Chair of Spacecraft Systems
TUM School of Engineering and Design
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Optimizing Digital Twin Methodology for CubeSats

Quantitative Analysis for Design, Performance, and Implementation Strategies

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I hereby declare that this thesis is entirely the result of my own work except where otherwise indicated. I have only used the resources given in the list of references.

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Zusammenfassung

Das Thema Digitale Zwillinge hat in den letzten Jahren durch das wachsende Interesse von Forschung und Industrie erheblich an Aufmerksamkeit gewonnen. Ursprünglich im Produktlebenszyklusmanagement eingeführt, lassen sich Digitale Zwillinge am besten als digitale Repräsentationen physischer Komponenten mit bidirektionalen Datenverbindungen beschreiben, die eine Konvergenz zwischen physischen und digitalen Zuständen ermöglichen. Dieses Konzept verspricht ein verbessertes Verständnis von Produkten während ihres gesamten Lebenszyklus.

In den letzten 20 Jahren hat der Raumfahrtsektor einen starken Zuwachs an Satellitenstarts erlebt, insbesondere bei kleineren Satelliten wie CubeSats. Ursprünglich zur Technologiedemonstration von Universitäten eingesetzt, tragen CubeSats mittlerweile zunehmend wissenschaftliche Nutzlasten und ermöglichen kostengünstige, maßgeschneiderte wissenschaftliche Missionen. Dieser Wandel hat die Nachfrage nach Risikomanagement, Zuverlässigkeit und vorhersagbarer Datenbereitstellung erhöht. Der zunehmende Wettbewerb in der Raumfahrtindustrie hat den Bedarf an effizienteren Methoden verstärkt. Die Digitale Zwillinge bieten einen datengesteuerten Ansatz zur Bewältigung dieser Herausforderungen während des gesamten Lebenszyklus von CubeSats.

Diese Forschungsarbeit stellt eine optimierte Methodik für Digitale Zwillinge vor, die auf CubeSats zugeschnitten ist und Design-, Leistungs- und Implementierungsstrategien analysiert. Die wichtigsten Herausforderungen und Anforderungen werden durch eine Untersuchung des gegenwärtigen Stands von Digitalen Zwillingen in der Literatur und einer Branchenevaluierung ermittelt. Die Evaluierung umfasst einen Fragebogen und Experteninterviews, die den aktuellen Stand der Implementierungen in der Branche anhand eines Reifegradmodells bewerten. Die Experteninterviews bieten einen detaillierten Einblick in die aktuellen Branchenpraktiken und das wahrgenommene Potenzial dieser Technologie. Die gesammelten Daten werden analysiert, um verwertbare Erkenntnisse zu gewinnen, die eine breitere Perspektive ermöglichen und dazu beitragen, dass das Konzept des digitalen Zwillings auf die spezifischen Bedürfnisse der CubeSat-Entwicklung zugeschnitten wird.

Um das allgemeine Verständnis zu verbessern, wird eine Architektur mit den detaillierten Beschreibung der verschiedenen Elemente und deren Interaktionen vorgestellt. Der Digitale Zwilling des CubeSat wird in allen Phasen des Lebenszyklus beschrieben und mögliche Implementierungen und Anwendungen werden vorgestellt. Ein besonderes Augenmerk wird auf die Anpassung der digitalen Domänenarchitektur an die Eigenschaften des CubeSat gelegt, um die Effizienz der Implementierung zu verbessern und um wiederverwendbare Module für andere Missionen zu entwickeln. Es wird ein Rahmenwerk vorgestellt, in dem die grundlegende Architektur, die Verbindungen zwischen verschiedenen Komponenten, mögliche Anwendungen im CubeSat-Sektor und die daraus resultierenden Vorteile beschrieben werden.

Um die Machbarkeit und die Vorteile dieses Ansatzes zu demonstrieren, wird die Methodik in einem CubeSat-Projekt, dem EventSat, des Lehrstuhls für Spacecraft Systems an der Technischen Universität München umgesetzt. Bei diesem Projekt handelt es sich um einen 6U CubeSat, der die Objekterkennung im Weltraum mit Hilfe einer ereignisbasierten Kamera verbessern soll. Die Implementierungsstrategie konzentriert sich auf das Energiemanagement des Satelliten und veranschaulicht dessen praktische Anwendung durch die Entwicklung eines digitalen Zwillings, der das Verhalten des Satelliten mit einem automatischen Regelkreis widerspiegelt. Dieses System korreliert Daten aus der realen Welt mit Simulationen und passt den Betrieb der physischen Nutzlast an sich ändernde Parameter an. Diese Implementierung zeigt die Vorteile einer frühzeitigen Datenkorrelation während des Lebenszyklus, die das Verständnis für das Verhalten des Satelliten verbessert und eine frühzeitige Konfigurationsoptimierung ermöglicht, um die Einsatzzeit der Forschungsmission zu verlängern.

Abstract

The topic of Digital Twins has gained significant attention in recent years, with increased research and industry interest. Initially introduced in product lifecycle management, Digital Twins are best described as digital representations of physical components with bidirectional data connections to enable convergence between physical and digital states. This concept promises an improved understanding of products throughout their lifecycle.

The space sector has seen a surge in satellite launches over the past 20 years, particularly with smaller satellites like CubeSats. Initially used for technology demonstrations by universities, CubeSats now increasingly carry scientific payloads, enabling low-cost, custom science missions. This shift has heightened the demand for risk management, reliability, and predictable data delivery. The increasing competition in the aerospace industry has intensified the need for more efficient methods. Digital Twins offer a data-driven approach to addressing these challenges over the entire lifecycle of CubeSats.

This research presents an optimized methodology for Digital Twins tailored to CubeSats, analyzing design, performance, and implementation strategies. Key challenges and requirements are identified through an analysis of the current state of Digital Twins in literature and an industry evaluation. The evaluation includes a questionnaire and expert interviews, which are conducted to assess the current state of implementations within the industry through a maturity model. The expert interviews offer in-depth insights into current industry practices and the perceived potential of this technology. The collected data is analyzed to derive actionable insights, providing a broader perspective and helping to tailor the Digital Twin concept to the specific needs of CubeSat development.

An architecture is presented with a detailed description of the different elements and their interactions to enhance understanding. The CubeSat Digital Twin is described throughout the lifecycle stages, presenting potential implementations and applications. Particular emphasis is placed on aligning the digital domain architecture with CubeSat characteristics to potentially improve implementation efficiency, proposing reusable modules for other missions. An overall framework is introduced, detailing the basic architecture, connections between different components, potential applications in the CubeSat sector, and the resulting benefits.

To demonstrate the feasibility and benefits of this approach, the methodology is implemented in a CubeSat project, the EventSat, by the Chair of Spacecraft Systems at the Technical University of Munich. This project involves a 6U CubeSat designed to advance object detection in space using an event-based camera. The implementation strategy focuses on the power management of the satellite and illustrates its practical application by developing a Digital Twin to mirror the satellite's behavior with an automated control loop. This system correlates real-world data with simulations and adapts the operation of the physical payload to changing parameters. This implementation demonstrates the advantages of early lifecycle data correlation, enhancing the understanding of the satellite's behavior and enabling early configuration optimization to increase the operational time of the scientific mission.

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Acronyms

AAS Asset Administration Shell. 10, 72

ADCS Attitude Determination and Control System. 48, 60

AI Artificial Intelligence. 45, 62, 63, 68, 71

AIA Aerospace Industries Association. 6

AIAA American Institue of Aeronautics and Astronautics, Inc.. 6

COM Communication. 60

ConOps Concept of Operations. ix, 65

COTS COmmercial off-the-shelf. 46, 60, 61

CPU Central Processing Unit. 62, 68

EPS Electrical Power System. 60

EVK-3 Evaluation Kit 3. 62, 63

GPU Graphics Processor Unit. 62

HIL Hardware-in-the-Loop. 46, 48

IEC International Electrotechnical Commission. 7, 8, 39, 42, 43

IoT Internet of Things. viii, 3, 10, 11, 72

ISO International Organization for Standardization. 7, 8, 39, 42, 43

NASA National Aeronautics and Space Administration. 1, 5, 6, 9, 11, 12

OBC On-Board Computer. 60

PCB Printed Circuit Board. 62

PLM Product Lifecycle Management. viii, 1, 5, 6

SSD Solid State Drive. 62

SSH Secure Shell Protocol. 63, 68

TUM Technical University of Munich. 2, 15, 58

TVAC Thermal Vacuum Chamber. 46, 48

UHF Ultra-High-Frequency. 60

1 Introduction

1.1 Motivation

CubeSats have evolved in the last 25 years from an educational platform to a capable technology for space research, presenting numerous advantages, such as an expanding size and increasing complexity of CubeSat missions. These missions are becoming more scientific and are paving the way for a future "easy access to space"[9]. The development of CubeSats for sophisticated and complex science missions in harsh environments, alongside growing launch opportunities for CubeSats, is a significant step forward. These advancements enable more and more companies, start-ups, academic programs, and government agencies to build and launch a spacecraft to reach Low Earth Orbit, Geosynchronous Equatorial Orbit, and lunar and interplanetary space. CubeSat constellations will likely grow in number due to their ability to capture simultaneous, multipoint measurements with identical instruments across large areas, significantly improving our understanding of the space environment and enhancing Earth observation [9] [5].

However, these advancements come with challenges. The reliability of subsystems will become a key design criterion. Technology demonstrations, comprehensive test facilities, and enhancements in incorporating new technologies are crucial as more CubeSats are launched and designed to operate beyond Low Earth Orbit [10]. The increasing digital transformation affects all elements of society, constantly improving available computational resources and making complex topics such as artificial intelligence more accessible for anybody than ever before. This availability of digital engineering technologies is necessary for managing such complex systems during the development, manufacturing, and operation into which CubeSats have evolved [11]. One of the technologies that is especially promising to support the product throughout its lifecycle to simulate, analyze, and optimize the performance as a virtual representation of the physical system is the Digital Twin. Repeatedly reported as one of the top 10 strategic technology trends by Gartner Inc., Digital Twins offer valuable information on maintenance and reliability. They provide insights for optimizing product performance, deliver data on new products, and boost efficiency [12].

Similar to the CubeSat technology, the Digital Twin progressed from theoretical research to pragmatic implementations over the last 20 years, being introduced in 2003 by Michael Grieves in the context of Product Lifecycle Management (PLM) [1], currently undergoing a period of rapid development with more than a thousand papers published per year concerning this topic [13].

The increased interest in research also brings an increase in perceived inaccessibility and intangibility of the concept of Digital Twins in industries such as the New Space sector, as the concept is often connected to the traditional space sector. Thus, complex and expensive projects are connected to the concept, as National Aeronautics and Space Administration (NASA) has already been involved in the research of Digital Twins in the early stages and proposed an ambiguous concept integrating a broad range of technologies to a singular focus [14].

1.2 Research Question

The perception that a Digital Twin is inaccessible is a problem, as it hinders the deployment of the technology in the CubeSat sector. The benefits of the Digital Twin concept can be used for the individual applications of a CubeSat, as it has unique characteristics of modular design and cost-effectiveness. Especially as the technology of the Digital Twin could address the problems and challenges. CubeSats face an increased demand and complexity. This thesis aims to optimize the Digital Twin methodology for CubeSats in a quantitive analysis to address the objectives of design, performance, and implementation strategies. The success of the CubeSat format is based on the standardized interfaces, which set clear boundaries and allow unified integration. However, as these boundaries do not limit the complexity of the small satellite, the outcome of this thesis aims to provide a simplified approach for designing a Digital Twin of a CubeSat. The approach encompasses a detailed digital model architecture focusing on improving CubeSat development throughout the lifecycle, elaborating the final product's performance with long-term reduced usage of resources and advanced reliability. This shall be supplemented by the analysis of implementation strategies and the presentation of a recommended process addressing the challenges of different maturity levels for different subsystems of a CubeSat across the life cycle phases. Special attention is given to tailoring the outcome to the 6U CubeSat of the Chair of Spacecraft Systems at the Technical University of Munich, named the EventSat. This 6U CubeSat with an optical payload consists of an event-based camera and an AI computation unit.

Thus, the following research questions have been identified:

- What are the key challenges and system requirements for developing a digital twin for a satellite? How can these be derived and tailored for the nanosatellites focusing on a 6U CubeSat with an optical payload? How do these requirements differ regarding the level of detail of the various subsystems and their prioritization?
- How can the architecture and configuration of a digital twin be optimized to enhance the efficiency, accuracy, and performance in supporting CubeSat development and operations in the new space domain?
- What are the implementation strategies, limitations, and potential areas for improvement of digital twins for CubeSats, considering the industry's evolving needs and technological advancements?

1.3 Thesis Outline

This thesis is structured as follows:

- *Section 1: Introduction* encompasses the introduction to the topic and gives an overview of the research questions that have guided the thesis.
- *Section 2: Literature Review* describes the literature research of the identified topics of Digital Twin and CubeSats. It gives a brief overview of the state of the art and shows the lack of research on both topics, giving opportunities for contributions to the knowledge of the topic of CubeSat Digital Twins.
- *Section 3: Industry Evaluation* shows the approach, methodology, and execution of the conducted survey, including a questionnaire and an expert interview to collect the knowledge and processes already implemented in the industry towards this topic.
- *Section 4: Methodology of the CubeSat Digital Twin* Dives into the thesis's main contribution to the methodology of a CubeSat Digital Twin. It discusses the different definitions and identifies the requirements for developing a Digital Twin for a CubeSat. An architecture accompanying the Digital Twin throughout the lifecycle of the CubeSat is presented, focusing on the core element of a Digital Twin, the modelling and simulation element. Finally, it determines the applications and benefits of the methodology and presents a framework for implementing a Digital Twin for a CubeSat.
- *Section 5: EventSat Case Study* presents a case study implementation of the methodology on the CubeSat project of the Chair of Spacecraft Systems at TUM. It discusses the gathered data of the implementation and shows the application of the benefits to a real project.
- *Section 6: Conclusion and Future Work* Concludes the work of the thesis and gives an outlook of future research on the topic of the thesis.

2 Literature Review

The introduction of this thesis provides an overview of the interconnected topics and disciplines addressed in the study. Two primary topics have emerged as dominant: Digital Twin and CubeSat. Initially, both topics are explored in a general context to comprehensively understand their current state of the art. Subsequently, the focus narrows to literature that discusses the application of Digital Twins for CubeSats and explores their intersection.

The selection of the thesis topics emerged from an investigation into current developments within the CubeSat market, which is increasingly attracting professional companies. As production processes are optimized, the demand for reliable components and subsystems has surged, although testing remains prohibitively expensive due to high workload [15]. Concurrently, advancements in computational power and progress in other domains have sparked interest in applying Digital Twins within the space sector. Concepts from Industry 4.0, Artificial Intelligence, and the Internet of Things are now more prevalent and utilized across various applications, becoming key enablers for Digital Twin implementations [16].

2.1 Literature Review Approach

Given the broad approach and complexity of the different domains and the scarcity of initial search results for the Digital Twin in the space sector, the literature review has been conducted using a multi-faceted approach. The research in this thesis has been systematically performed using keyword searches across multiple databases: Web of Science, Scopus, TUM OPAC, and Nautos. The keywords used, and the corresponding number of publications for each are detailed below (data last retrieved in July 2024)

Table 2.1 Keyword Search Results - Last Updated July 2024

Keyword	Source	Results
Digital Twin	Web of Science	15085
	Scopus	25713
	TUM OPAC	149097
	Nautos	160
Digital Twin Satellite	Web of Science	245
	Scopus	405
	TUM OPAC	10159
Digital Twin Space	Web of Science	1613
	Scopus	2374
	TUM OPAC	56558
Digital Twin Aerospace	Web of Science	714
	Scopus	389
	TUM OPAC	28494
Digital Twin CubeSat	Web of Science	2
	Scopus	6
	TUM OPAC	150

Continued on next page

Keyword	Source	Results
CubeSat	Web of Science	3427
	Scopus	6720
	TUM OPAC	10779
CubeSat Digital Engineering	Web of Science	74
	Scopus	46
	TUM OPAC	1753

Additional Research Strategies

A white paper analysis has been conducted to complement the academic research. This approach has been essential for understanding the current industry status quo, as large companies do not always publish their results in journals or conferences. The search included keywords such as "Digital Twin Whitepaper."

Further research has been conducted using the Nautos Standards research database of DIN Media GmbH to locate German, European, and international standards distributed by Beuth-Verlag [17]. Additional literature has been identified manually by examining references in already-reviewed papers, uncovering relevant articles that might not have been directly found through keyword searches.

An industry evaluation, incorporating a quantitative questionnaire and qualitative interviews, has been carried out to gain deeper insights into the ongoing industry and academic processes and collect individual opinions from professionals regularly working with Digital Twin technology. This approach and its outcomes are explained in detail in Chapter 3.

Each analyzed paper and publication has been documented with the following:

- A content summary
- A list of interesting references and topics for further research
- A personal summary of the paper's potential impact on the thesis
- A classification score for easier recognition and reference later on

This structured approach ensured a comprehensive and detailed understanding of the current state of research and industry practices related to Digital Twin and CubeSats.

2.2 Digital Twin Literature Review

Interest in the topic of Digital Twin has significantly increased over the last decade in both academia and industry. This trend is evidenced by the substantial growth in the number of publications per year listed on Scopus, visualized in Figure 2.1. Additionally, the increased introduction of standards related to Digital Twins has facilitated broader integration of the technology [17]. Gartner Inc. has consistently listed Digital Twins among the top 10 strategic technology trends for several years [18][19][12].

In the following, the research outcomes have been categorized into three primary topics.

1. General research on the state of the art of Digital Twins and examining the term itself.
2. Digital Twin research specific to various domains, highlighting significant discrepancies in development across different fields.
3. The applications of Digital Twin technology in the aerospace industry and especially in the satellite sector.

2.2.1 State of the Art of Digital Twins in General

This section introduces the origins of the Digital Twin, explaining the various definitions of the concept, the architectural terms, and the different possible types of Digital Twins.

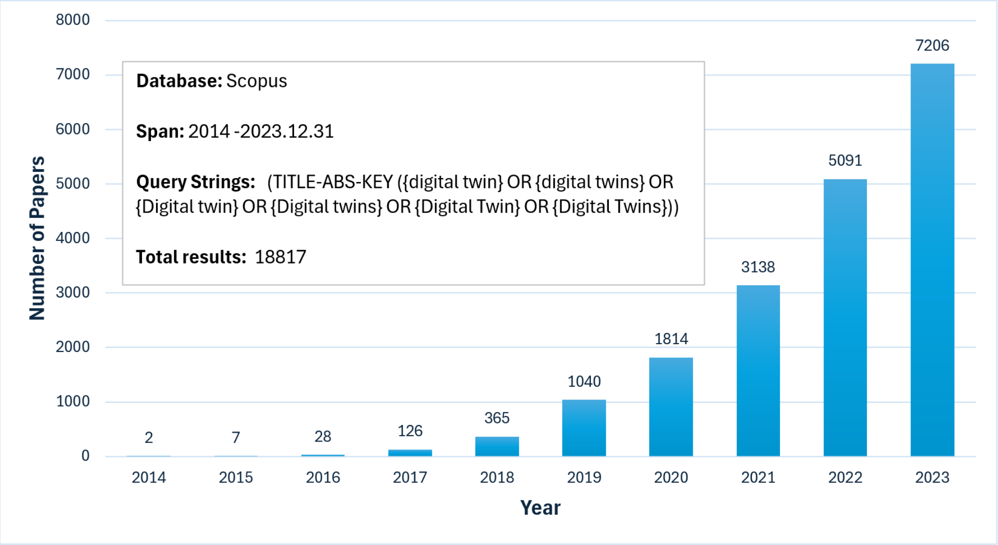

Figure 2.1 Number of Papers Published per Year over the Last Ten Years on the Topic of Digital Twins

Digital Twin Definition

The Digital Twin concept originates from Michael W. Grieves' introduction of the "Mirrored Space Model" in a 2003 lecture on PLM [20]. Grieves later expanded on this model in a paper, defining it as comprising three elements:

- "The model consists of three elements: real space, virtual space(s), and a linking mechanism, referred to as data and information/process connection between real space and virtual space(s)." [21]

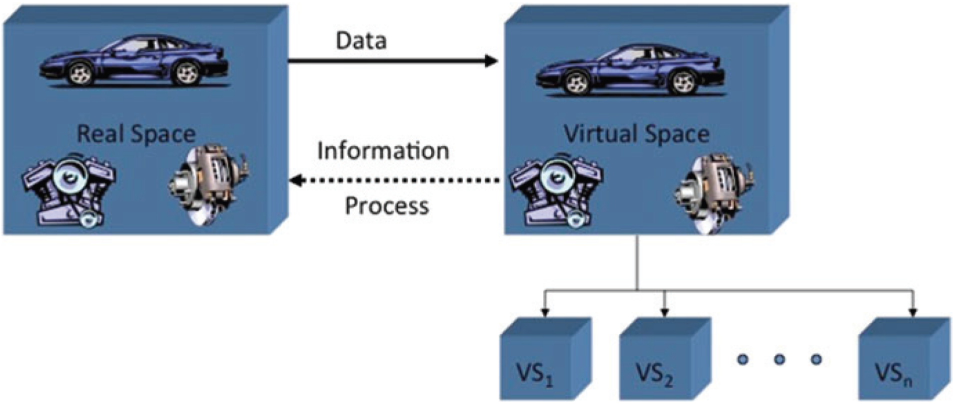

Figure 2.2 Conceptual Ideal for the Mirrored Spaces Model in Product Lifecycle Management (PLM) by [1]

As depicted in Grieves' original Figure 2.2, the circular loop represents the bidirectional connection from the real space to the virtual space(s), defining the system spaces and boundaries of the concept, which have remained largely unchanged since then. The term "Digital Twin" is attributed to Grieves by John Vickers of NASA, who collaborated with Grieves on this topic [1].
In 2010, Glaessgen and Stargel presented the future paradigm for NASA and US Air Force Vehicles, outlining the state-of-the-art engineering processes and how the Digital Twin could transform them. This paper included one of the most widely used definitions of a Digital Twin, emphasizing its capabilities and the revolutionary approach it necessitates:

- "A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin. The Digital Twin is ultra-realistic and may consider one or more important and interdependent vehicle systems, including airframe, propulsion and energy storage, life support, avionics, thermal protection, etc" [14].

