickly to operational changes and anticipate potential complications. These simulation environments are designed to be lightweight yet comprehensive, enabling rigorous operational and design optimization with minimal computational overhead. This ensures that changes in one subsystem are rapidly reflected throughout the model, facilitating an in-depth analysis of interdependencies. Moreover, the modularity of these systems supports scalability and interoperability, ultimately reducing development costs and operational risks by allowing exhaustive virtual testing that replicates true conditions with high accuracy.

The architecture of a spacecraft digital twin can be conceptualized through a multi-layered structure, as seen in Figure 2, consisting of four main dimensions:

- Physical entity: This represents the real satellite, offering the basis for the digital twin, encompassing all hardware elements and physical aspects.

- Virtual entity: Being the digital counterpart, this involves the comprehensive simulation of the physical entity, mimicking key parameters such as satellite dynamics and orbital behaviors.
- Data layer: Located at the core of the system, this layer aggregates simulation, sensor, and telemetry data. It serves as the foundation of predictive and analytical capabilities of the digital twin, by providing a robust dataset for continuous monitoring and simulation.
- Communication network: Enables data exchange between the physical and virtual systems. Beyond the individual satellite, this constitutes a network of interconnected spacecraft to facilitate cooperation among several spacecraft. It is designed to ensure scalability and interoperability such that a DSS can be operated as a single unit.

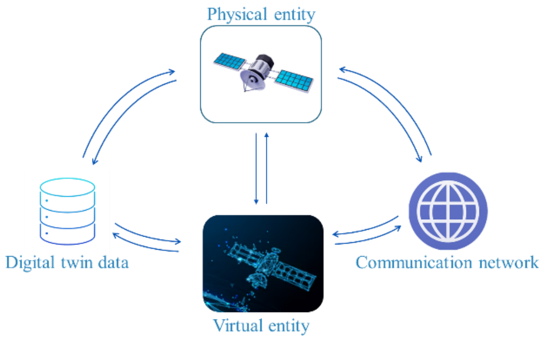

Figure 2: Four-dimensional model of spacecraft digital twin

However, currently several challenges make widespread practical implementation of spacecraft digital twins difficult. Processing real-time data efficiently is a major challenge, since high accuracy is required, which could lead to a potential cost increase that should be weighed against the benefits. Furthermore, security concerns must also be addressed, given the sensitivity of satellite data and the risks associated with cyber threats. Finally, validation and verification of digital twin models to ensure they are trustworthy throughout a mission life cycle is an ongoing and technically demanding process.

The proposed digital twin for a satellite is sketched in Figure 3, which shows all subsystem interconnections between subsystems can be observed. The power subsystem is the central node, integrating power consumption data from the attitude determination and control system (ADCS), the on-board computer (OBC), the thermal, the propulsion, the payload, and the telemetry, tracking, and command system (TT&C). The ADCS and OBC work together to determine the optimal attitude, based on the pointing requirements defined by TT&C or the payload, to position the satellite. Moreover, accurate orbit propagation and disturbance calculations depend on the attitude data and consumed propellant mass, with the resulting position data feeding back to both the ADCS and thermal subsystems.

Up to this point, the framework could be used for a conventional simulator. Nevertheless, what distinguishes a digital twin is the addition of live sensor data – primarily impacting ADCS, orbit dynamics, and power monitoring – which refines the simulation. A dynamic data fusion mechanism, through techniques such as adaptive weighting and filtering, would help prioritize real-time sensor inputs over predicted data, in order to alleviate problems such as sensor noise and latency without compromising high-fidelity in the model.

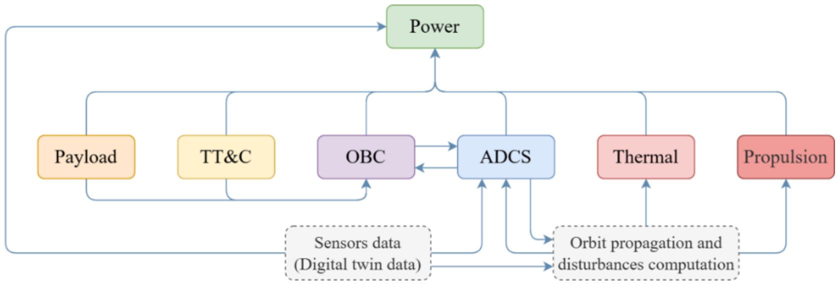

Figure 3: Digital twin satellite subsystems interdependencies flowchart

For extrapolating to a DSS digital twin, each satellite would maintain its own digital twin with the same modular design and operate as previously described. These individual digital twin nodes are interconnected through a robust communication network, which gathers real-time sensor data and simulation outputs from all satellites, being also the foundational data exchange point from the physical and virtual entities. This intermediate DSS layer enables coordinated operations, and inter-satellite data transfer facilitates joint maneuver planning, dynamical adaptation to changing mission requirements, collision avoidance, optimal formation geometry maintenance, and synchronized task execution.

Control requirements and actuator management are of paramount importance in this framework, particularly relative positioning between satellites. To achieve coordinated maneuvers and formation flight, the system would utilize Clohessy-Wiltshire (CW) equations to model the relative dynamics between satellites. Thus, the generated precise control commands for actuators, such as thrusters and reaction wheels, are transferred to each satellite. These actuators would position and orient the satellite, ensuring that the relative positioning remains within the required tolerances.

By integrating these elements into the overall digital twin architecture, as seen in Figure 4, the framework would facilitate both real-time operating adjustments and high-fidelity simulations, enhancing performance and reliability of DSS.

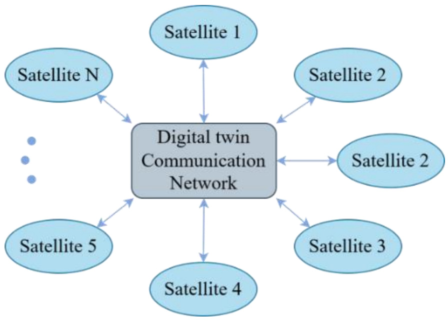

Figure 4: Digital twin communication network scheme for DSS

6. CONCLUSIONS

This paper has explored the existing gaps in Distributed Space Systems (DSS), particularly the lack of integrated subsystem modeling, limited adaptability in mission design, and challenges in coordinating formation-level operations. In response to these limitations, this work proposes a novel digital twin framework that emphasizes modularity, subsystem interconnectivity, and adaptability to a wide range of mission scenarios. By accurately modeling the interdependencies among all satellite subsystems, the framework provides better insights into both system-level behavior and individual satellite dynamics.

Extension to formation flying allows for coordinated operations and joint task execution, helping to overcome key challenges in DSS such as synchronization and control complexity. This software would be designed to facilitate iterative mission design and performance analysis while remaining computationally lightweight. Moreover, to demonstrate its applicability, a case study within the GLITTER project [64] would showcase how the framework can be employed to support GNSS-R missions using CubeSat formations and beamforming, addressing existing gaps in high-resolution surface analysis. Overall, the proposed digital twin solution offers significant advancement towards bridging current gaps in DSS, enabling more flexible, scalable, and insight-driven satellite mission design.

7. ACKNOWLEDGEMENTS

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