Numerous new definitions and publications on Digital Twins have emerged alongside these Definitions of Grieves and Glaessgen.
The standard "Digital twin - Concepts and terminology ISO/IEC 30173:2023" defines a Digital Twin as:

- "digital representation of a target entity with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronization Note 1 to entry: Digital twin has some or all of the capabilities of connection, integration, analysis, simulation, visualization, optimization, collaboration, etc. Note 2 to entry: Digital twin can provide an integrated view throughout the life cycle of the target entity" [22].

Trauer et al. offer a lifecycle-focused definition:

- "A Digital Twin is a virtual dynamic representation of a physical system, which is connected to it over the entire lifecycle for bidirectional data exchange" [23].

Madni et al. describe the concept as:

- "A Digital Twin is a virtual instance of a physical system (twin) that is continually updated with the latter's performance, maintenance, and health status data throughout the physical system's life cycle" [24].

The American Institue of Aeronautics and Astronautics, Inc. (AIAA) and Aerospace Industries Association (AIA) provide a provide a perspective of the aerospace industry on the Digital Twin, with a definition that represents their position on the concept:

- "A set of virtual information constructs that mimic the structure, context, and behavior of an individual / unique physical asset, or a group of physical assets, is dynamically updated with data from its physical twin throughout its life cycle and informs decisions that realize value" [25].

The different types of definitions reflect the progression and development of the Digital Twin concept. Despite the differences, all of these definitions have key elements in common but differ in naming and focus on different aspects. The biggest commonality is the reference point, which is already set by the early definition of Grieves for a Digital Twin: the physical space, the virtual space, and a connection of those elements.
Another additional element that is not directly mentioned in the first version of the definition by Grieves is the lifecycle coverage, which can be found stringently in most of the definitions or the additional notes. As Grieves' research covered the introduction of PLM, the Digital Twin represents the model of the information core that enables PLM through the exchange of data [21].
A notable definition is NASA's future paradigm, which aims to define the highest achievable state of a Digital Twin rather than the minimal state to motivate integrating detailed information about the physical product into the digital element. The diversity of the definitions highlights the importance of context and specific application areas, which may prioritize different aspects of the Digital Twin. This has led to a lack of a universal, comprehensive definition, complicating discussions about the concept and its applications. Additionally, the high variance in architectures and frameworks proposed for different Digital Twins contribute to this complexity [26].
This provides a comprehensive overview of different definitions and their perspectives on the concept of the Digital Twin. Since these perspectives are often linked to the architectures and components associated with Digital Twins, the next section will analyze these terms in more detail.

Architectural Terms

Due to the varying definitions of architectural terms, Jones et al. [26] conducted an extensive study to explore the terminology used in various papers and consolidate their definitions. This research covered terms across different domains to identify common themes and ensure a coherent understanding. Similarly, the ISO/IEC standard defines the terms and definitions applicable to the Digital Twin.

The study revealed that the term "physical entity" is generally employed to describe a "real-world" existing product, system, or artifact. When this entity is part of a twin, it is referred to as the "physical twin." Conversely, the "virtual entity" denotes the digital counterpart, with interchangeable terms such as ’cyber,’ ’model,’ etc., the standard When the virtual entity is part of a twin, it is called the "virtual twin." Jones et al. also acknowledged the concept of multiple virtual entities, a notion initially proposed by Grieves, but emphasized that the interaction and integration of these multiple entities still necessitate further research and clarification.

The physical environment has been discussed as well, which is the space where the physical entity exists. This is often referred to as the ’real world’ or ’real space,’ where any influencing parameter can be measured and, if necessary, fed back into the simulation to closely match reality. Similarly, the virtual environment, often termed the ’virtual world’ or ’virtual space,’ encompasses all digital domain simulations that mirror the physical environment.

The connection between these entities is critical. The physical-to-virtual connection transfers information measured by sensors from the physical entity to the virtual one, updating parameters to better align simulations with the real world. Conversely, the virtual-to-physical connection sends data from the virtual entity to the physical one, altering its behavior based on virtual insights. This continuous loop improves the synchronization between physical and virtual entities.

Furthermore, the paper highlighted the importance of defining the data, information, and processes exchanged between the physical and virtual entities, commonly referred to as parameters. The fidelity of the Digital Twin, which describes the number of parameters or the level of abstraction transferred between the virtual and physical entities, is also a key aspect.

Introducing the fidelity characteristic for Digital Twins addresses when referring to a system as a Digital Twin is appropriate. This discussion often overlaps with considerations of the Digital Twin’s fidelity. In this context, the term "maturity" of the Digital Twin is also frequently used. The ongoing discussion in the literature specifies different maturity models and at what point a system can be called a Digital Twin [27].

According to Kritzinger et al. [2], the level of integration and the differences in the connections between the physical and virtual entities are the primary distinctions between different terms. Kritzinger et al. present the different levels of maturity, as shown in Figure 2.3.

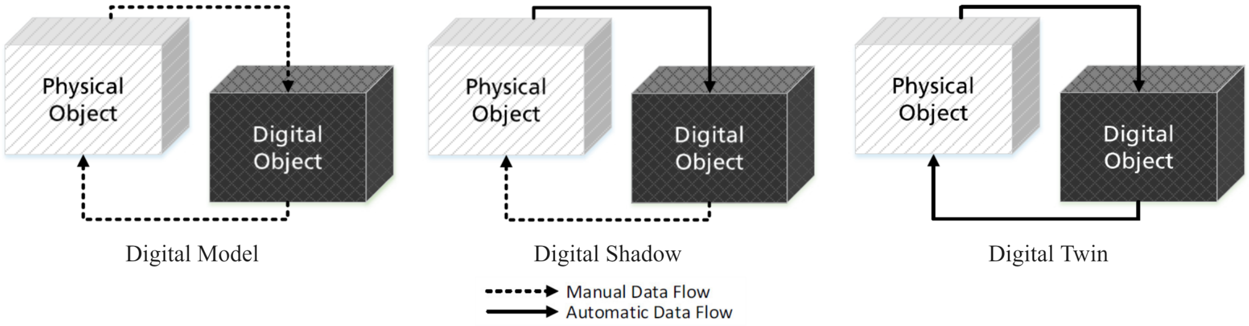

Figure 2.3 Different Levels of Digital Twin Integration: Digital Model, Digital Shadow, and Digital Twin by [2]

1. **Digital Model**: Represents only the digital representation of an existing or planned physical object with manual data flow exchange. Changes in the state of the physical object do not influence the digital object and vice versa.

2. **Digital Shadow**: Shows a physical entity with a one-way automated data flow connection from the physical to the virtual entity. If there is a change in the physical object, it directly influences the state of the digital object. However, the feedback loop to the physical object is still manually operated.

3. **Digital Twin**: Identifies a fully integrated system with automated data flow in both directions. Changes in either the physical or virtual entity influences the other entity.

This distinction highlights the different development and integration stages and defines what constitutes a Digital Twin based on the level of interaction and synchronization between the physical and virtual components [2]. The definition is widely used in research, but additional efforts have been made to measure the fidelity or maturity of a Digital Twin and differentiate between integration stages using this definition as a baseline [27].

Several approaches have been proposed to assess the maturity of Digital Twins. Singh refines a maturity model by Madni, dividing it into four stages: Pre-Digital Twin, Digital Twin, Adaptive Digital Twin, and Intelligent Digital Twin [24]. In Singh's application to a battery system Digital Twin, the first two levels are classified as Digital Shadows, while Levels 3 and 4 are classified as Digital Twins. This research focuses on achieving Level-3 Digital Twins by providing guidelines and applicable tools and methods for Digital Twin creation [7].

Medina et al. propose a similar approach with four levels of maturity and ten dimensions. This model aims to benchmark Digital Twin implementations in the commercial aerospace industry. It also enables differentiation of Digital Twins across different companies [28].

Uhlenkamp et al. develop a classification framework to categorize existing Digital Twins and support the development of future Digital Twins. This framework identifies seven maturity models, each divided into dimensions for a detailed description. This method allows for comprehensive analysis and computational classification of Digital Twins, but it requires significant effort to assess the maturity level [27].

Klar reviews various maturity models to promote interoperability among Digital Twins. Comparing eight different approaches, Klar introduces an additional model due to the high domain specificity of existing models. Klar describes the current maturity models as domain-specific and isolated, which limits their interoperability. Klar extends a previous model by adding "Level 6: Interoperability," which is defined as "Highly linkable systems characterized by a high level of standardization, ontology definition, and semantic modeling." This maturity model builds upon Kritzinger's classification of Digital Model, Digital Shadow, and Digital Twin, identifying a Digital Twin from level four onwards ("two-way data communication and interaction") and extending the classification to include a connected Digital Twin at level six [29].

With a detailed understanding of the architectural terms and components associated with Digital Twins, the various types of Digital Twins are explored.

Types of Digital Twins

Different types of Digital Twins play a crucial role in each implementation, warranting further discussion. Generally, the further along the lifecycle, the larger the system that can be covered by the Digital Twin. However, this does not imply that a Digital Twin in a later lifecycle stage needs to cover the entire lifecycle, nor must it be a huge model, as the scope of the Digital Twin can differ.

Digital Twin types are classified into two layers: one based on the scope of the target entity and the other on the lifecycle stages. These are independent classifications but help better understand the discussion. The scope of Digital Twin types can be derived from the ISO/IEC standard [22] and includes the following categories:

- **Component Digital Twin**: A major element significantly impacting the performance of the target entity to which it belongs, related to system complexity. For example, a Digital Twin for a complex motor or pump within a system, where the system itself has a separate system-level Digital Twin.
- **Asset Digital Twin**: Collections of component Digital Twins, providing visibility at the unit level. An asset Digital Twin can consist of a single component, thus being considered both an asset Digital Twin and a component Digital Twin.
- **System Digital Twin**: A collection of target entities and digital entities performing a system- or network-wide function, providing visibility into interconnected or interdependent target entities.
- **Process Digital Twin**: Focuses on a set of activities or operations consisting of physical entities or system Digital Twins but emphasizes the process rather than the physical entities.

In addition to classification by the scope, it is essential to consider the type of Digital Twin concerning the product lifecycle. This particularly applies to space products, as space projects often follow a highly structured lifecycle approach due to the stringent requirements and challenges associated with space missions [30]. Nevertheless, it is important to note that most products across various industries also adhere to lifecycle phases to ensure systematic development, deployment, and maintenance. Therefore, Eigner et al. [3] categorized the Digital Twin into as-designed, as-built, and as-maintained phases aligned to the general project lifecycle phases. The Digital Twin categorization always summarizes two cycle phases into one Digital Twin phase, as depicted in Figure 2.4 in more detail. NASA divides its project lifecycle into seven phases from Pre-Phase A to Phase F. As the Pre-Phase is considered conceptual, only the subsequent phases align with Eigner's categorization. Phase A, "Concept and Technology Development," and Phase B, "Preliminary Design and Technology Completion," correspond to Eigner's phases of product planning and development, covering the "As-Designed" lifecycle stage of the Digital Twin system. The "As-Built" phase encompasses the project lifecycle phases Phase C, "Final Design and Fabrication," and Phase D, "System Assembly, Integration & Test, Launch & Checkout", which Eigner refers to as Process Planning and Production. The "As-Maintained" lifecycle stage of the Digital Twin includes Phase E, "Operations and Sustainment," and Phase F, "Closeout," which Eigner similarly refers to as Operation and Recycling [30].

- **As-Designed Phase**: Encompasses product development phases and concludes with the product's release for production.
- **As-Built Phase**: Describes the configuration-specific production of a product and extends to its handover to the customer.
- **As-Maintained Phase**: Accompanies the product's remaining service life until closeout.

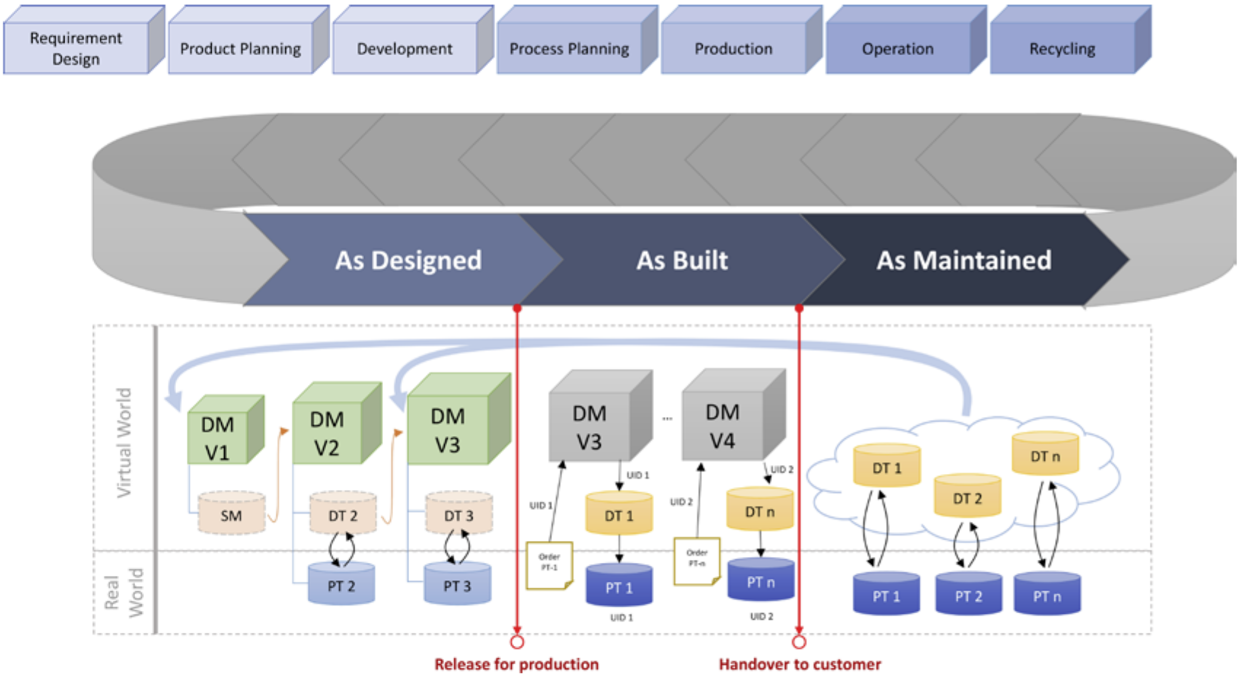

Figure 2.4 Digital Twin in the Product Lifecycle by [3]

This general overview provides a comprehensive understanding of Digital Twins, summarizing various definitions, clarifying architectural terms, and illustrating different classification possibilities. To further contextualize the applications of Digital Twins, the next section will explore their implementation across different domains.

2.2.2 Digital Twin Applications Various Domains

Digital Twins have found applications in a multitude of domains, each leveraging the technology to address unique challenges and enhance operational efficiency. This section first provides an overview of Digital Twin implementations across diverse fields such as manufacturing and logistics. It then focuses in more detail on the applications of Digital Twins in the aerospace sector, with a particular emphasis on satellites.

General Domains

The Digital Twin has already been applied in different domains. Most applications can be found in manufacturing and smart cities as well as use cases for logistics, healthcare, and computer networks [22]. Along with these different domains come various use cases, all leveraging similar benefits, such as investigating the physical entity's behavior in various scenarios, testing system enhancements through simulation, and troubleshooting incidents in the operational physical entity. Various studies have suggested that Digital Twins can significantly enhance supply chains by providing improved visibility, traceability, and authentication. They have also been highlighted as valuable decision support systems for risk management and methods to boost resilience and robustness, incorporating multimodal options and improving integration [29]. Specific applications in the computer network domain include optimizing the network through a Digital Twin Network or maintaining the network by implementing available meta-information into the Digital Twin to quickly identify the roots of errors. As physical networks often constitute critical infrastructure, trial runs in the actual network can lead to negative outcomes. Therefore, a Digital Twin Network serves as an environment to test new protocols or applications without risking the physical network and thereby fostering innovation in the sector [31]. The increasing connectivity through IoT is enhancing the effectiveness of Digital Twins in smart cities. As more cities adopt smart technologies, the use of Digital Twins grows, leveraging vast data from IoT sensors. These sensors enable monitoring and management of urban services, aiding in planning, development, and energy optimization. Digital Twins provides a virtual testbed for scenario testing and learning from environmental data, facilitating growth and future-proofing. The viability of Digital Twins rises with the expansion of smart city connectivity and data availability [16]

The manufacturing industry is rapidly transforming, with growing interest in exploiting Digital Twins. This technology holds significant potential to revolutionize various manufacturing activities by enabling real-time monitoring, optimization, and remote control of physical assets through virtual simulations. Advances in Industry 4.0 have facilitated the precise implementation of Digital Twins, enhancing sensing, monitoring, and decision-making tools [13]. The Digital Twin manages the product from the design stage through all manufacturing stages to the finished product [22]. This sector has also developed an advanced standard for its domain, defining common terms, aligning on applications and benefits, and establishing general principles within a common framework displayed in Figure 2.5.

For example, the application of "Off-line analytics" involves comparing the Digital Twin to the observable manufacturing element to identify trends and changes in the product. This process can lead to recommendations for future modifications, thereby benefiting loop planning, validation, and adjustment of manufacturing processes, ensuring the successful completion of the process.

This advancement is also evident in technologies developed under industry involvement through Industry 4.0 for enhanced operability, such as the Asset Administration Shell (AAS). The AAS is a Digital Twin solution for interoperable Cyber-Physical Production Systems, to which factories have evolved. The AAS serves as an information carrier, accessible through various interfaces, capturing different facets of the asset or entity and providing tailored views for different users based on their use cases [32]. The growth already accomplished in the manufacturing domain is applicable to aerospace Digital Twins, at least for the manufacturing phase of the product lifecycle [4]. However, as noted in the topic identification Section 2, aerospace research lags behind manufacturing. Despite this lag, the aerospace sector is increasingly recognizing the potential of Digital Twins to enhance various aspects of design, testing, and operations. The following section discusses the applications of Digital Twins within the aerospace industry, specifically in the satellite domain.

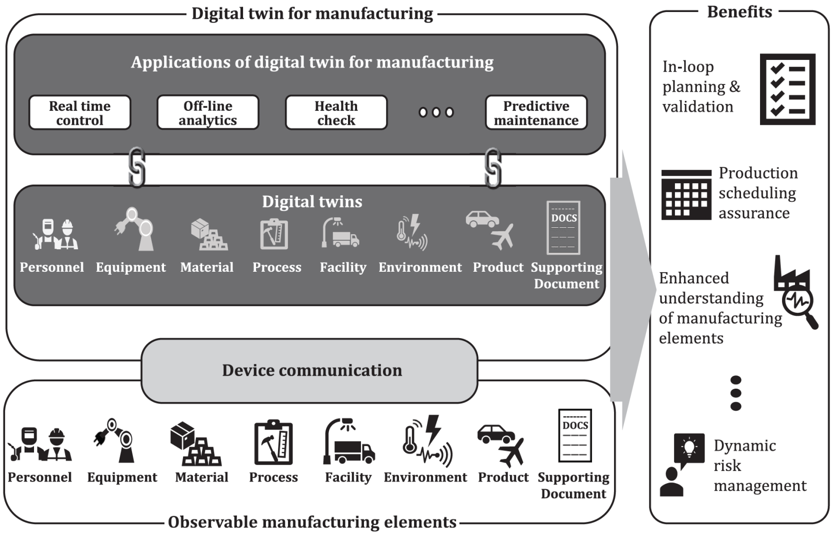

Figure 2.5 IoT Framework for Digital Twins in Manufacturing, Summarizing the Potential Components, Applications, and Benefits by [4]

Aerospace & Satellite Domain

Twins of spacecraft have been used in the aerospace sector since the 1960s [1], starting with mock-ups of spacecraft to internalize procedures before launch and try out solutions and approaches during spaceflight to solve problems and unscheduled events in a safe environment without risk to human beings. This approach was adopted for satellites by creating non-flight versions of satellites for testing and verifying designs with engineering models. These models remain on the ground and are used to try new procedures before implementation on the actual spacecraft, reducing the risk of damaging flight hardware. However, this traditional approach is resource-intensive, requiring significant time, material, and energy costs due to the high expense and uniqueness of spacecraft [33]. In the 2010s, NASA began investigating the use of Digital Twins in their projects, publishing a future roadmap outlining their potential applications and benefits [14].

Research has since expanded, and Digital Twins are now applied in various aerospace applications, from space science to commercial aircraft, covering single components to system-level twins [34]. This is reflected in the position paper by the American Institute of Aeronautics and Astronautics (AIAA) and the Aerospace Industries Association (AIA), which defines a common Digital Twin definition, applications, and value examples for different lifecycle stages [25].

Most research, however, focuses on aeronautics, particularly aircraft, with fewer studies on astronautics. Research on astronautics centers on spacecraft cockpit simulations or planetary missions [35][36]. While vendors of large digital simulation environments promise seamless integration for satellite systems, research specifically on Digital Twin implementation for satellites is limited [37].

Publications on Digital Twins for satellites tend to dive deeply into specific disciplines. Shangguan focuses on fault diagnosis and health monitoring calculations for geostationary satellites [38]. Plattner approaches Digital Twins indirectly through design space exploration of a satellite payload design for optimized thermal using a distributed processor system [39]. Schluse combines Virtual Testbeds and Digital Twins to create an "Experimental Digital Twin" approach that shows the application of a reference implementation of a modular satellite. They present a solution for the cooperation of multiple simulation processes but do not clearly explain the interaction of the physical to the digital domain, which a Digital Twin requires [40].

Koch presents a correlation strategy for a CubeSat to enhance mission understanding by feeding telemetry data back into the simulation tool [41]. NASA supported the University of Alabama in Huntsville 2017 with a grant to create a Digital Twin of their CubeSat to ensure mission success, but no further documentation has been found [42]. Borges et al. showed an implementation of a Digital Twin model for a CubeSat, with the aim to set a starting point for further establishment of a methodology for a reliable framework for the operation of a nanosatellite. However, they underline that although this topic has been studied in the aerospace field, the use and applications of Digital Twin technology in the context of small satellites are still nascent, with very few examples and systems implemented so far [43].

The observations throughout this chapter highlight the benefits of Digital Twin implementation and underscore the gap in the applications to small satellites like CubeSats. To address this gap, the next section presents CubeSats's state of the art, examining their current capabilities and challenges.

2.3 CubeSat State of the Art

Typical 3-axis stabilized spacecraft in the traditional space sector range between 900 kg to several tons, launching in large launch vehicles like the Ariane 5, which can bring up to 18 tons to LEO. Typically, launching two satellites in one configuration gives a rough estimation of the size of these satellites [33].

In contrast to the development of large communication or institutional satellites designed for multiple science missions, the evolution of small satellite missions began in the 1970s with NASA Ames Research Center launching Pioneer 10 and 11. As satellites' mass and associated costs increased, NASA initiated the Small Explorer program in the late 1980s to encourage the development of smaller spacecraft ranging from 60 to 350 kg. By the late 1990s, NASA shifted its focus to lunar exploration with the Ames' SmallSat program, targeting masses between 380 kg and 700 kg [5]. Parallel to these developments, the California Polytechnic State University and Stanford University collaborated to create the so-called "CubeSat", a small educational platform for space exploration and research. The CubeSat initiative aimed to reduce costs and development time while increasing access to space through frequent launches. Alongside the development of this platform, the CubeSat standard has been established to ensure the success and safety of future missions, providing baseline requirements that enable compatibility with various CubeSat dispensers and launch opportunities, independent of the satellite producer [44].

Although spacecraft with masses up to 700 kg have been classified as small historically, the growing interest in small satellites necessitated a more detailed classification. According to the NASA State of the Art Small Spacecraft Technology Report, small satellites are classified into five categories based on their mass as depicted in Figure 2.6 [5].

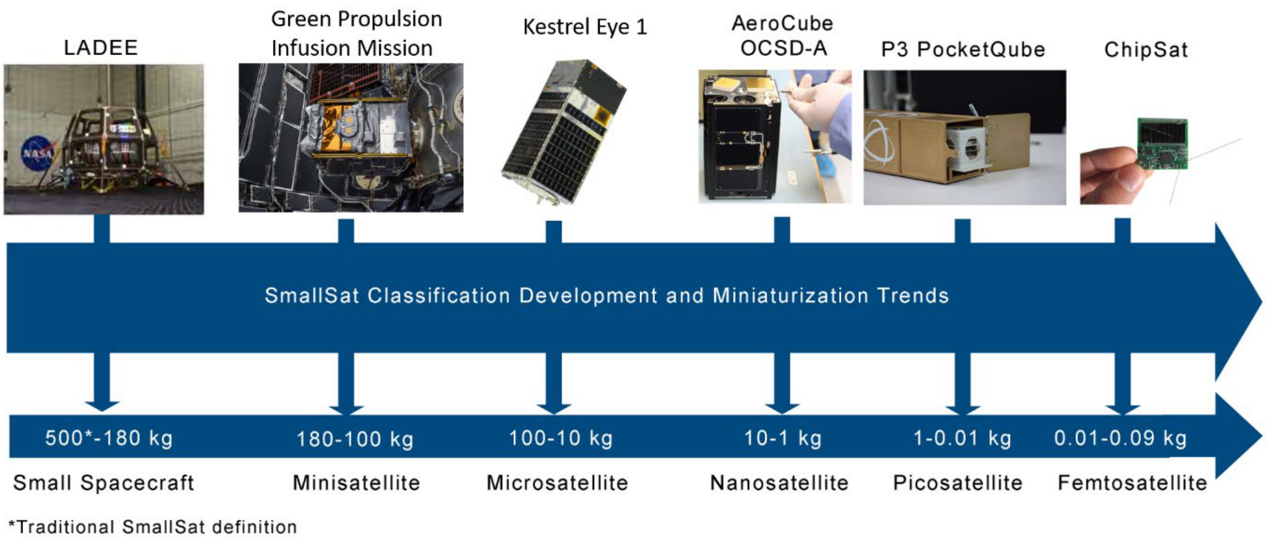

Figure 2.6 Overview of Small Spacecraft Categories by [5]

Initially designed as educational platforms, CubeSat has become a common type of small spacecraft based on a 10 cm cube called one unit (1U). While the original size has been 1U, combining multiple cubes, with sizes ranging from 1U to 12U covered by the current standard is state of the art. Larger sizes, such as 16U to 27U, are not included in the standard but are addressed in an advanced standard [45]. CubeSats and NanoSats are often used interchangeably, as the original 1-3U sizes fall under the nanosatellite category. With the increase in size, CubeSats also fall into the microsatellite category [5]. An overview of the different sizes compared to each other and classified into the different categories of small satellites is depicted in Figure 2.7.

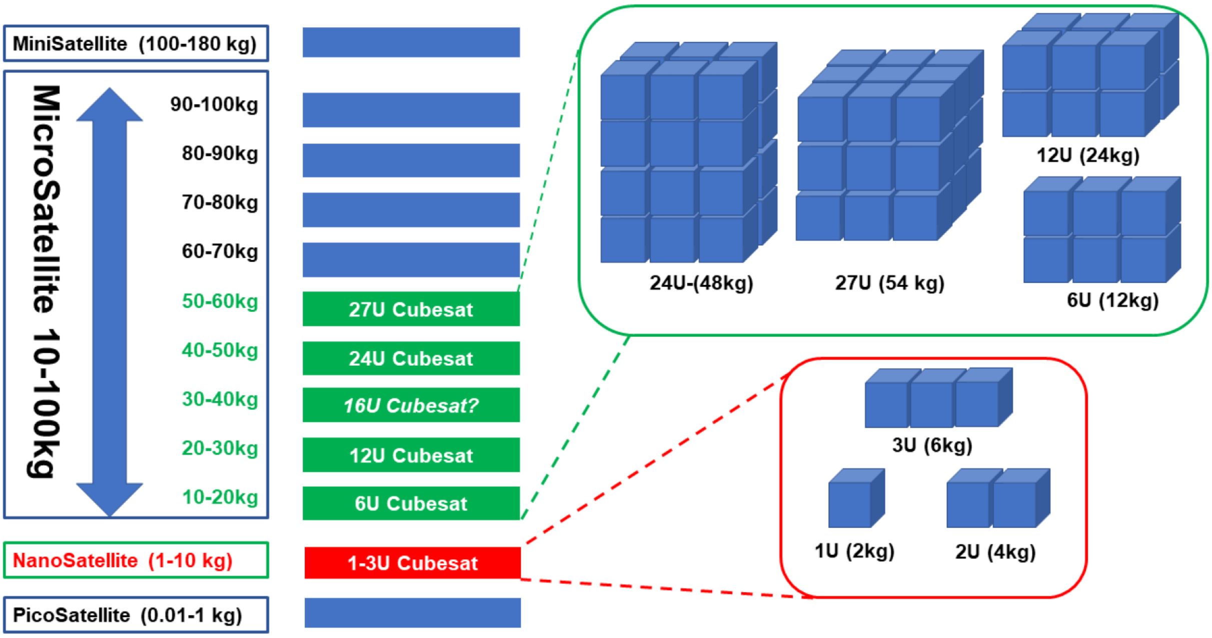

Figure 2.7 Nanosatellite Sizes Compared to CubeSat Containerized Sizes by [5]

CubeSats have been initially envisioned for educational or technology demonstration missions, with development timelines of 1 to 2 years. However, they have evolved to support more sophisticated missions with significant scientific and commercial value while maintaining low costs. Covering a wide range of mission objectives, including earth science, spaceborne applications, deep space exploration, heliophysics, space weather, astrophysics, spaceborne in situ laboratories, and technology demonstrations, this diversity and volume of missions underscore the substantial interest in CubeSat technology within the industry [46].

Advancements in technology miniaturization have facilitated the construction of small spacecraft using low-cost, low-power Commercial Off-The-Shelf (COTS) components. This development has significantly reduced the cost and complexity of launching CubeSats compared to traditional robust satellites with multiple redundant subsystems. Over the last fifteen years, the small satellite industry has experienced explosive growth, particularly within the nanosatellite class, with CubeSats being a major contributor to this growth [46]. To date, in May 2024, over 2604 nanosatellites have been launched, and over 2080 are expected to launch in the timeframe of 2022 to 2027 [47].

Companies specializing in CubeSat components have emerged, offering complete CubeSat platforms configurable online, with components available for purchase akin to other commercial products [48]. The low-cost strategy, coupled with short development times and standardized hardware components, enables rapid iterations of missions, integrating new technological advancements and lessons learned from previous missions [46]. Many new launch service companies offer or are soon to offer innovative, low-cost commercial launch systems designed to accommodate small satellite missions and will reduce the bottleneck of available launches [49].

Despite these advancements, the reliability of CubeSats remains a concern. A survey conducted by Langer revealed that 65% of CubeSat missions fail to meet all their mission objectives due to various issues, such as data bus failures, and 20% do not operate for their designed lifetime [50]. Testing is time and labor-intensive, and thus cost-intensive. Measures have already been taken in this direction, such as automated test benches to increase the actual resources of modern CubeSats in orbit, but these are only a single example of a growing market [15].

These statistics indicate that while significant progress has been made, further research is needed to enhance the reliability of CubeSat missions and help ensure mission success for the many missions to come.

2.4 Research Gap

The last chapter highlighted the significant evolution of CubeSats into a commercial platform available for a variety of scientific and commercial missions. The process of getting a satellite into space has become more accessible than ever. This development has led to an industry that disrupts the traditional space market with innovative approaches in all fields of satellite development, from engineering to sales. Examples include satellite-as-a-service models and CubeSat companies offering products through online stores with rapid delivery times. The sheer number of satellites expected to launch demonstrates the high industry interest. Despite the iterative approach of replacing failed CubeSats with new ones, the lack of reliability remains a critical issue, necessitating advanced verification and prediction methods. This is particularly important for the long-term future when space becomes more crowded, and failing satellites could cause significant chain reactions. CubeSats have the opportunity to achieve advancements due to their similar interfaces, form factors, modular structures, and higher launch rates compared to traditional space satellites.
Notably, the space sector, particularly the CubeSat sector, shows insufficient research in conjunction with Digital Twins. Literature specifically addressing Digital Twins in CubeSats is scarce, as evidenced by the substantial differences in literature search results in Table 2.1. Other authors support this observation. In contrast, the manufacturing sector has established standards for Digital Twin technology, with numerous companies already implementing it in their operations [4][51]. The technology is evolving, along with the recognition of its benefits and its application throughout the lifecycle.

Despite these advancements, implementing a Digital Twin is not yet easily accessible. There is still a lack of Digital Twin implementations in research, and clear frameworks are missing. This gap highlights the need for a concise clarification of the criterion of Digital Twins, the proposal of a methodology for the implementation of a CubeSat Digital Twin, and the demonstration of its application in a practical example. This research contributes novelty by presenting a comprehensive methodology for a CubeSat Digital Twin.

3 Industry Evaluation

A survey has been conducted to expand the knowledge of Digital Twins in the satellite domain. It collects insights into the conception and understanding of the Digital Twin, its usage, and its relation to CubeSats in the industry. The survey consists of a questionnaire and an interview aimed at addressing industry experts. Beyond the research conducted through the literature review, an empirical evaluation of the topic of Digital Twins in the satellite industry by means of a survey provides further insights into the state-of-the-art development. Additionally, it enables gathering the challenges companies face when considering implementing a Digital Twin. This gives further insights into current projects that are under development in institutions that do not publish their work, which is especially the case in the private industry or projects that have not reached the stage of development that brings novelty to the field of research.

3.1 Survey Design

The survey has been designed based on the methodology of the book *Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften*[1] by Döring and Bortz [52] to ensure consistent results, which can be used to compare to the existing literature. This methodology has been selected based on recommendations of professors from Human Factors Research at TUM, who regularly conduct studies with surveys and interviews. The survey has been approached systematically following the guidelines and recommendations of this book, which have been adjusted to the required needs and circumstances. These can be summarized into the following five steps:

1. Identifying the characteristics of the research design
2. Evaluating the population and the appropriate sample size
3. Formulating a strategy to identify and recruit the appropriate participants for the survey
4. Developing a framework for designing the questionnaire
5. Establishing the framework for conducting interviews

3.1.1 Research Design Characteristics Identification

The literature review has shown that there are only a few publications exist on the direction of a Digital Twin for CubeSats. A clear hypothesis about a proposed CubeSat Digital Twin or its usage is missing. Therefore, the study has been approached in an explanatory manner to develop a hypothesis about the current status of the satellite industry regarding the Digital Twin and use this outcome to develop an optimized methodology.

In designing the survey, multiple factors have been considered: achieving optimal results through integrating quantitative and qualitative methods, minimizing response barriers to enhance participation rates, and ensuring that the time and personnel investment is commensurate with the anticipated outcomes. Therefore, a questionnaire and an expert interview have been selected. The questionnaire addresses the broader satellite sector to find the differences between Digital Twins for various satellite sizes and their purpose. Answering this highly structured format enabled the individual to answer by self-scheduling the response time in a discreet and anonymous way and enabled them to raise their interest in the topic to contribute additional knowledge. An

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[1] [Eng.] Research methods and evaluation in the social and human sciences

additional expert interview allows for a follow-up on the outcome of the questionnaire and provides background information about the interviewees and the topic itself, giving access to much more information in less time. Another reason for the interview has been the aim to collect more information in the direction of a CubSat Digital Twin and collect their open opinion on the topic of CubeSats without being held back by the boundaries of a structured questionnaire [52]. The survey aims to understand the current situation within a population. Therefore, a cross-sectional study, in which a sample of the base population is interviewed at a single point in time, is entirely sufficient [53]. This approach has been chosen for this thesis to focus on the present state of the Digital Twin in the satellite domain.

3.1.2 Population Evaluation and Sample Size

The study's target population is people involved in Digital Twin developments in any form and work in Digital Twins and the satellite industry. The lack of publicly available numbers of people counting to this population causes a challenge in selecting the correct population. Therefore, no fixed sample size can be determined. However, since the study is exploratory in nature, a small, non-random sample size is sufficient according to [52]. Marshall et al. further emphasize that 20 to 30 interviews should generally be conducted for grounded theory qualitative studies [54]. The sample's representativeness should always be considered when interpreting the results. This does not imply that the study lacks value for the topic. However, it is crucial to recognize that only a non-representative sample has been collected. Consequently, the study results cannot be generalized to the entire satellite industry.

3.1.3 Participants Recruiting Strategy

The target population represents a specialized group of people, making it challenging to identify potential members. There is no publicly available register of experts relevant to the study nor a centralized location to reach them all within the limited time frame of this research. Consequently, a snowball sampling approach has been employed, wherein initial respondents have been asked to recruit further potential experts for the study. This method inherently limits the ability to claim sample representativeness, as the sample is arbitrary and non-probabilistic, making its representativeness for the target population unknown [52].

This has been achieved through the distribution of the questionnaire via multiple channels. On the one hand, the personal networks of the authors and supervisors have been utilized to distribute the questionnaire to potential representatives of the population. Additionally, personal invitations to the questionnaire have been sent to selected authors of publications with overlapping topics. All invitees have been encouraged to provide additional contacts who could answer the questionnaire or to share the questionnaire with potential representatives. To avoid compromising the survey results, public distribution of the survey has been avoided. This measure ensured that only relevant experts participated, preventing responses from individuals outside the field.

The questionnaire concluded with the invitation to participate in the qualitative interview of the survey.

3.1.4 Framework Questionnaire

A quantitative or fully standardized questionnaire has been used for the survey. This type of questionnaire consists of closed questions or statements with predetermined answer options, allowing respondents to select the most appropriate responses. The scientific questionnaire is targeted to systematically generate numerical self-reports from respondents on selected aspects.

The questionnaire is divided into several sections, each with a specific focus and set of questions, ensuring a systematic approach to gathering information from respondents. The diagram in Figure 3.1 below provides an overview of the questionnaire structure.

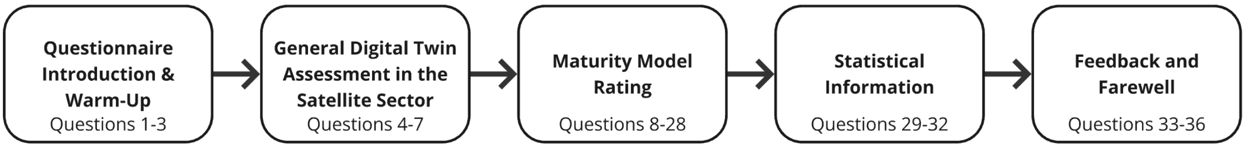

Figure 3.1 Setup of the Questionnaire

- Questionnaire Introduction & Warm-Up (Questions 1-3) - This section contains introductory questions that are straightforward and easy to answer. The purpose is to ease respondents into the survey, making them comfortable with the process before moving on to more specific topics.
- General Digital Twin Assessment in the Satellite Sector (Questions 4-7) - These questions focus on assessing the general understanding and implementation of Digital Twin technology within the satellite sector. This section aims to gather broad insights from experts, providing foundational data on the current state of Digital Twins in this field.
- Maturity Model Rating (Questions 8-28) - This block includes questions based on an adopted maturity model, featuring yes/no paths to assess the maturity level of the respondent's organization or projects. The detailed questions help evaluate the progress and sophistication of Digital Twin implementations in various contexts.
- Statistical Information (Questions 29-32) - This section collects demographic and statistical data to classify the respondents. These questions are crucial for analyzing the survey results in relation to the backgrounds and characteristics of the participants.
- Feedback and Farewell (Questions 33-36) - Questions or prompts allow respondents to provide questionnaire feedback and conclude the survey.

The questionnaire design aims to ensure that participants can answer the questionnaire regardless of whether they have implemented a Digital Twin in their organization. All questions have been created to collect as many opinions as possible on the topic. The Appendix A.2 depicts a printed version of the questionnaire and can be found on the thesis's Gitlab [2] repository.

The survey begins with easy questions to avoid overwhelming respondents and aims to make respondents comfortable, encouraging more thoughtful and detailed responses in subsequent sections. The first question intends to lightly classify them from the start by addressing their familiarity with the context of a Digital Twin in satellite technology. The second question targets the general interest of the organization in the topic. The third question treats the discrepancy found in the definitions of the Digital Twin, asking them to select their three most fitting terms for the Digital Twin out of eleven possibilities.

The second block of questions addresses the general implementation of the Digital Twin for a satellite. The fourth question asks to rate the interest in implementing a Digital Twin according to the lifecycle stages of projects. Question five evaluates the potential future for a Digital Twin in the aerospace sector. The next two questions try to address the potential advantages the participants see for different satellites in implementing a Digital Twin. First, the satellites are classified after their purpose, and second, they are classified after their mass.

The Maturity Model constitutes the primary block of the questionnaire. It is based on the maturity model for aerospace by Medina et al. [28]. The original maturity model, designed for original equipment manufacturers in the commercial aerospace sector, has been adapted for this questionnaire to ensure its applicability to the satellite domain. While retaining the scientifically validated foundation of the original model, modifications have been made to shift the focus from classifying Digital Twins of aircraft to classifying Digital Twins of satellites. The adopted maturity model can be found in Appendix A.1. In order to clearly separate the answers,

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[2] https://gitlab.lrz.de/leonhard.kessler/leonhard-kessler-master-thesis

a separation question has been included in the maturity model block, asking whether or not a Digital Twin exists in their organization. Accordingly, the following questions ask respondents to rate their implemented Digital Twin or an envisioned one.

The last block with questions is created to collect statistical information of the participants. This serves primarily to describe the surveyed sample based on general sociodemographic characteristics. Question 29 is designed similarly to Question six, but this time not to rate the potential Digital Twin advantages but to describe their organization's primary focus. Question 30 asks for the educational background, and Question 32 assesses the years of experience in the industry.

The last block brings the questionnaire to an end. Question 33 asks for additional contacts to share the survey with. If they give a positive answer, they are forwarded to the next question to insert the contacts there. Question 35 brings up the topic of the interview and asks if they want to participate. The last question asks for feedback on the questionnaire and additional thoughts. A last statement thanks for participating and provides contact information for further inquiries.

Pre-existing question items have been utilized as answer options for various questions in the questionnaire to enhance comparability with other studies. This approach has been applied to the maturity model, which served as the main block, and to the user profiling and initial questions. The answering possibilities, often referred to as items, have been sourced from different references, such as the State-of-the-Art of Small Spacecraft Technology report of NASA [5] and the NASA Systems Engineering Handbook [30]. Definition phrases have been carefully selected from relevant literature sources [55] [23] [24] [26] [27]. The statistical questions have been based on established questionnaire items [56], and further inspiration has been drawn from sources like the satellite classification taxonomy [57]. All questions have been designed to mitigate the central tendency bias, which is common in questionnaires offering mirrored solution spaces, to avoid respondents favoring moderate responses.

After the development of the questionnaire, the logic and the questions have been implemented into Typeform [58]. This online survey tool has been selected because of its professional appearance, the multiple possibilities to set up the questions, the implementation of the logic in a way as intended, and the fact that there is no need to log in when answering. Another option would have been Google Forms [59]. However, due to the lack of options for customizing the questions and answers, as well as the logic and the lack of a professional appearance or the integration of a logo in Google Forms, Typeform has been chosen for the execution of the questionnaire. The "Basic" plan of Typeform was selected.

The final questionnaire has been shared with participants via this link [3].

3.1.5 Framework Interview

The aim of the interview is to obtain scientifically qualified answers from experts in the fields of satellites and Digital Twins, bringing important insights into the topic in a more natural setting. The interview allows for discussions in an asymmetric communication situation with a clear and coordinated role distribution. The expected outcome is a clear interview transcript that provides intersubjectively traceable conclusions about the usage of Digital Twins in the satellite sector, with a stronger focus on their relation to CubeSats.

The qualitative interview is designed in a semi-structured manner. This design is based on a catalog of open questions stated by the interviewer that the interviewee answers in his own words, but it allows the interviewer, depending on the interview situation, to make adjustments to the flow and the direction of the interview. The interviewee can answer questions in their own words, and the interviewer can ask pertinent follow-up questions. This approach not only captures the respondents' answers but also their thoughts, feelings, and reactions, which enrich the final analysis of the topic. The interviews are primarily conducted on a one-to-one basis, but group interviews are also possible if multiple participants from one institution are available. Group interviews can uncover contradictions and capture shared perspectives in a natural conversation setting [52].

The interview setup is broad to include as many experts as possible while adhering to scientific standards. Interviews can be conducted in person, via phone, or through online conferences, ensuring there is always an audio recording for later comparison. Multiple online conference tools are offered, and the invitation to

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[3] https://form.typeform.com/to/FISivI2Q

participate is as open as possible, allowing interviewees the freedom to choose the method and timing of the interview.
Similar to the questionnaire, there are two versions of the interview: one for participants who have implemented a Digital Twin in their institution and one for those who have not. The interview is structured into four sections, along with an introduction and a conclusion.

Introduction

- The interviewer introduces themselves and outlines the broad goal of the interview: "Collect stories and voices about implemented/the absence of Digital Twins in the satellite domain," providing context for the study and emphasizing the commitment to maintaining anonymity throughout the study.

Section 1: Biographic Information

- This section gathers biographic information about the interviewee, identifying their connection to the topic of Digital Twins and any known experience with CubeSats.

Section 2: Description of Digital Twin/Current Practices

- For interviewees with a Digital Twin, questions focus on an in-depth description of the Digital Twin, including physical and digital coverage, organizational structure, simulation models, and analytical techniques used.

- For interviewees without a Digital Twin, questions focus on their current practices and methods for managing, developing, and operating satellite systems, their approaches to digital engineering, and the tools they use for simulation and data analysis.

Section 3: Strategy Towards Digital Twin/Understanding the Absence of a Digital Twin

- For Digital Twin users, this section explores their strategy towards Digital Twin implementation, including their research and practical implementation strategies, key success factors, and challenges faced during development.

- For non-Digital Twin users, questions explore their considerations and reasons for not implementing a Digital Twin, challenges and barriers faced, and constraints influencing their decision.

Section 4: Potential Benefits and Opportunities

- Both interview versions converge in this section, focusing on the potential benefits and values of Digital Twins, opinions on the need for consistent guidelines, and their impact on the field. Questions also address the differences and unique challenges of developing Digital Twins for CubeSats compared to other satellites. The section concludes with a discussion on the interviewee's future plans related to Digital Twins.

Conclusion

- The interview concludes with a reiteration of the commitment to anonymity and an offer to share the final results and transcript of the interview, allowing interviewees to reflect on the questions and their responses.

This comprehensive interview setup aims to gather nuanced insights into the adoption and development of Digital Twins in the satellite sector, contributing to a deeper understanding of the topic.

Conducting the Interviews

The interviewees are invited to participate in the interview via email after they provide their consent through the questionnaire. This email communication allows them to decide on the time and date of the interview, as well

as their preferred mode of conducting the interview. With the interviewee's consent, the interview is recorded using built-in tools of online meeting platforms like Zoom or Microsoft Teams [60][61], providing audio and video files for subsequent analysis. In addition to the recording, the interviewer takes notes on a printed version of the interview questions to capture key responses and plan follow-up questions to guide the interview.
Following the interview, the audio file is used to create a transcript. Given the transcript's importance as a valuable artifact, high accuracy is prioritized in its creation. A stepwise approach is employed for the transcription process:

1. **Initial Transcription**: The first textual version of the audio file is generated using the Whisper model by OpenAI, a general-purpose speech recognition model implemented in a Python script [62]. The large model is chosen for its superior accuracy despite slower transcription speeds.
2. **Speaker Diarization**: The spoken segments are then diarized to attribute them to individual speakers using Pyannote.audio, an open-source toolkit in Python [63][64]. This toolkit employs pre-trained models and pipelines to identify different speakers in the interview. Pyannote.audio is also implemented in a Python script, outputting data in an Excel file for further manual revision.
3. **Manual Revision**: Manual revision ensures the transcript reproduces spoken words accurately. This step includes reviewing text segments, verifying speaker assignments, tagging key themes in different segments, annotating the segments, and aligning the interview sections with the corresponding transcript segments.

After the transcription process, detailed documentation and a summary of the interview are created to provide a concise information source for review. This documentation is sent to the interviewee and anonymized for the scientific documentation of the research. In accordance with research ethics, the interview material containing personal data is deleted after the submission of the thesis, as interview statements are personal data, and the anonymized transcripts serve as the primary scientific artifacts.

The final interview guides are depicted in the Appendix A.3. Together with the transcripts, they can be found on the thesis's Gitlab[4] repository.

3.2 Outcome

3.2.1 Results Questionnaire

This section presents the results of the questionnaire to gather insights into the usage of Digital Twins in the satellite sector. The questionnaire aimed to collect comprehensive data from experts, focusing on their experiences and views on Digital Twins, particularly in relation to satellites in general.

General Achievements

The questionnaire achieved the following results by July 2024:

- **Views:** 99
- **Starts:** 55
- **Submissions:** 28
- **Completion rate:** 55.5%
- **Average time to complete:** 22:15 minutes

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[4] https://gitlab.lrz.de/leonhard.kessler/leonhard-kessler-master-thesis

The goal of obtaining a sufficient quantity of answers to draw meaningful conclusions has been met with 28 responses, according to Marshall's criteria [54]. However, the average time to complete the questionnaire exceeded the intended 10-15 minutes, indicating a potential area for improvement.
Several challenges have been identified during the questionnaire:

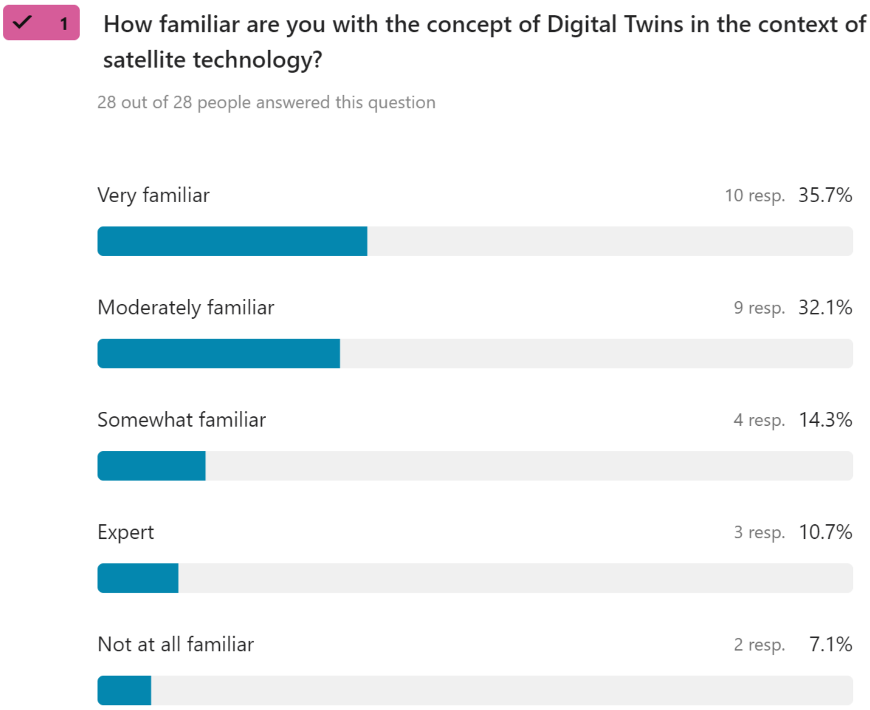
- A significant number of participants viewed the questionnaire but did not start it.
- The time to complete the questionnaire has been longer than anticipated.
- There has been a noticeable drop-off between the number of starts and the number of submissions.

Detailed Outcome by Sections

The following subsections present an overview of the answers to the questionnaire, organized by the relevant sections. The extensive list of single answers can be found on Typeform[5] as well as on the thesis's GitLab[6] repository.

Questionnaire Introduction & Warm-Up

- The first question in Figure 3.2 aimed to gauge the respondents' familiarity with the concept of Digital Twins in the context of satellite technology. The distribution indicates a high familiarity among the respondents, with over 78% indicating at least moderate familiarity with Digital Twins.



How familiar are you with the concept of Digital Twins in the context of satellite technology?

28 out of 28 people answered this question

Very familiar	10 resp.	35.7%
Moderately familiar	9 resp.	32.1%
Somewhat familiar	4 resp.	14.3%
Expert	3 resp.	10.7%
Not at all familiar	2 resp.	7.1%

Figure 3.2 Outcome Question 1 - Questionnaire Introduction & Warm-Up

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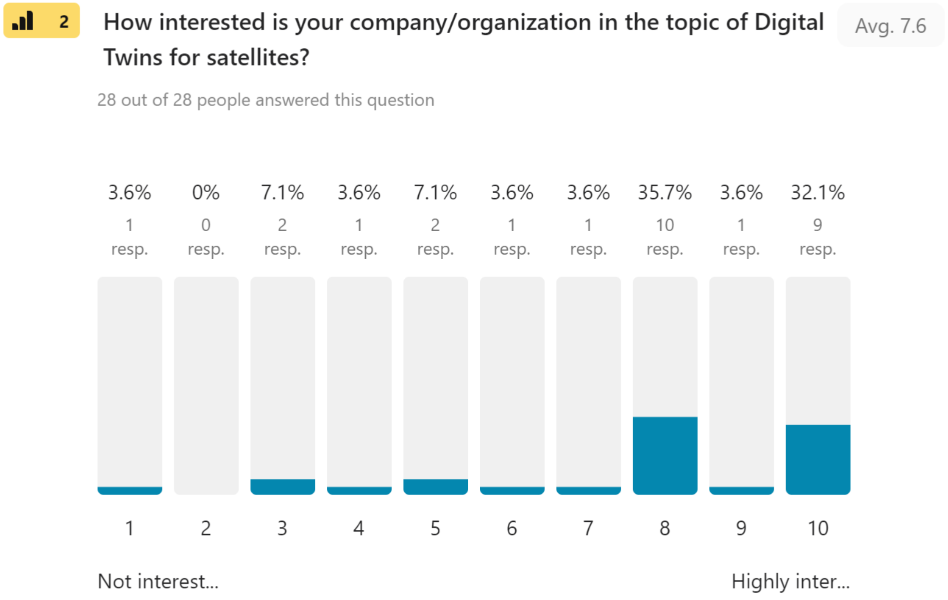
[5] https://qp5qxpdwn4e.typeform.com/report/FISivI2Q/42G9ifT0iLW4aiO7?view

[6] https://gitlab.lrz.de/leonhard.kessler/leonhard-kessler-master-thesis

- The second question in Figure 3.3 assessed the level of interest of the respondents' companies or organizations in the topic of Digital Twins for satellites. The average interest level has been 7.6, indicating a generally moderate to high interest in Digital Twins for satellites among the respondents.



2 How interested is your company/organization in the topic of Digital Twins for satellites?

Avg. 7.6

28 out of 28 people answered this question

Figure 3.3 Outcome Question 2 - Questionnaire Introduction & Warm-Up

- The third question in Figure 3.4 asked respondents to select the three most fitting terms for their definition of a Digital Twin. The top three terms selected have been "Dynamic digital representation," "Behavior mirroring," and "Integrated simulation," highlighting these as key characteristics in the respondents' understanding of Digital Twins.

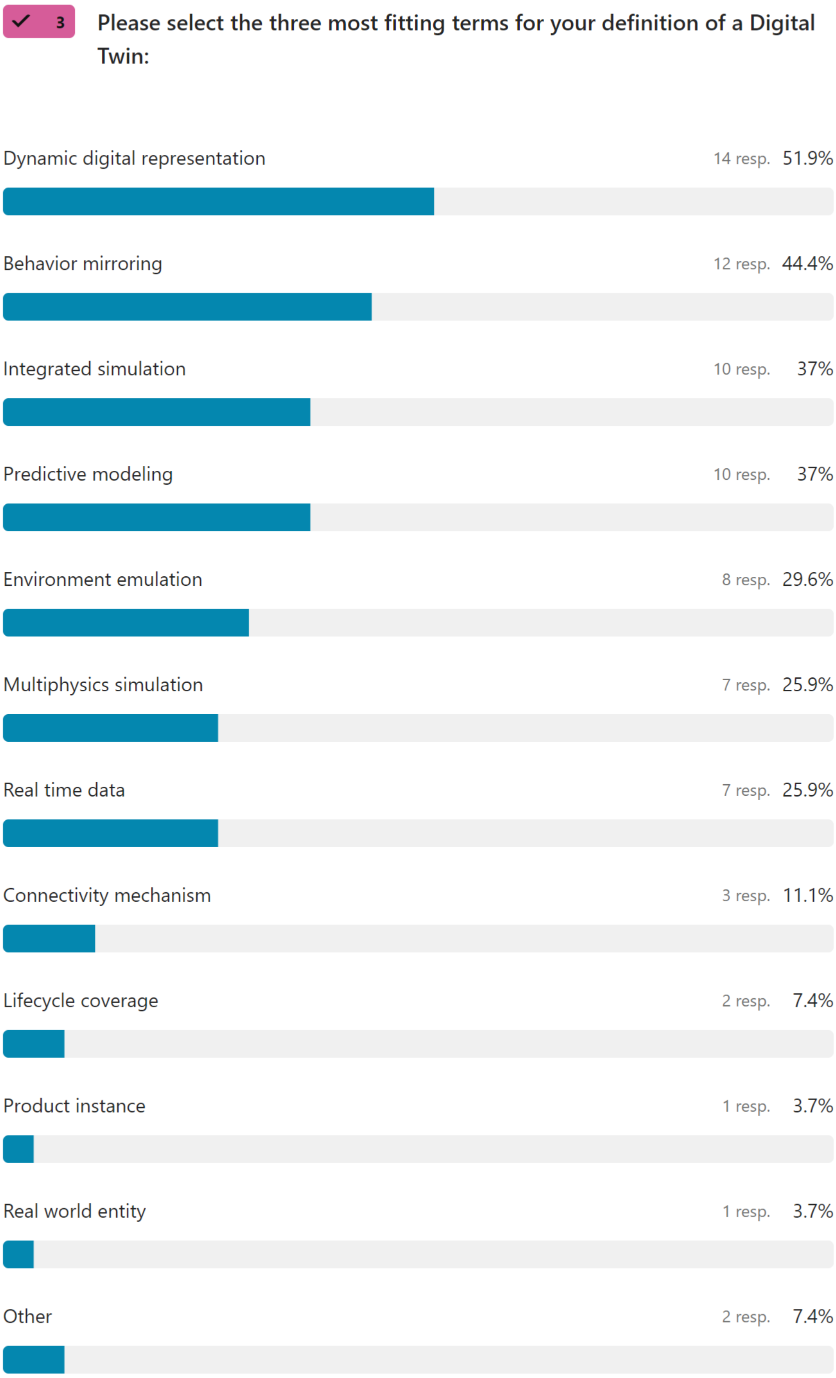
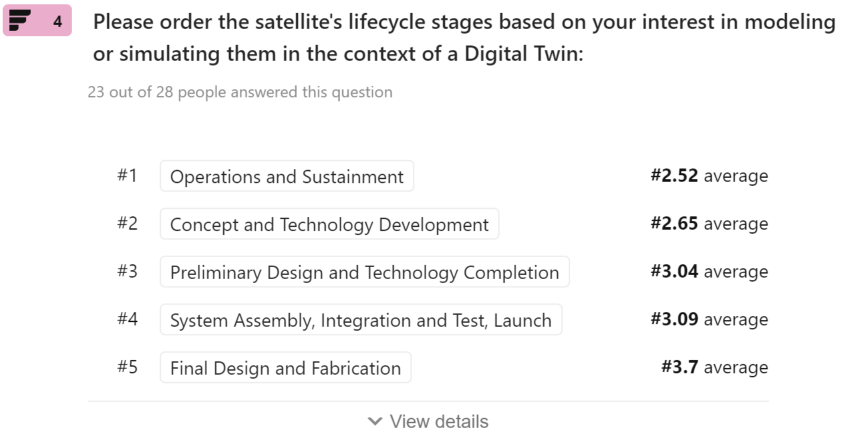


Figure 3.4 Outcome Question 3 - Questionnaire Introduction & Warm-Up

General Digital Twin Assessment in the Satellite Sector

- The fourth question in Figure 3.5 asked respondents to rank the satellite lifecycle stages based on their interest in modeling or simulating them within the context of a Digital Twin. The ranking indicates that the respondents are most interested in using Digital Twin technology for the operations and sustainment stage, followed by concept and technology development.



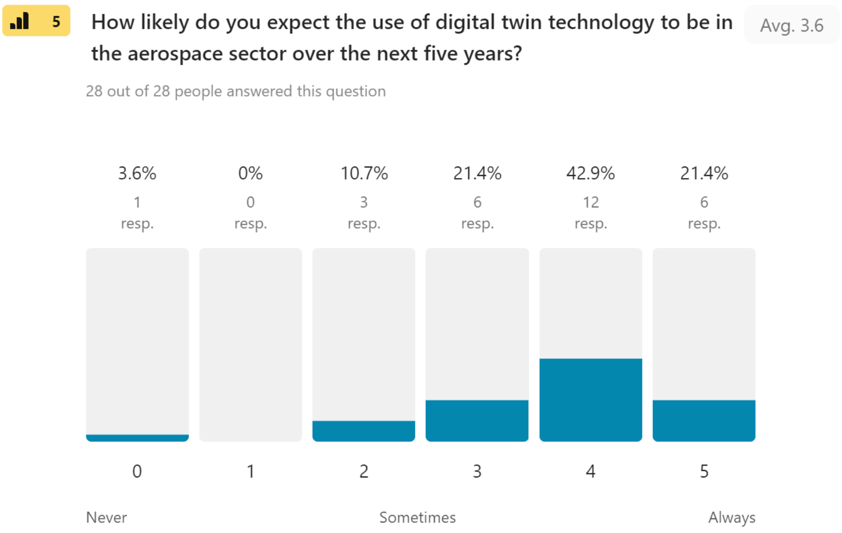
4 Please order the satellite's lifecycle stages based on your interest in modeling or simulating them in the context of a Digital Twin:

23 out of 28 people answered this question

#1	Operations and Sustainment	**#2.52** average
#2	Concept and Technology Development	**#2.65** average
#3	Preliminary Design and Technology Completion	**#3.04** average
#4	System Assembly, Integration and Test, Launch	**#3.09** average
#5	Final Design and Fabrication	**#3.7** average

Figure 3.5 Outcome Question 4 - General Digital Twin Assessment in the Satellite Sector

- The fifth question in Figure 3.6 aimed to understand how likely respondents believe Digital Twin technology will be used in the aerospace sector over the next five years. The average likelihood has been 3.6, indicating a moderate expectation that Digital Twins will see increased use in the aerospace sector in the next five years.



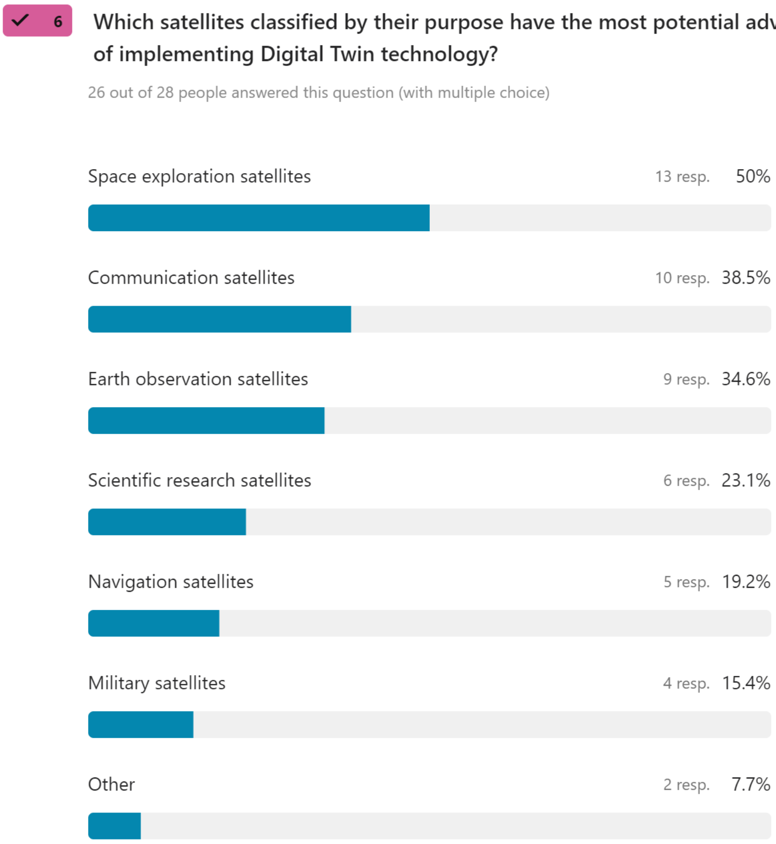
5 How likely do you expect the use of digital twin technology to be in the aerospace sector over the next five years?

Avg. 3.6

28 out of 28 people answered this question

Figure 3.6 Outcome Question 5 - General Digital Twin Assessment in the Satellite Sector

- The sixth question in Figure 3.7 asked which types of satellites, classified by their purpose, have the most potential advantages from implementing Digital Twin technology. The outcome indicates that space exploration is perceived to benefit the most from Digital Twins, shortly followed by Communication satellites and Earth Observation satellites.



✓ 6 Which satellites classified by their purpose have the most potential advantages of implementing Digital Twin technology?

26 out of 28 people answered this question (with multiple choice)

Figure 3.7 Outcome Question 6 - General Digital Twin Assessment in the Satellite Sector

- The seventh question in Figure 3.8 asked which types of satellites, classified by their mass, have the most potential advantages from implementing Digital Twin technology. The distribution of answers suggests that medium and large spacecraft are seen as having the most potential advantages from Digital Twin technology.

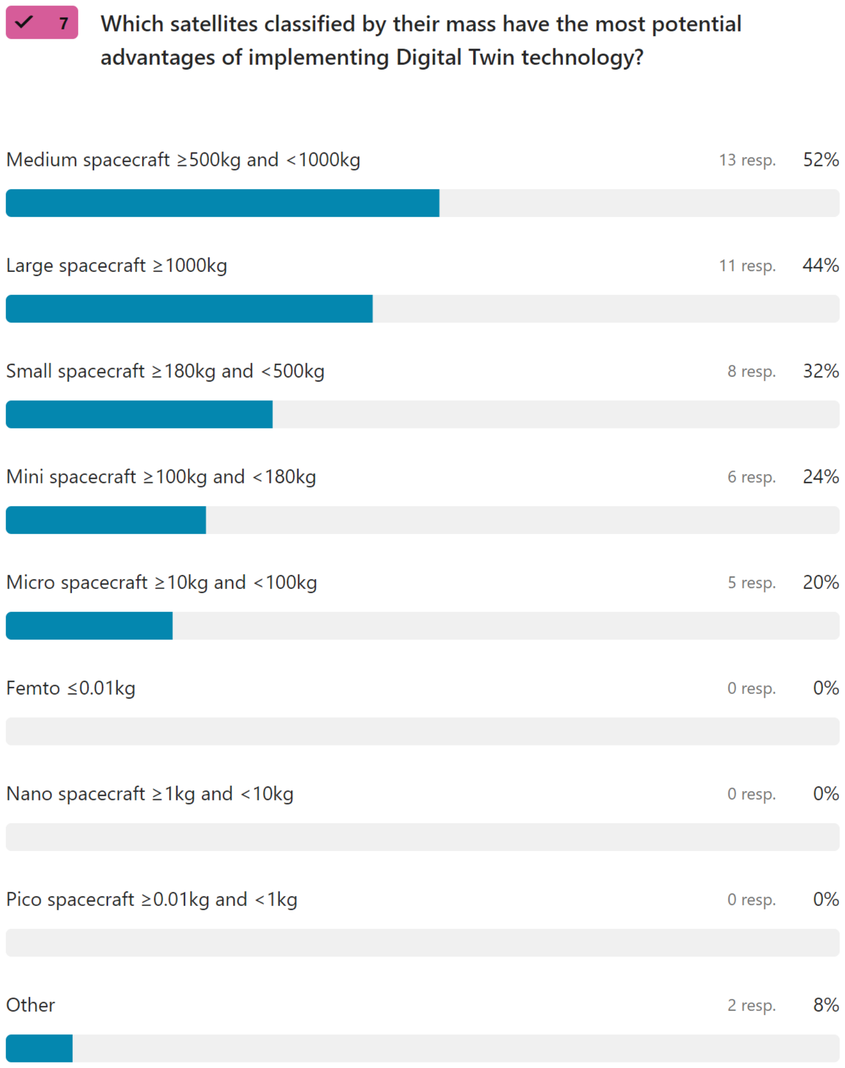


Figure 3.8 Outcome Question 7 - General Digital Twin Assessment in the Satellite Sector

Maturity Model Rating

In Figure 3.9, answers of participants with an implemented Digital Twin are displayed, and in Figure 3.10, answers of participants without a Digital Twin are depicted. Each chart reflects different dimensions of Digital Twin maturity, with the number of votes and corresponding percentages indicating the prevalence of each level of maturity for this category.

Rating of participants that have implemented a Digital Twin

Respondents rated various aspects of their Digital Twin implementations within their organizations.

- The majority of respondents indicated that their Digital Twin is primarily used for Monitoring and Prediction, each receiving 42.9 % of the votes.
- Most organizations update their Digital Twin on a weekly basis, followed by daily and minute-based updates.
- Data collection is predominantly scheduled (35.7 %) or irregular (28.6 %).

- The focus of modeling is largely on complete products (35.7 %) and product environments (28.6 %).
- Decision-making is mostly supported by a "Human in the Loop" approach (42.9 %).
- The majority of respondents (57.1 %) integrate the Digital Twin in a single lifecycle stage.
- Most organizations individualize the Digital Twin with "As-operated" data (78.6 %).
- The Digital Twin primarily affects business processes (35.7 %) and design (28.6 %).
- Operational data access is equally split between conditional, restricted, and full access (each 21.4 %).
- Most respondents indicated that their Digital Twin implementation is in the development stage (71.4 %).

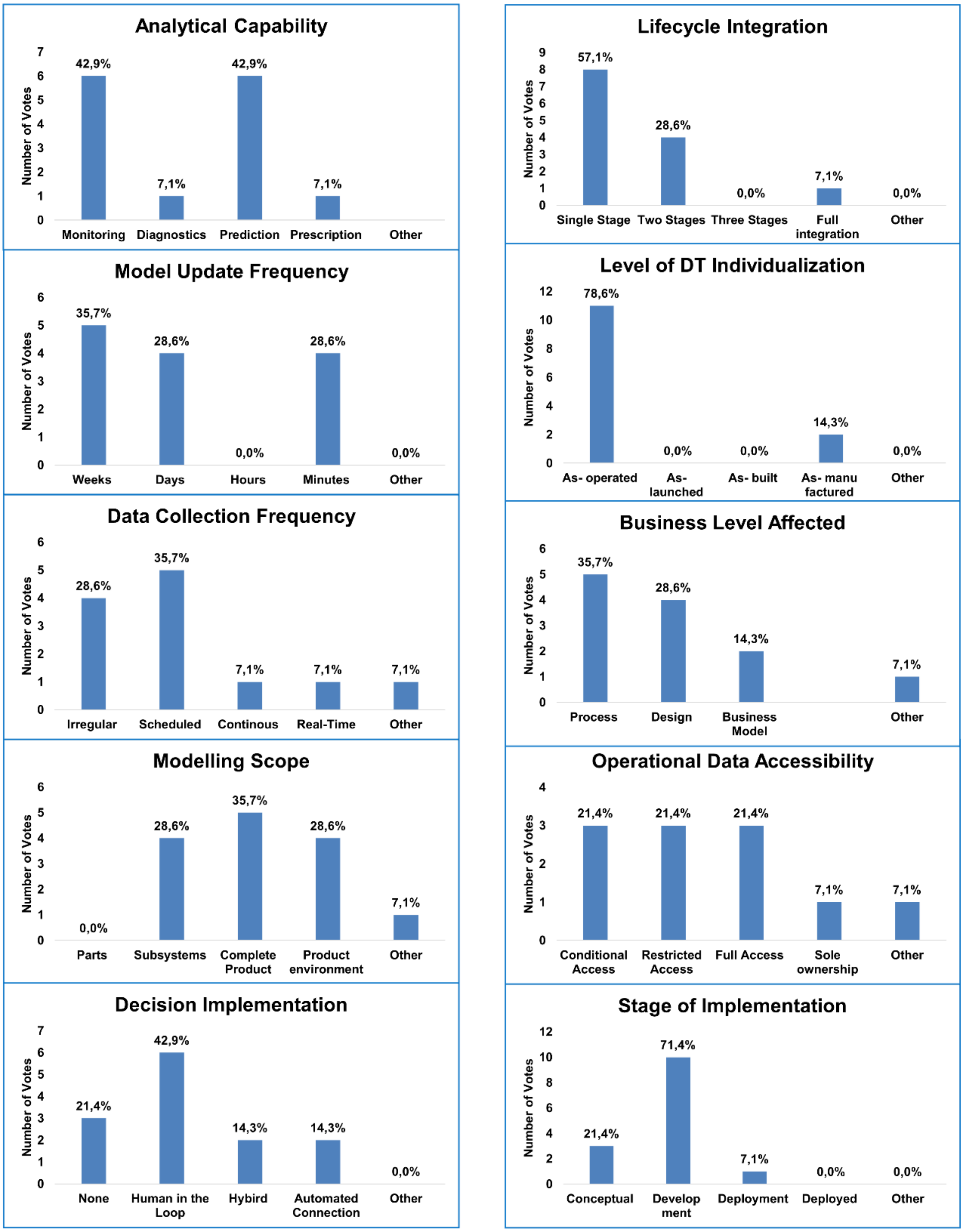


Figure 3.9 Ratings of the Maturity Model with a Digital Twin Implemented - 15 Participants

Rating of participants that have not implemented a Digital Twin

Respondents without an existing Digital Twin implementation rated various aspects of their envisioned Digital Twin.

- The majority of respondents indicated that they envision their Digital Twin being primarily used for Prediction (53.8 %).
- Envisioned Digital Twins are expected to be updated most frequently on a weekly basis (30.8 %), with significant consideration for updates in minutes and hours as well.
- Data collection is evenly distributed among irregular, scheduled, continuous, and real-time frequencies (23.1 % each).
- Envisioned Digital Twins are expected to focus largely on complete products and product environments (30.8 % each).
- Decision-making is expected to be mostly supported by a Hybrid approach (46.2 %).
- Respondents envision a significant portion of Digital Twins achieving full integration (30.8 %).
- Most respondents expect their Digital Twins to be individualized at the "As-operated" stage (61.5 %).
- Envisioned Digital Twins are expected to impact the business model significantly (30.8 %).
- Operational data is envisioned to be mostly conditionally accessible (30.8 %).
- The envisioned stage of implementation is mostly in the development phase (38.5 %), with a significant portion aiming to be deployed (23.1 %).

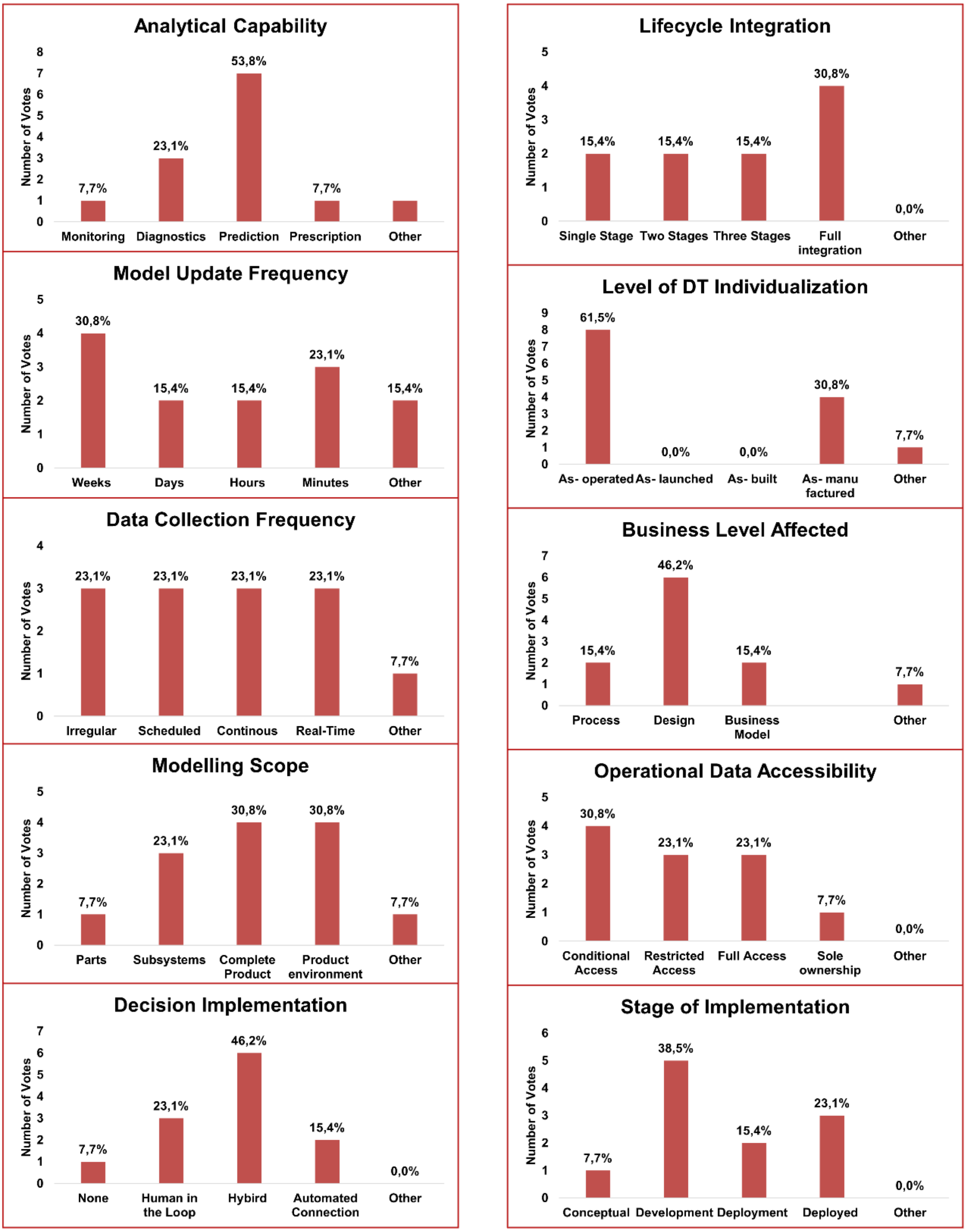


Figure 3.10 Ratings of the Maturity Model with No Digital Twin Implemented - 13 Participants

Statistical Information

- The twenty-ninth question in Figure 3.11 asked respondents to describe their department's primary focus within the satellite sector. The distribution indicates that the largest focus area among respondents' organizations belongs to Earth observation satellites, followed by various other focuses.

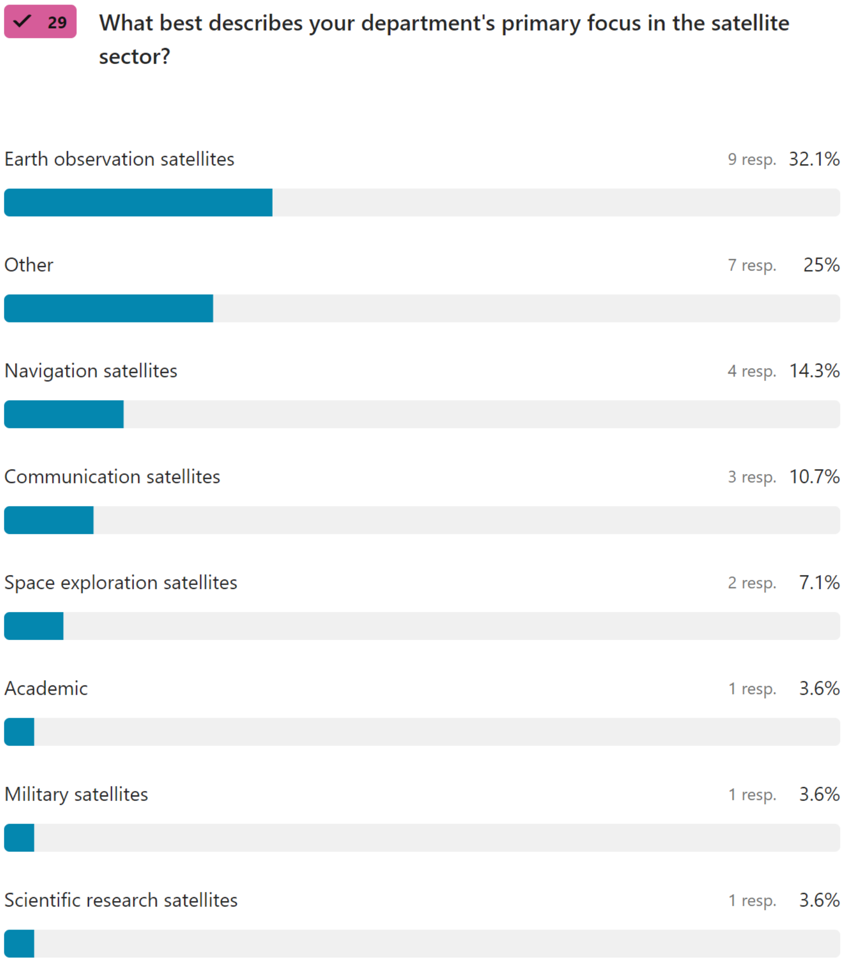


Figure 3.11 Outcome Question 29 - Statistical Information

- The thirtieth question in Figure 3.12 aimed to identify the respondents' roles within their companies. The majority of respondents identified their roles as Engineering/Technical, followed by Management/Leadership roles.

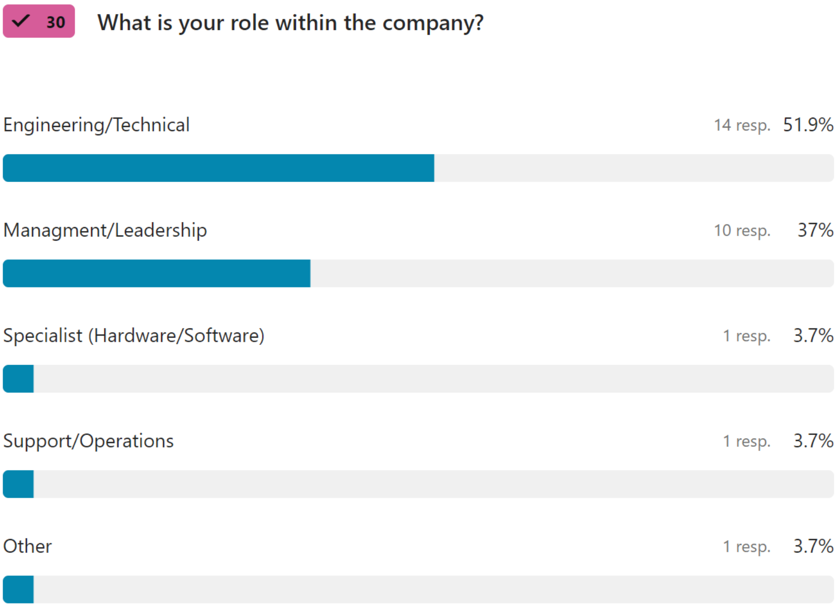


Figure 3.12 Outcome Question 30 - Statistical Information

- The thirty-first question in Figure 3.13 asked respondents about their educational background. Most respondents have an educational background in Engineering, followed by Computer Science and Natural Sciences.

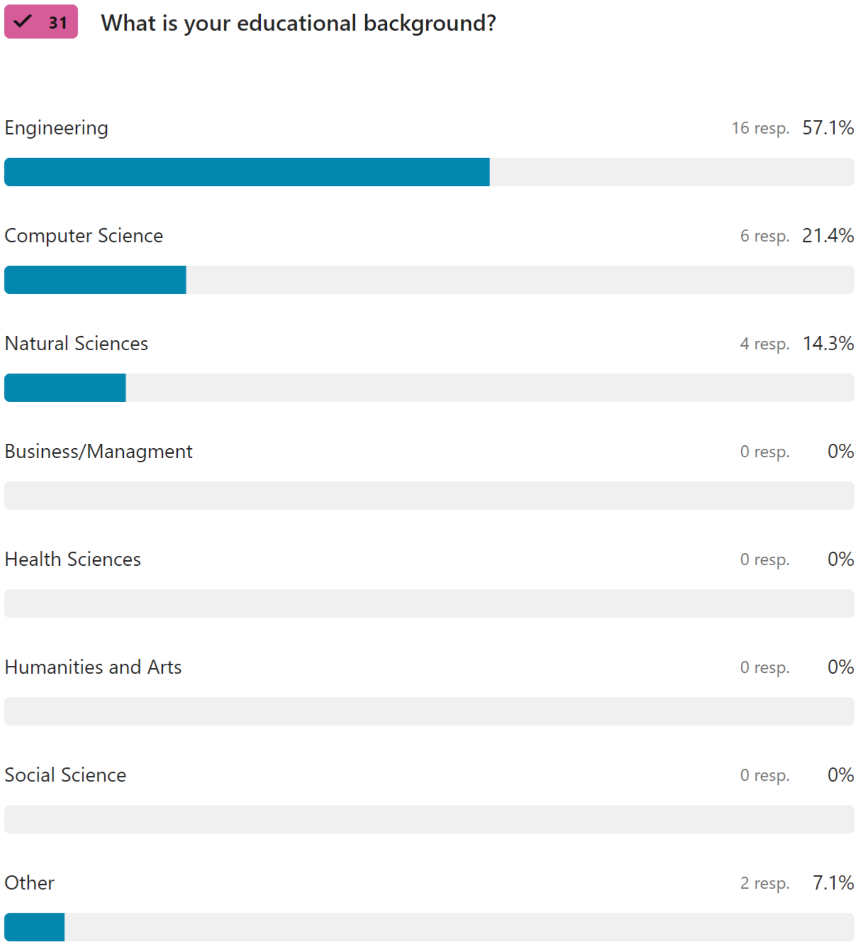


Figure 3.13 Outcome Question 31 - Statistical Information

- The thirty-second question in Figure 3.13 assessed the distribution of years of experience in the aerospace industry among respondents. The graph shows a varied range of experience, with respondents having experience from less than five years to more than 35 years. The distribution indicates a balanced mix of experience levels, with a tendency to fewer years of experience and a total average of 10.8 years.

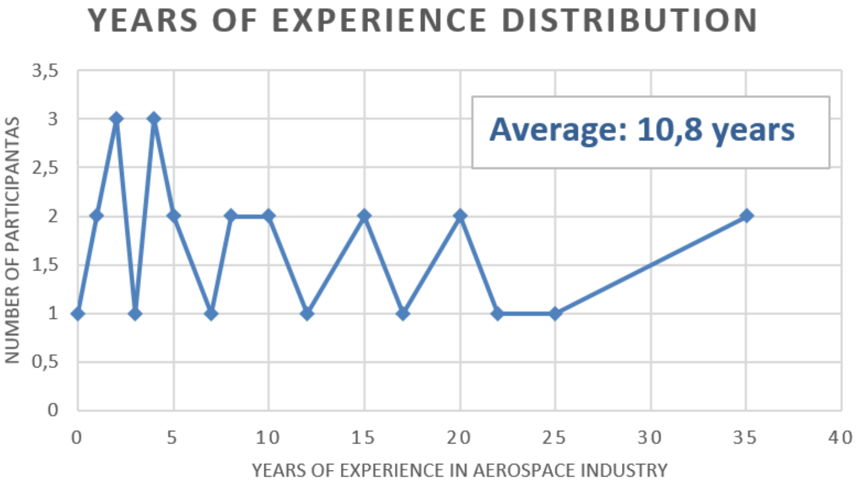


Figure 3.14 Outcome Question 32 - Statistical Information

Questionnaire Summary

The responses to the questionnaire provide a comprehensive overview of respondents' interest in and perceptions of Digital Twins, particularly in relation to their defining characteristics, the stages of the satellite lifecycle, potential adoption in the aerospace industry, and the types of satellites that could benefit most from their introduction.

The high levels of familiarity and interest suggest that the concept of Digital Twins is well-recognized and considered valuable within the industry. The emphasis on dynamic digital representation and behavior mirroring aligns with the core principles of Digital Twin technology, underscoring its relevance in satellite applications.

The insights into the stages of the satellite lifecycle where Digital Twin technology is most valued, the expected adoption of this technology in the aerospace sector over the next five years, and the types of satellites that could benefit most from its implementation. The high interest in operations and sustainment stages and the potential advantages for medium and large spacecraft indicate a targeted focus on Digital Twin applications.

The assessment of the maturity levels of different Digital Twin implementations and an envisioned Digital Twin gives a comprehensive sectional image of the industry's status on the topic of Digital Twins. The responses illustrate the inherent contrast between the characteristics of an existing system and the aspirations for an idealized future state. Despite this contrast, both groups recognize the importance of prediction, human involvement in decision-making, and a focus on development stages. Participants with a Digital Twin implemented tend to focus the approach on detailed and frequent updates, integration within a single stage of the lifecycle, and maintaining operational data accessibility. In comparison, participants without a Digital Twin desire potential broader business impacts and varying stages of the lifecycle.

The detailed view of the demographic and professional background of the survey participants shows an overall distributed coverage of the sector, enabling the general assumption for the sector. The prevalence of engineering/technical and management roles indicates the importance of the topic's evolution from a technical abstraction to a relevant technique applicable in the industry. The strong educational background in technical disciplines highlights the respondents' expertise required and specific interests in the satellite and aerospace sectors. The varied years of experience further underscore the depth of knowledge and diversity of perspectives in the survey, enriching the overall findings and insights gathered.

3.2.2 Results Interview

This section presents the results of the interviews to gain deeper insights into the absence and potential of Digital Twin technology in the satellite sector. The interviews aimed to follow up on the questionnaire and provide a platform for experts to share their open opinions on Digital Twins. This approach allowed for a deeper understanding of current practices and approaches towards the topic and insights into the perceived benefits and opportunities of Digital Twin technology. Additionally, the interviews explored the key differences experts see for Digital Twins in CubeSats compared to other satellites.

General Achievements

Two interviews have been conducted with experts who do not currently employ Digital Twin technology. Unfortunately, additional participants could not be secured due to their tight schedules and the time constraints of this thesis. As a result, the limited number of interviews precludes these findings from being representative of the Digital Twin environment in the satellite sector.

Despite the limitation in quantity, the conducted interviews provided valuable insights into the current practices of these experts, their understanding of the absence of a Digital Twin, and the constraints they face regarding the adoption of this technology. While not exhaustive, these insights contribute to a deeper understanding of the challenges and considerations involved in implementing Digital Twin technology in the satellite sector.

Detailed Outcome by Interview

Based on the verbatim transcript and the documentation produced during the interviews, the two interviews are summarized and presented. The complete anonymized transcript document can be found on the thesis's GitLab[7] repository.

Summary of Interview 1

The first interviewee has an academic background in computer science and space engineering, holding a PhD in small satellite engineering. With extensive experience in CubeSats and small satellite projects focused on technology demonstration and Earth observation, the interviewee's company operates within the new space sector. Characterized by small, agile teams often comprising students, the company prioritizes digital engineering methods, minimizing paper documentation and adopting an agile development approach. They utilize a "single source of truth" and automation strategies to generate code, documentation, and simulation configurations from a centralized machine-readable format, enhancing consistency and reducing manual tasks. Python is the primary tool for automation, model generation, and ensuring interoperability across different software platforms. CAD software is used for mechanical engineering tasks, and data integration is achieved across various platforms. The company maintains an engineering model for training and testing purposes. It does not employ an integrated Digital Twin, focusing instead on agile development with continuous iterations rather than maintaining a detailed, real-time Digital Twin. The main identified challenges include the high complexity and significant effort required to develop and maintain a Digital Twin and the perceived lack of substantial benefits over existing practices. Organizational and budget constraints further limit the adoption of a Digital Twin approach. Despite recognizing the potential benefits of Digital Twins, especially in development acceleration through standardization and long-term improvements through data sharing between vendors and operators, the interviewee notes that practical implementation is demanding and not currently justified for small projects. Future possibilities include leveraging machine learning to create surrogate models that simulate specific behaviors, aiding in optimization without the need for manual implementation. The interviewee suggests that standardized interfaces for software and hardware components could facilitate the creation and use of Digital Twins. Collaboration across the industry to develop common standards and repositories of digital components is recommended. Although there are no immediate plans to implement a Digital Twin, the interviewee acknowledges the community's need for standardized interfaces and expresses interest in contributing to such efforts. Future research and potential projects could focus on developing these standards and integrating Digital Twin concepts into small satellite projects.

Summary of Interview 2

The second interviewee, who works at a company specializing in communication systems and particularly

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[7] https://gitlab.lrz.de/leonhard.kessler/leonhard-kessler-master-thesis

focuses on Beyond Visual Line of Sight (BVLOS) operations of drones, shares a similar perspective. The company uses various access technologies for satellite communication, emphasizing a multi-link system and the use of Linux and open-source software. They elaborate on their simulation practices, focusing on TCP/UDP stacks and integrating different technologies for data links. Although they simulate data links, they do not have a Digital Twin. The interviewee sees potential in using Digital Twins for satellite communication networks to improve data link prediction and reliability. However, challenges such as the small operations volume, difficulty obtaining network quality metadata, and limited computing power for embedding Digital Twins in drones have been highlighted. Financial and organizational constraints are significant barriers to implementing Digital Twins, particularly in small-scale operations. The interviewee supports the idea of developing consistent guidelines and standards for Digital Twins, particularly for APIs and interfaces, to ensure reliability and compatibility across different technologies and systems. The discussion emphasized the importance of such standards, drawing parallels with the CubeSat design standard, which has facilitated easier integration and modular component environments. The company mentions plans to integrate satellite interfaces into their architecture, aiming for compatibility with terrestrial networks. However, due to the evolving nature of their field, no concrete future plans have been provided.

Insights of the Interviews

The interviews revealed several key findings, highlighting gaps in the current methodology and valuable insights for future action:

1. Complexity and Effort: Both interviewees noted the high complexity and effort required to develop and maintain Digital Twins, particularly for small-scale operations.
2. Organizational and Budget Constraints: Financial and organizational limitations have been major barriers to adopting Digital Twin technology, making it difficult to justify its implementation, especially in smaller projects.
3. Potential Benefits: Despite challenges, the interviewees acknowledged the potential benefits of a Digital Twin, particularly in reliability and accelerating development. However, these benefits are not sufficient to justify the current effort and cost for small-scale projects.
4. Future Directions: Both interviewees expressed interest in future Digital Twin developments and emphasized industry collaboration to create common standards and repositories.

Interview Summary

The interviews provided valuable insights into Digital Twin technology's current state and future potential in the satellite sector. While the small sample size limits a generalized view of the findings, the discussions highlighted several important themes and potential areas for future research and development. The identified gaps and challenges underscore the need for guidelines and the importance of collaboration and innovation to advance the implementation of Digital Twins in the industry.

3.3 Discussion of the Industry Evaluation

The content of the industry evaluation reveals several key insights. The significant differences in the most fitting terms indicate varied understandings among different players in the industry. There is a notable focus on dynamic digital representation, behavior monitoring, and integrated and predictive simulation. This focus suggests a need to involve physical systems more in simulations and correlate them to each other, providing a better understanding of system dynamics and minimizing emergent behaviors.

There is a slight tendency towards the applicability of Digital Twins in the earlier lifecycle stages, likely due to lower costs associated with design changes. However, the wide distribution of individual responses may also reflect the diverse disciplines of participants or differing views on the size and demands of Digital Twins for subsystems versus entire systems in operations. The restrained expected use of Digital Twins may be connected to the high financial and technical demands, unclear approaches, and limited supplier support.

The satellite classes identified as most benefiting from Digital Twin technology, both in terms of purpose and mass, are likely influenced by participants' experiences in projects with more workforce dedicated to simulation and verification and larger budgets. This pattern is similar in systems engineering, where larger companies engage more extensively due to the involvement of more people and stakeholders. Space exploration satellites, ranked highest in classification, require high reliability with no margin for failure. Communication satellites are associated with established companies operating multiple satellites, thus benefiting from higher sample rates and significant investment. The lack of responses for spacecraft weighing less than 10kg might be due to the high effort and low cost associated with these missions, where it is more feasible to send another unit if one fails.

Regarding maturity, high responses should be acknowledged but interpreted with caution as it often depends on the company's focus. This is evident in the radar chart in figure 3.15, which shows significant differences among companies. Data collection is expected to increase with more relay constellations for inter-satellite communication, a trend also seen in envisioned Digital Twins, as participants are already considering future developments.

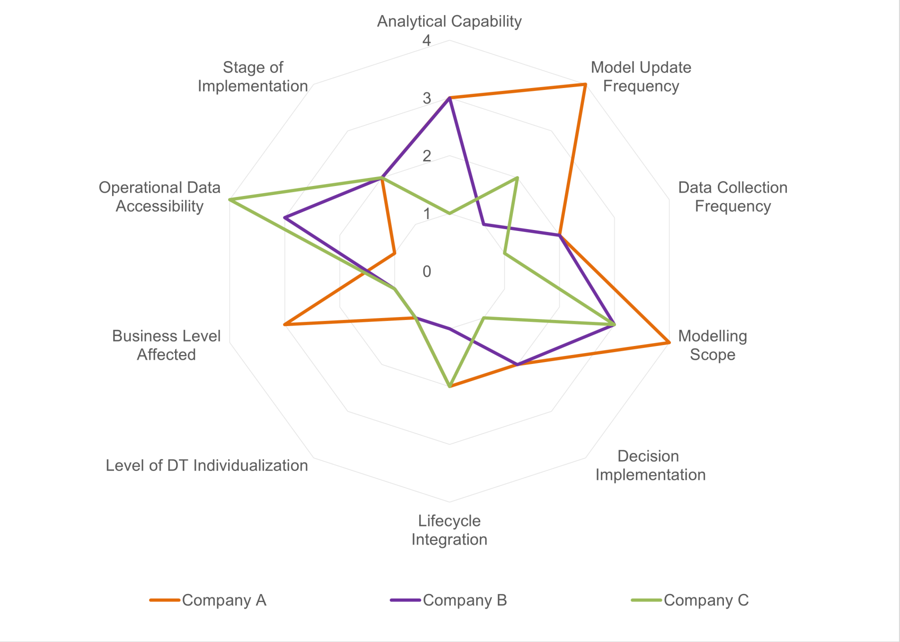

Figure 3.15 Radarchart Illustration of a Comparative Assessment of Digital Twin Maturity for three Different Companies.

The focus on the product environment likely stems from satellite operations' highly challenging space environment. The preference for human-in-the-loop systems indicates a lack of trust in fully automated connections and updates, emphasizing the importance of expert knowledge in decision-making. Lifecycle differences highlight the gap between the current state and potential future improvements, underscoring the necessity of a Digital Twin that is extendable throughout the lifecycle to minimize workload.

The high focus on Digital Twin individualization could be due to several factors, including the technical requirements of incorporating more data than just flight data for historical evaluation processes. The space environment is vastly different from the ground, making ground data less valid for space systems. Additionally, there may be a lack of proper explanation of this maturity model from the research side.

Operational data accessibility appears to be distributed equally among participants. Non-existing Digital Twin participants realistically see that sole ownership involves high costs and a legal workforce, which may not be available. The focus on development stages indicates the technology's infancy, showing it is not yet fully deployed in engineering processes or only marginally so, highlighting the need to reduce development time to benefit from Digital Twins in real use cases.

Departmental focus is well-distributed but can be highly influenced by the selection of contacts. The high number of "Other" responses suggests either a lack of coverage of primary focuses or a significant number of interdisciplinary departments working on this topic. The focus on engineering roles has been expected due to the technical nature of Digital Twins, requiring a deep understanding of technology for simulation and twinning. The presence of management and leadership roles indicates the strategic importance of this technology at the C-level. The average experience level of around ten years suggests the topic is relatively new, with younger industry participants being more open to new technology. This could also result from the selection of respondents, as younger professionals may be more prevalent in certain networks.
The interviews conducted have been smooth and provided valuable insights, but the process has been highly demanding in terms of personal effort. Automating parts of this process could be beneficial. The industry evaluation demonstrated a high interest in Digital Twin technology. However, due to the busy schedules of industry professionals, arranging interviews has been challenging. This suggests that the approach should be reconsidered, and the questionnaire and interview may need to be separated depending on participant preference. The interview should be feasible without participation in the survey being a requirement, this can be achieved by offering participants both in advance and allowing them to choose according to their preference. Additionally, contacting more people and possibly sharing the survey publicly in the future with mechanisms to filter out non-relevant participants could improve the response rate.

The industry evaluation, in general, provided a very interesting observation into the current practices and status of the Digital Twin industry. The high interest in the topic among respondents highlights its relevance and confirms the need for further research. The questionnaire has been helpful in providing an overview, as it is aimed at the overall satellite sector, not only towards CubeSats. Sometimes, the lack of context in the responses raised additional questions that could have been clarified through an interview, and especially, the topic of the thesis could have been analyzed in more detail. Therefore, no clear hypothesis can be realized, which is only valid for implementing a CubeSat Digital Twin. Nevertheless, the study contributed to the knowledge of the overall relationship between satellites and Digital Twins and has created a basic understanding that can now be actively pursued further.

4 Methodology of the CubeSat Digital Twin

After this comprehensive overview of the state of the art of Digital Twin and CubeSat technology, the industry evaluation has been presented, and the challenges and opportunities for Digital Twin implementations for CubeSats have been shown. In the next step, the CubeSat Digital Twin implementation is introduced. This work is approached in a systematic manner, described visually in Figure 4.1, beginning with an alignment of common terms for better comprehensibility, incorporating the results of the literature review and the survey. This fosters a discussion without misconceptions throughout the work. In the second part, the requirements for the Digital Twin and the CubeSat are identified, and the CubeSat Digital Twin requirements are derived and outlined. The third part presents the indented architecture and describes the Cubesat Digital Twin throughout its lifecycle. In the fourth part, a special focus is put on the core element of the Digital Twin, modelling and simulation. This will result in the final part, which is the presentation of a framework combining the previous work.

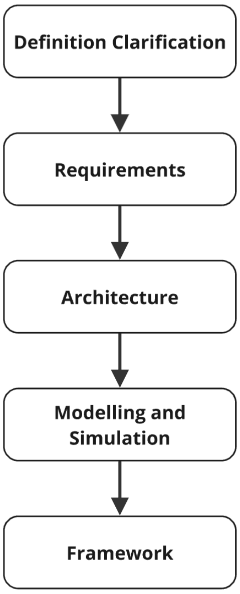

Figure 4.1 Top Down Approach for the Methodology of the CubeSat Digital Twin

4.1 Definition of Terms

Covering the whole lifecycle with the Digital Twin should not be the initial goal. As seen in the questionnaire, most responses from those already working with a Digital Twin focus on one lifecycle stage. A light trend towards full lifecycle coverage is visible in the responses from those not working with a Digital Twin. This suggests that beginning the implementation in one stage and gradually evolving it could be advantageous. Additionally, with a modular approach, it is feasible to incorporate additional data and simulations at a later stage, thereby expanding the Digital Twin to cover more lifecycle stages. Consequently, adopting a definition encompassing the entire lifecycle from the outset is not essential. Technology and the concept have evolved a lot in recent years. Therefore, a definition that incorporates this development and represents the state of the art of Digital Twin ensures the longevity of the methodology without a lot of maintenance effort.
The definition of the ISO/IEC standard is chosen as the given definition for a Digital Twin:

> "digital representation of a target entity with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronization Note 1 to entry: Digital twin has some or all of the capabilities of connection, integration, analysis, simulation, visualization, optimization, collaboration, etc. Note 2 to entry: Digital twin can provide an integrated view throughout the life cycle of the target entity" [22].

Including the aforementioned reasoning, the definition is used for the following reasons:

- Key elements of a physical domain, a digital domain, and the control loop.
- Important definition characteristics are further defined in the entry notes.
- Defines the different elements of the Digital Twin comprehensively throughout the document.
- Leaves enough space for different design solutions to the problem, not restricting the implementation of different kinds.
- Represents the current situation, released in 2023, and is maintained by the standardization organizations.

4.2 Requirements

After establishing the definition of the concept of the Digital Twin, it is crucial to depict the desired outcomes and the necessary constraints for the product. To follow the top-down approach, the requirements for the CubeSat and the Digital Twin are defined separately. Based on these requirements, a more detailed set of requirements for the Digital Twin of a CubeSat is derived to highlight the unique characteristics of this methodology.
CubeSats have undergone significant evolution. Rendering the repetition of the CubeSat design standard for technical requirements is unnecessary. This research focuses on the non-functional requirements of CubeSats, which contribute to their distinctiveness and appeal.

CubeSat Requirements

- The CubeSat design shall be simple and explicit to facilitate ease of understanding, assembly, and maintenance.
- The CubeSat shall be designed to be modular, allowing for upgrades and reconfiguration of subsystems.
- The CubeSat design shall support extensibility to accommodate additional features and capabilities in future iterations.
- The CubeSat design shall support portability to ensure integration and operation with various ground stations, control systems, and launch vehicles.
- The CubeSat design shall prioritize reliability, incorporating robust fault tolerance mechanisms and redundancy in critical systems to ensure continuous operation and mission success.
- The CubeSats shall be capable of autonomous operation, reducing the need for extensive ground support and enabling more entities to participate in space missions.

The definition of Digital Twins already covers some important requirements for a Digital Twin. Further requirements aim to connect the different characteristics of the Digital Twin and to enhance the implementation of a Digital Twin:

Digital Twin Requirements

- The Digital Twin shall represent a specific instance of a product.

  - Digital Twin shall provide a digital representation of the physical product, including relevant physical and functional parameters.
  - Digital Twin shall enable comparison of the physical and digital models through gathered parameters.
- The Digital Twin shall support interdisciplinary collaboration.
  - The Digital Twin shall enable the collaboration of different stakeholders (Designer, Management, Customer).
  - The Digital Twin shall incorporate a multi-simulation environment to facilitate discipline collaboration.
- The Digital Twin shall collect and update lifecycle data.
  - Digital Twin shall continuously collect data from product lifecycle stages.
  - Digital Twin shall update the digital model data based on the collected lifecycle data.
- The Digital Twin shall provide analytical and decision-support capabilities.
  - Digital Twin shall offer decision support for system performance, maintenance, and optimization.
  - Digital Twin shall adjust and refine its models based on feedback and new data inputs.
- The Digital Twin shall support comprehensive verification and validation processes, ensuring model outputs meet predefined accuracy criteria.
- The Digital Twin level of fidelity shall be scalable, matching the complexity of the product and its current lifecycle phase.

Using this predefined set of requirements for CubeSats and a general Digital Twin, a tailored set of requirements can be developed for the implementation of the CubeSat Digital Twin:

CubeSat Digital Twin Requirements

- **Fidelity and Simplicity**
  - The CubeSat Digital Twin shall fit the level of fidelity of a CubeSat, ensuring that the digital model accurately reflects the physical CubeSat's behavior and performance.
  - The CubeSat Digital Twin shall be simple to implement initially, facilitating ease of understanding, assembly, and maintenance.
  - The CubeSat Digital Twin shall follow a scalable approach, starting with reduced complexity and refining the model with additional details as needed.
- **Feasibility and Modularity**
  - The CubeSat Digital Twin shall consider the feasibility of component implementation, including the use of Commercial Off-The-Shelf (COTS) components to reduce costs and improve accessibility.
  - The CubeSat Digital Twin shall be modular, enabling easy upgrades, reconfiguration, and scalability of both physical and digital components.
- **Simulation and Representation**
  - The CubeSat Digital Twin shall enable behavior simulation to reflect the CubeSat's real-world conditions and responses.
  - The CubeSat Digital Twin shall support simulations of subsystems and payload disciplines, ensuring modelling of their performance and interactions to provide a dynamic digital representation.
- **Predictive Analytics and Decision Support**

  - The CubeSat Digital Twin shall support the analysis of "What-if" scenarios to prepare for various mission conditions and unexpected events.
  - The CubeSat Digital Twin shall enhance predictive analytics and decision-support capabilities, providing insights for system performance, maintenance, and operational decision-making.
- **Testing and Validation**
  - The CubeSat Digital Twin shall include commanding capabilities to validate and test CubeSat operations before deployment.
  - The CubeSat Digital Twin shall provide a controllable test environment to ensure reliable testing and validation of the CubeSat's functions and operations.
  - The CubeSat Digital Twin shall prioritize reliability by incorporating robust fault tolerance mechanisms and redundancy.
- **Traceability and Iterative Improvement**
  - The CubeSat Digital Twin shall provide traceability of changes, allowing for precise documentation and analysis of modifications throughout the lifecycle.
  - The CubeSat Digital Twin shall support iterative analysis to facilitate continuous improvement and refinement of both the digital and physical models.

By defining and adhering to these specific requirements, the unique characteristics and capabilities of the CubeSat Digital Twin can be effectively implemented and optimized further. The requirements are a trade-off between feasibility and fidelity, enabling implementation while maintaining data accuracy to benefit from comprehensive analysis. This approach addresses the challenges inherent to CubeSats and focuses on providing lifecycle-long support. With this defined set of requirements, the architecture of the Digital Twin can be developed in the next step.

4.3 Architecture of the CubeSat Digital Twin

It has been observed that a common way of presenting the structure of a Digital Twin is based on the original conceptual idea by Grieves, as depicted in his industry presentations, shown in Figure 2.2. This presentation style highlights the main components of a Digital Twin: real space, virtual space, and the data connection with detailed flow information. Viola and Chen's version in Figure 4.2 aligns with this approach, adapting it with elements specific to the manufacturing industry [6]. While valid, the high-level nature of these diagrams makes them open to interpretation, which can support to the vague understanding of the Digital Twin. Furthermore, the diagrams place insufficient emphasis on the connections and interactions between different components of the Digital Twin, rendering their practical implementation challenging. The lack of clear guidance on the placement of components hampers the translation of theoretical models into real-world applications and does not support a clear methodology for implementing a CubeSat Digital Twin.

Another approach observed in the literature is characterized by a very high level of detail tailored to a specific domain and use case. For instance, Figure 4.3 presents a seven-layer architecture by Singh et al. for a battery system. This diagram shall offer a baseline methodology to guide product and process designers during the development of Digital Twins. However, the categorization in the diagram does not align with our chosen classification, which adheres only to the ISO/IEC standard, which consists of the physical domain, the digital domain, and the control loop. Such detailed and domain-specific diagrams lack clarity and ease of understanding, making it difficult for new users or stakeholders to grasp the concepts being presented.

In summary, the current models and diagrams in the literature do not provide sufficient detail or clarity. They inadequately address the crucial aspects of connections and interactions, and their implementation guidance is lacking. Consequently, these models are not easily transferable from their specific domains to the domain of CubeSats, underscoring the need for a more comprehensive and adaptable approach to Digital Twin implementation.

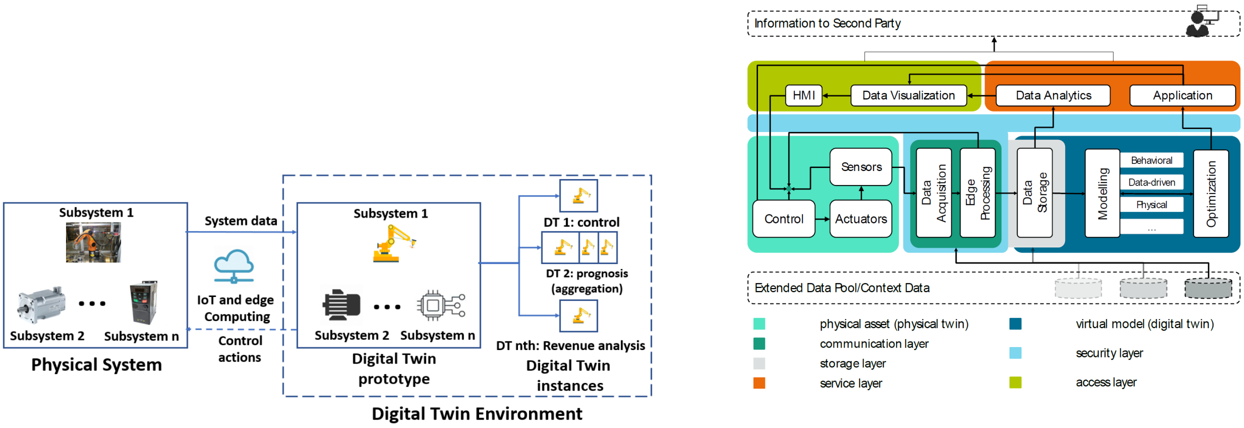

Figure 4.2 Digital Twin Structure by [6]

Figure 4.3 Digital Twin Framework with Seven Layers by [7]

Figure 4.4 Comparison of Two Different Approaches to Digital Twin Architectures

Similar to the high-level approaches, the starting points for the architecture of the CubeSat Digital Twin, displayed in Figure 4.5, are the three main components derived directly from the standard: the physical domain, the digital domain, and the control loop. The physical domain encompasses the target entity and the ecosystem, and the digital domain encompasses the database, modelling and simulation, and analysis elements. The control loop is represented as a stand-alone element with designated components. This approach emphasizes the distinction between virtual-to-physical and physical-to-virtual connections rather than arrows connecting the physical and digital domains. Additionally, the architecture illustrates the possible connections among different elements within each domain, enhancing the understanding of potential interactions and influences throughout the operation.

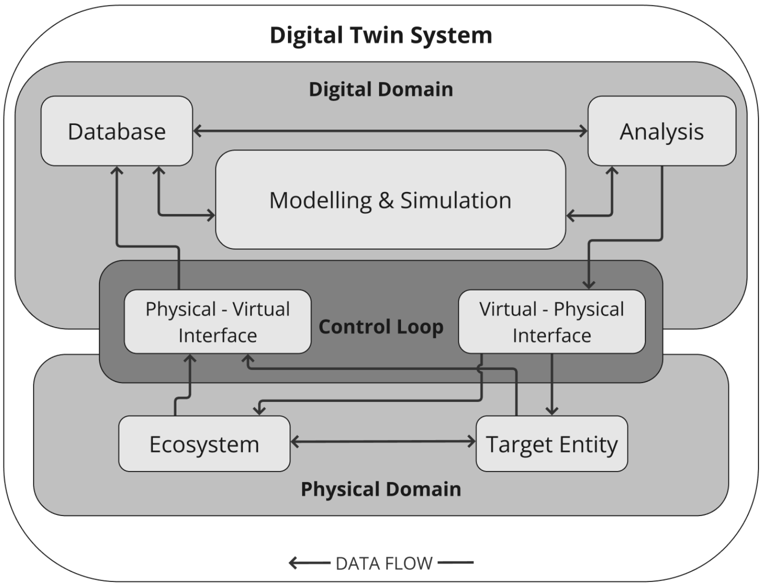

Figure 4.5 Digital Twin Architecture

In the following section, the architecture is presented in more detail. First, emphasis is placed on defining each architectural component in depth, extending the ISO/IEC standard definitions. This detailed description improves understanding of the architecture and facilitates implementation. Secondly, the architecture is demonstrated throughout the lifecycle, highlighting various potential applications and benefits. Finally, the modelling and simulation element is discussed in detail, representing the core component of the Digital Twin.

4.3.1 Architecture Description

The comprehensive architecture of the CubeSat Digital Twin is essential for understanding and optimizing its functionalities. By meticulously defining each component and its interactions, the architecture serves as a blueprint for implementation and eases integration.

Physical Domain

The physical domain encompasses the physical entities of the product and its surrounding environment. All elements within the physical domain may be subject to modelling and simulation within the Digital Twin framework.

Ecosystem
The ecosystem represents the environment in which the product operates. It comprises the infrastructure and services that are supported by a network of organizations and stakeholders.

Target Entity
The target entity refers to the physical entity that is the subject of digital representation and serves a functional purpose in reality. This physical entity includes the product itself along with all its corresponding components, sensors, and properties. The physical entity is constructed based on customer requirements and is capable of fulfilling its goals independently of the Digital Twin. The target entity can be either physical or digital, as long as it provides a functional purpose in reality. This includes software components or digital constructs that can also be considered target entities.

Control Loop

The control loop represents the connecting interface between the physical and digital domains and the interface between the ecosystem and the digital domain. This connection and the information exchanged through it may vary significantly among different versions of Digital Twins. However, the key characteristics include the perception of data from the target entity and the ecosystem by the digital domain, as well as the feedback of data to the target entity to modify its behavior. The control loop can be further divided into the physical-to-virtual interface and the virtual-to-physical interface, enabling various levels and methods of implementation.

Physical - Virtual Interface
The physical-to-virtual interface facilitates data transfer from the target entity to the digital domain and from the ecosystem to the digital domain. This interface encompasses all information collected about the physical domain, either directly or indirectly. Information from the target entity itself is transmitted via this interface, including sensor and actuator data from the physical entity. Additionally, the ecosystem provides sensor, actuator, and emulator data, which offer insights into the surrounding conditions and external factors affecting the physical entity.
This interface is primarily responsible for transmitting synchronized data from the physical to the digital domain. This data is subsequently stored in the database, ensuring the collection of comprehensive and necessary information for the Digital Twin's accurate representation and functionality.

Virtual - Physical Interface
The virtual-to-physical interface serves as the directive interface that transmits data from the digital domain to the target entity in the form of commands or updates, resulting in modifications to the target entity. This enables the physical entity to change parameters, adjust behavior, or even undergo software updates/upgrades. Furthermore, if the ecosystem involves changeable infrastructure, the virtual-to-physical interface manages data synchronization from the digital domain to the ecosystem, adjusting the ecosystem of the physical entity accordingly.
For a CubeSat, this is particularly relevant during the design and manufacturing stages, where the ecosystem is man-made and represented by test setups and emulators, as well as in controlled laboratory settings. However,

once the satellite is operational in space, altering the ecosystem is no longer feasible.

Digital Domain

The digital domain encompasses all digital entities involved in twinning the physical entity and its ecosystem. Despite its name, this domain also includes physical components, primarily computation and storage units. The digital domain may be operated by a human or automated through algorithms, like machine learning or AI ones. It consists of three main interconnected elements essential for mirroring the behavior of the physical domain: the Database, the Model and Simulation, and the Analysis component.

Database
The data provided by the physical domain and data from previous developments are stored and organized in the Database. The Database may facilitate graphical visualization of the data through graphs or networks, enhancing human interaction and comprehension.

Modelling and Simulation
The modelling & simulation component encompasses all digital models and simulations that describe the product. The model employs formal languages to create an abstract representation of the physical domain. In the simulations, an equivalent system is used to replicate the physical domain, ensuring it behaves or appears like the real system. This component incorporates data from the physical domain to better align parameters with real-world conditions. The simulations may vary in type and be categorized in different ways.

Analysis
The Analysis component of the digital domain utilizes the outcomes of simulations and data from the physical domain for decision-making, optimization, and prediction. This analysis provides feedback to the physical domain, allowing for parameter adjustments and behavioral changes to improve the physical entity. Additionally, it helps validate and refine the models and simulations. best state of this process is an automated manner, but depending on the level of integration, a human operator may interact through inspection tasks and intervene when necessary.

Interfaces
Some interfaces have been partially covered but not in detail. Therefore, they are specified in more depth to understand the connections between the different elements. It is important to note that, apart from the interface between the target entity and the ecosystem, all other flows between elements in the Digital Twin system are data-based. In the abstract view of architecture, this connection aligns with principles of physics and information theory, where every physical event can be described in terms of data exchange. This perspective is crucial for understanding the Digital Twin system comprehensively and viewing it in an abstract manner.

The most logical interface is the connection between the target entity and the ecosystem. The ecosystem surrounds and influences the target entity in various ways.
The two interfaces, which connect the physical-to-virtual interface from the ecosystem and the target entity, can be described as one since both transfer data from the physical domain to the control loop. This enables the synchronization of the physical domain with the digital domain. This synchronization is made possible by relaying parameters from the physical-to-virtual interface to the database.
The database has two interfaces: it can provide data to the simulation as input or updates for further simulations, and it can supply raw data to the analysis component to enable comparison with previous parameters and validate previous updates made by the analysis. The modelling and simulation component delivers its outputs to the analysis component, facilitating decision-making based on the simulation results. The connection between the virtual-to-physical interface enables updates to the physical domain by transferring data from the digital domain to the control loop.
These updates are then divided into updates for the ecosystem and the feedback loop, which is often considered the most important connection of the Digital Twin. This feedback loop issues parameters back to the target

entity to modify its behavior.

This overview provides a clear understanding of the different elements and interfaces of the Digital Twin system. This general framework could be transferred to various domains and products, even if the methodology of this thesis focuses on the CubeSat. Therefore, the subsequent chapters will describe the components in different lifecycles, providing examples from CubeSats and placing a special focus on the modelling and simulation element. This focus will demonstrate how the CubeSat Digital Twin achieves its goals effectively.

4.3.2 CubeSat Digital Twin throughout the Lifecycle

The categorization of the lifecycle phases, as presented in Section 2.2.1 outlined how the focus of a Digital Twin can evolve over the lifecycle. This evolution is also applicable to the CubeSat Digital Twin. By categorizing the Digital Twin into the "As-Designed," "As-Built," and "As-Maintained" phases, different focuses and components of the Digital Twin throughout the product lifecycle can be highlighted.

This categorization allows for showcasing the varying operations and components representing the different elements of the Digital Twin at each lifecycle phase. The following sections systematically examine the lifecycle phases, moving from "As-Designed" to "As-Built" and finally to "As-Maintained." Similarities and differences, potential application use cases, and the inherent benefits of a CubeSat mission at each phase are discussed.

As-Designed Phase

A physical product is required for the implementation of a Digital Twin. Therefore, the lifecycle of a CubeSat Digital Twin starts with the design and development phase, referred to as "As-Designed," and is visually depicted in Figure 4.6.

In the design and development phase, the Digital Twin focuses on exploring different components in various environments, discovering the behavior in different scenarios, and determining the correct parameters of components under certain conditions. In this phase, the CubeSat Digital Twin aims not to mirror the entire CubeSat and all its components in the highest fidelity possible, as many components and subsystems are still under development and prone to changes. This approach avoids excessive work in implementing all these variations, which is not justified for the CubeSat.

Particular emphasis should be placed on the payload in CubeSat missions, as it is the primary subsystem that delivers value to the customer, even if the payload is intended for technology demonstration. The majority of CubeSat subsystems utilize COTS components, which generally have a well-documented history. As a result, their behavior is thoroughly understood, and they can be acquired from CubeSat component providers with most parameters already specified in technical documentation or official reports [48] [5].

In contrast, the payload is often custom-developed for a specific CubeSat mission, typically featuring a low Technology Readiness Level, and defines the mission's objectives. Achieving a rapid and thorough understanding of this critical component is crucial for the development of a more efficient, cost-effective, and reliable satellite bus.

In the "As-Designed" phase of the CubeSat Digital Twin, the Target Entity includes physical CubeSat components, payload prototypes, and subsystem (breadboard) assemblies under consideration. It also encompasses digital entities such as algorithms and software, which preprocess data generated on the satellite to reduce downlink capacities or enable automated operations. The ecosystem consists of infrastructure and services surrounding the target entity, including ground support equipment, simulators like Hardware-in-the-Loop (HIL) simulators, and the entirety of the laboratory environment, from workbenches to Thermal Vacuum Chamber (TVAC).

The control loop, which manages data flow between the physical and digital domains, is a critical component. Interfaces can be physical or wireless, supporting various network technologies. During the "As-Designed" phase, the control loop incorporates manual input and output to support the CubeSat Digital Twin implementation in its early stages. Data is manually read out and fed into the digital domain, stored in the database, and analysis results are manually input back into the physical system.

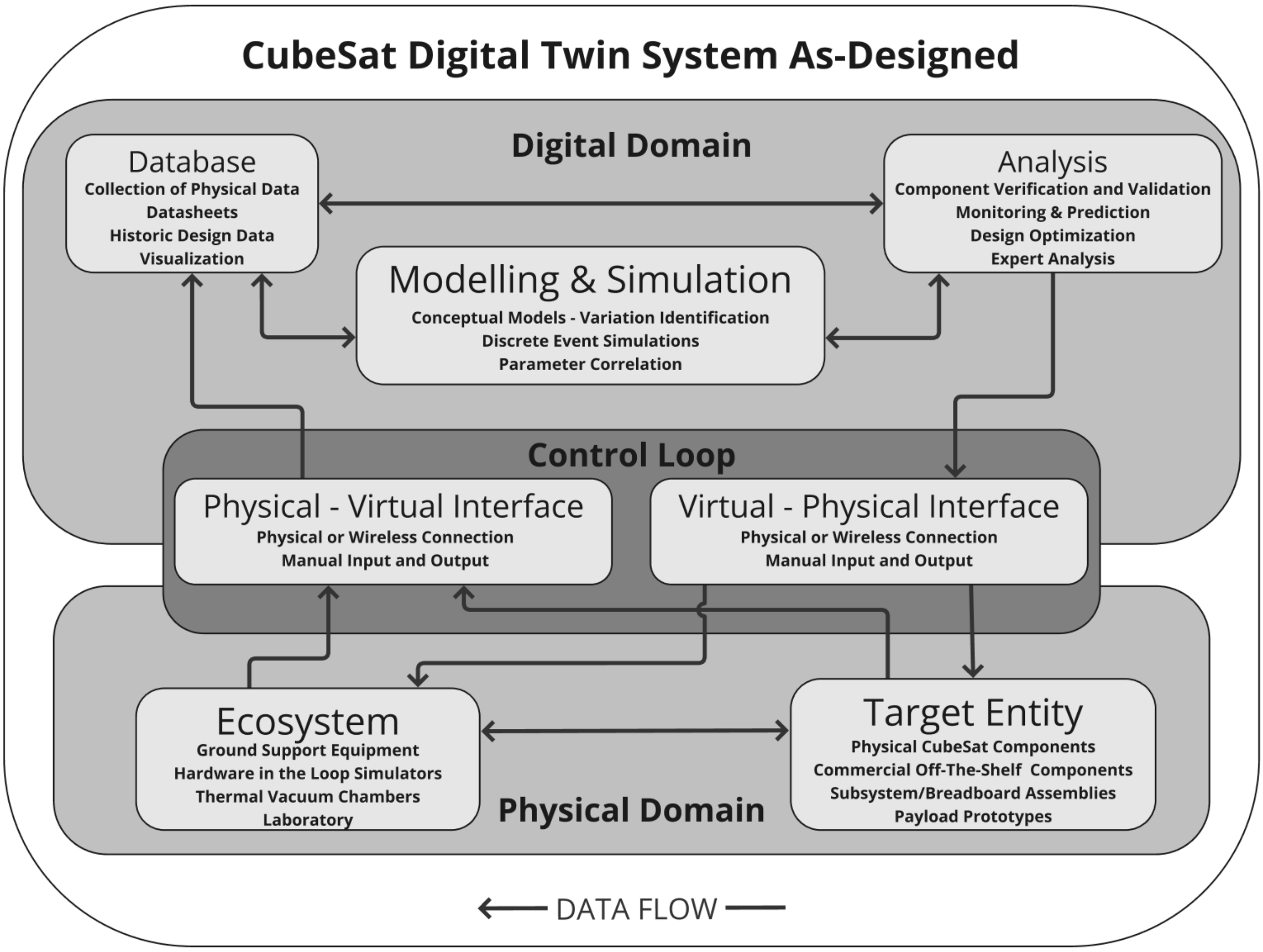

Figure 4.6 CubeSat Digital Twin: As-Designed covering the Design and Development Phase

In the digital domain, the database collects and stores all sensor values from the physical domain, prepares them for further use, and provides visualization capabilities. Historical design data and data from vendors through datasheets and reports about the physical entity components are incorporated for comparison and assurance. This phase's modelling and simulation element consists of conceptual models to identify system elements and variations, and simulations for important parts or disciplines to determine the ideal CubeSat configuration. Together, inputs from modelling and simulation and the database are used in the analysis for component-level verification and validation. The analysis correlates initial parameters with calculated or provided values, ensuring the system meets requirements and fulfills its intended purpose. Parameters are monitored and diagnosed to understand what occurred and why, though future predictions may be rough due to insufficient system data. The physical domain design is optimized based on collected data in the digital domain, with expert analysis guiding adjustments.

Data collection frequency may vary greatly depending on the Digital Twin setup. Discrete or demand-based data collection may suffice if physical domain values do not change, with updates occurring only when changes are detected. However, the laboratory environment enables continuous data collection and near real-time parameter updates for critical parameters through easy accessibility. The model update frequency in the digital domain is determined by the variability of the input data. The model structure and parameters require no adjustment if the input data remains consistent [28].

Designing is an iterative process, potentially resulting in multiple versions of the physical and digital domains.

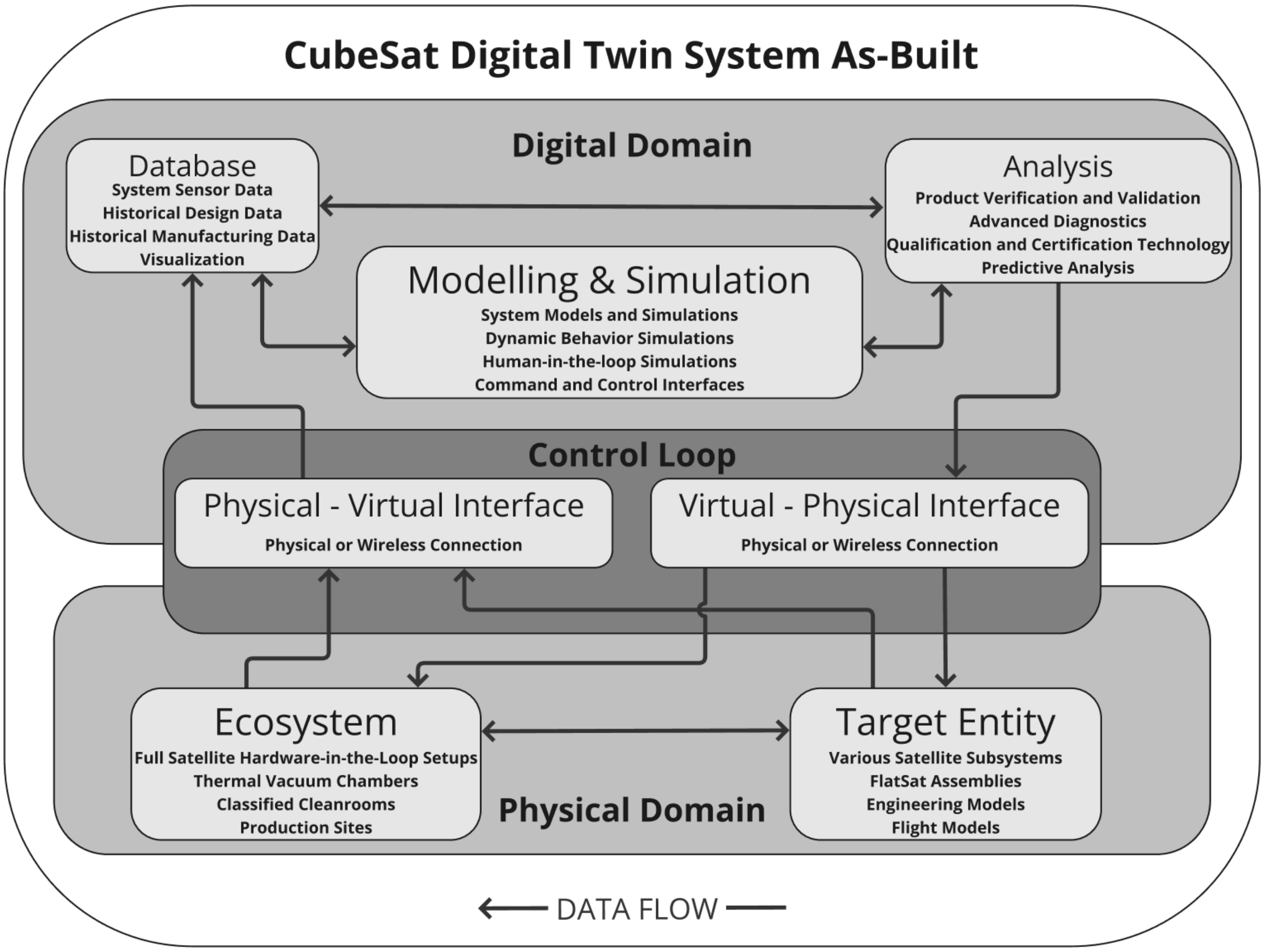

Figure 4.7 CubeSat Digital Twin: As-Built Phase covering Final Design, System Assembly until Launch

As-Built Phase

In the As-Built phase, the final design of the CubeSat is developed, manufactured, and fully integrated. This phase results in fewer iterations but involves a higher incorporation of data in the digital domain, as the complete system may produce more values. The CubeSat becomes more complex with additional components and interactions, increasing the likelihood and variety of emergent behavior. These behaviors present more significant challenges to the analytical capabilities of the Digital Twin. The focus shifts from the payload alone to ensuring all CubeSat subsystems function together as required to achieve mission success.

The CubeSat Digital Twin, depicted in Figure 4.7, addresses these challenges using the same elements and connections but with a more advanced depiction of the physical and digital domains. The control loop is also enhanced in terms of automation.

In the physical domain, the target entity comprises the various subsystems integrated into the satellite, up to the finished product, either as an engineering model or a flight model. FlatSat assemblies or final designs replace breadboard iterations. The ecosystem becomes more interactive with the target entity, with single-component simulators replaced by full satellite simulators such as ADCS HIL setups or TVAC chambers large enough to accommodate the entire satellite. Additionally, operations shift from unclassified laboratories to classified cleanrooms. The production sites of physical entity components are also considered in this stage to collect more data about the target entity, which can be incorporated into the digital domain if needed. Depending on production quantity, contracts with manufacturers, and manufacturing approaches, this can range from workshops to fully automated factories. Data accessibility remains a significant challenge in aerospace, impacting the Digital Twin system's information availability. Thus, data collection heavily depends on individual contracts and the level

of vertical integration within the CubeSat company. Higher vertical integration allows for more in-house data collection [28].
The control loop in the As-Built stage is similar to that in the As-Designed stage, maintaining existing connections but increasing the amount of data transferred. A notable change is the omission of manual data interaction, replaced by automated connections between the physical and digital domains. Interfaces are either physical or wireless.
Components in the digital domain evolve throughout the lifecycle, handling an increased scope of data. The database stores and organizes sensor data for the entire system, adding to historical design and manufacturing data. The modelling and simulation element now includes models and simulations covering the whole system, aiming to mirror the product's dynamic behavior across different mission modes. This element also supports human-in-the-loop simulations for training and advanced command and control interfaces with potential ground stations. The analysis component in the As-Built stage focuses on verifying and validating the product as a whole, providing advanced diagnostics and predictions. It also serves as a baseline for qualification and certification, reducing the need for costly qualification testing sessions.

Data collection frequency may reach a high level of maturity, enabling near real-time data implementation in controlled laboratory environments. However, this is not always possible. For example, during testing sessions at specialized facilities where connectivity may not be assured, data may need to be input into the Digital Twin after periods of no connectivity. The model update frequency aims to be as low as possible, constrained by computational resources and processing time in the digital domain. Updates occurring in less than a minute are typically not desired [28].

The As-Built stage is the final phase where humans can interact directly with the physical product and influence hardware components based on simulation and testing outcomes. This phase concludes with the CubeSat's launch into space.

As-Built Phase

The As-Maintained phase marks the period when the CubeSat serves its primary mission, operating in space until its end of life. The most significant differences in the CubeSat Digital Twin during this phase include changes in the control loop, the availability of data, and the shift in applications from design and manufacturing improvements to optimizing mission operations by utilizing all collected data.
This phase naturally sees the control loop's connection to the ecosystem diminish, as space cannot be influenced from the ground. The ecosystem is simply described as space, dependent on the mission's goals, orbit, and external influences acting on the CubeSat.

The target entity continues to encompass the physical and digital elements of the CubeSat. If the focus is on specific subsystems or elements, covering the entire system within the target entity is not necessary.
The control loop evolves into up and downlink communication. Additional data collection methods include external observations, such as radar measurements and potential inter-satellite links.
The digital domain now represents accumulated data and models, as well as lifecycle analysis. The database stores incoming telemetry and payload data, acting as a knowledge base for the As-Designed and As-Built phases and historical operational data. Feeding this information into the modelling and simulation elements allows for the correlation of operational simulations, describing the entire system and its system of systems. The analysis element utilizes all satellite data available, models, and simulations to predict future states and prescribe actions to achieve mission goals. It automatically monitors satellite health and reacts to events to ensure mission success.

Data collection frequency is bound to downlink availability. Depending on the mission design and ground segment setup, data collection can range from event-driven updates to regular passes with a single ground station, multiple ground stations, or continuous data collection through relay constellations and ground station networks. The model update frequency depends on the data collection frequency, aiming to minimize the delay

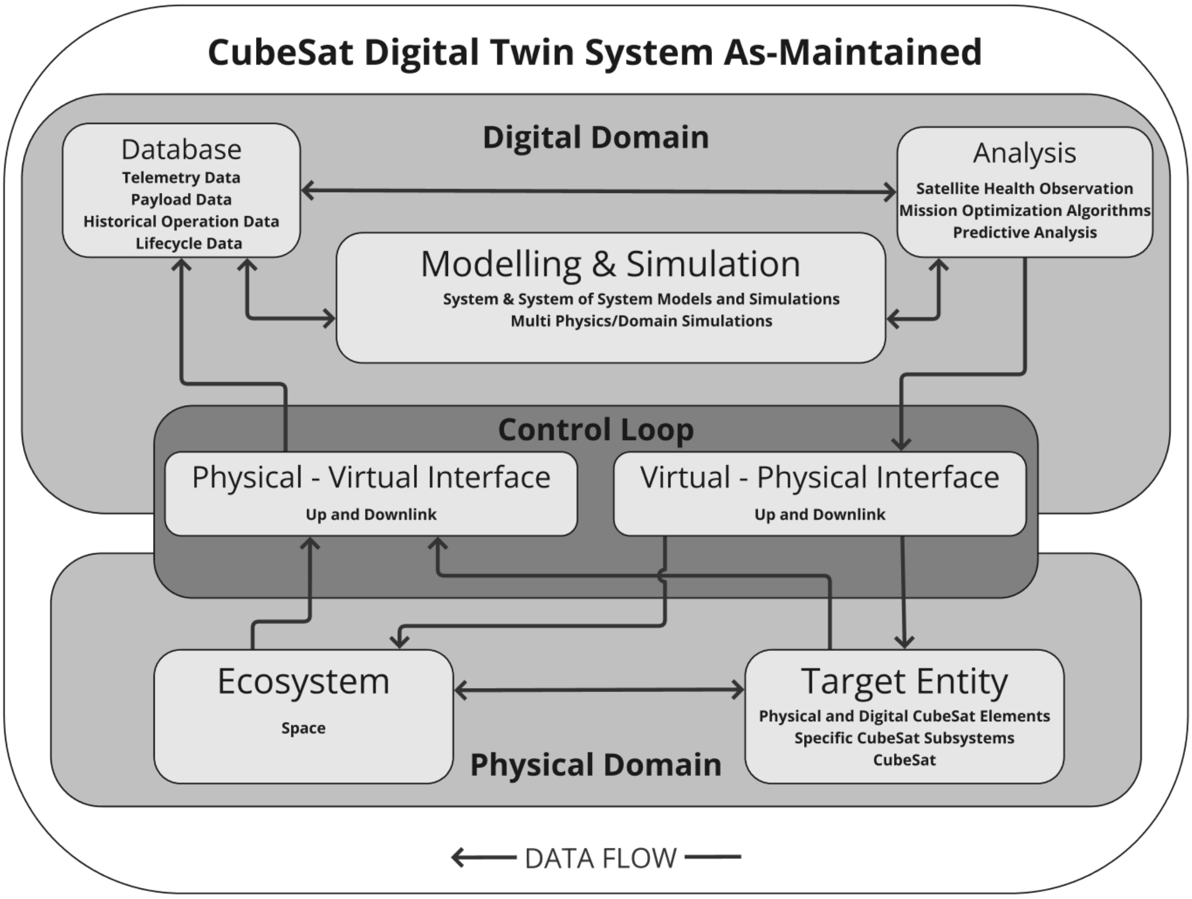

Figure 4.8 CubeSat Digital Twin: As-Built Phase covering Operation until Closeout

between data transmission and model updates.

This phase concludes with the mission's decommissioning, resulting in the unavailability of the product and its data. Therefore, all measures have to be taken beforehand to capture all available mission data for future use and incorporation into subsequent CubeSat Digital Twins

4.3.3 Modelling & Simulation Element

Research Question:

> "How can the architecture and configuration of a digital twin be optimized to enhance the efficiency, accuracy, and performance in supporting CubeSat development and operations in the new space domain?"

In the last section, the general architecture has been presented, as well as an in-detail description of applications throughout the different lifecycle phases of the CubeSat. The focus has been on understanding the different use cases, enabling an easier relation of the implementation, and how it is separated through the different elements of the CubeSat Digital Twin.
This chapter presents an in-depth analysis of optimizing the CubeSat Digital Twin architecture, emphasizing the unique characteristics that contribute to the success of CubeSats. By identifying and leveraging these features, the CubeSat Digital Twin advances to be more effective, to meet the specific needs of CubeSat developers in terms of accuracy and performance.

Some of these characteristics have already been discussed in the requirements section 4.2. However, given that the digital domain is predominantly a software-based system, the orientation focus lies on the requirements of modular software architectures for CubeSats. These requirements, as collected by Allam et al. [8], can be summarized in the following features:

- Modularity
- Reusability
- Extensibility
- Portability
- Re-Configurability
- Scalability
- Fault tolerance
- Autonomy

Singh et al. identified a significant lack of uniformity in understanding the modelling and simulation components of the digital domain [7]. Similarly, Medina et al. demonstrated that the implementation process of Digital Twin systems is rarely discussed in the literature [28]. Given that these studies have not been conducted within the satellite sector, the situation for CubeSats is even more challenging. Consequently, there is an extensive focus on this section to accurately transfer the functionalities of the CubeSat to the Digital Twin, particularly in the modelling and simulation element, which most closely mirrors the target entity CubeSat.

As a first step, the impact of the different identified functionalities on the modelling and simulation element is analyzed:

- **Modularity**: Develop and test different components of the Digital Twin independently, enabling modifications or updates to components without affecting others.
- **Reusability**: Use common components across different projects to save development time and reduce costs.
- **Extensibility**: Design the Digital Twin to easily incorporate new features or capabilities as technologies and requirements evolve.
- **Portability**: Ensure models and simulations can operate across different software environments for enhanced collaboration and independence from specific components and platforms.
- **Re-Configurability**: Allow adjustments of the simulation parameters to reflect changing mission scenarios or conditions.
- **Scalability**: Prepare the Digital Twin to handle increased complexity and data as the CubeSat Digital Twin grows over the lifecycle.
- **Fault Tolerance**: Ensure simulations can handle errors or unexpected inputs, maintaining reliability even under failure conditions.
- **Autonomy**: Automate decision-making and simulation adjustments based on real-time data, reducing the need for constant human oversight.

The identified functionalities significantly influence the entire design process of a CubeSat mission. To address this impact, the modeling and simulation framework is designed to approach CubeSat mission development in a modular and reusable manner, aiming to save time and resources. Many CubeSat missions share fundamental similarities that can be represented by reusable modules, which can be employed across different missions. This modularity facilitates the implementation of basic functionalities and lowers the entry barrier during the early design stages. Conversely, certain operations of CubeSats are mission-specific and require bespoke design efforts, which necessitate tailored solutions for each unique mission.
Based on this approach, the modelling and simulation element architecture setup is oriented towards a highly modular software framework, as El Allam et al. proposed in Figure 4.9, which follows a layered approach to minimize error propagation and enhance portability. The two bottom layers, the Hardware Abstraction Layer (HAL) and the Operating System Abstraction Layer (OSAL), can be omitted for the CubeSat Digital Twin since detailed hardware interaction modelling is not required. The focus is on higher-level, hardware-independent functionalities.

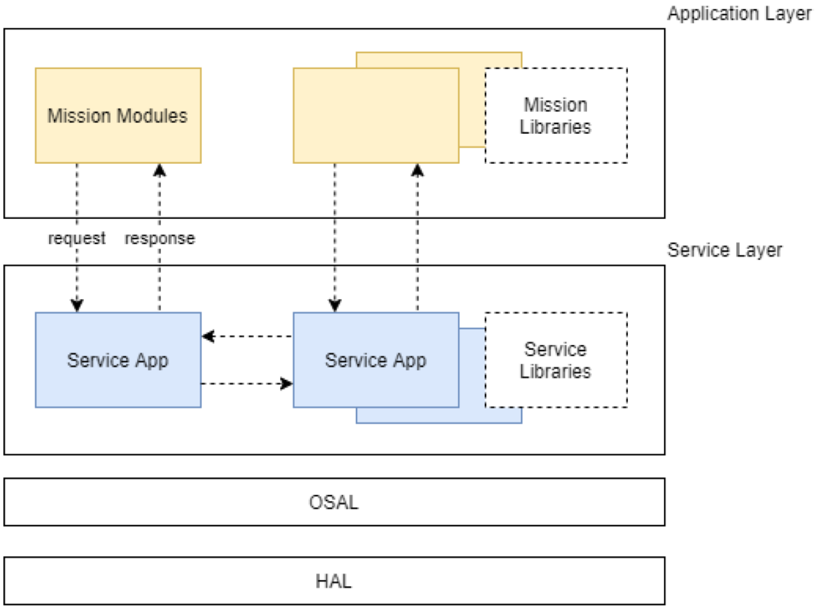

Figure 4.9 A Highly Modular Software Framework for CubeSats by [8]

The upper layers of the framework have been adapted similarly to the original software architecture. The uppermost layer is the application layer, specifically designed for mission-critical simulations and includes customizable modules developed by the simulation team. These modules may cover areas such as payload simulation, attitude dynamics modelling, system health monitoring, and simulated spacecraft initialization procedures. Below the application layer is the services layer, which provides reusable simulation components applicable to CubeSats. This could include modules for data handling, event simulation, and logging of simulated events. Users can employ these services directly in simulation scenarios or develop new service modules. Adhering to this approach has the advantage of creating a growing library of reusable services for future CubeSat missions. The architecture consists primarily of application modules, service modules, and request-response interfaces. This structure separates service requests from their execution, requiring application modules to send requests to service modules. The request-response paradigm, known for its simple yet effective messaging pattern, has been widely adopted across various fields, particularly in client-server architectures [8].

The following subsections provide detailed descriptions of each component within the framework:

Request-Response Architecture

The implementation follows a modular and asynchronous request-response architecture to ensure flexibility, scalability, and reliability. This architecture separates application and service modules, allowing seamless communication through defined interfaces.

Request and Response Classes

- **Request:** Contains command details such as ID, parameters, and priority.
- **Response:** Captures the result of requests, including status and any relevant data.

Communication Interface

- Manages sending, handling, and receiving of requests and responses using a priority queue for requests and a dictionary for responses.

Figure 4.10 shows the functionality of the request and response mechanism for a payload module.

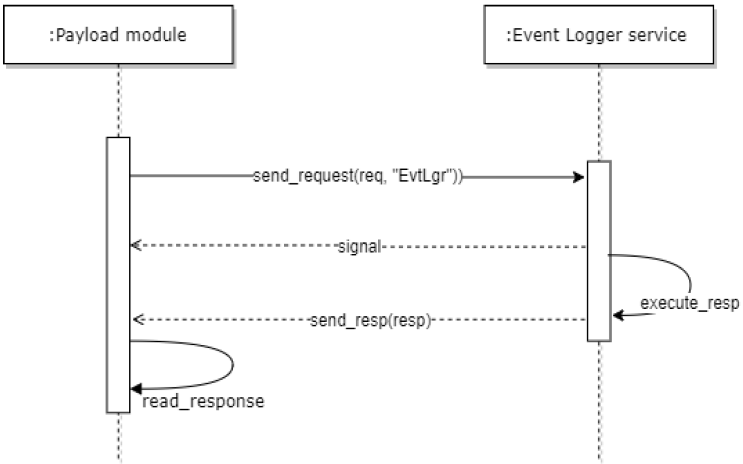

Figure 4.10 Request and Response Cycle by [8]

The architecture supports independent development, testing, and maintenance of modules. The decoupled request and response handling facilitates the easy addition of new modules or updates to existing ones without impacting the overall system structure.

Application Modules

The CubeSat Digital Twin modelling and simulation element's application modules are designed to meet mission-specific requirements using reusable service modules. Developers create applications to send requests to service providers and handle the responses. Direct communication between application modules is generally avoided to maintain modularity and predictability. Therefore, when communication between mission modules is required, it is facilitated either through a routing service within the service layer or, in certain cases, through direct interaction to support the operational fidelity of the Digital Twin.

Figure 4.11 shows a different perspective of the communication between different application modules and the battery, as a service module, through the communication interface via the request and response architecture.

Service Modules

The service modules offer reusable functionalities essential for CubeSat Digital Twin operations. Each service is defined by the commands it provides, with each command uniquely identified within the service. These

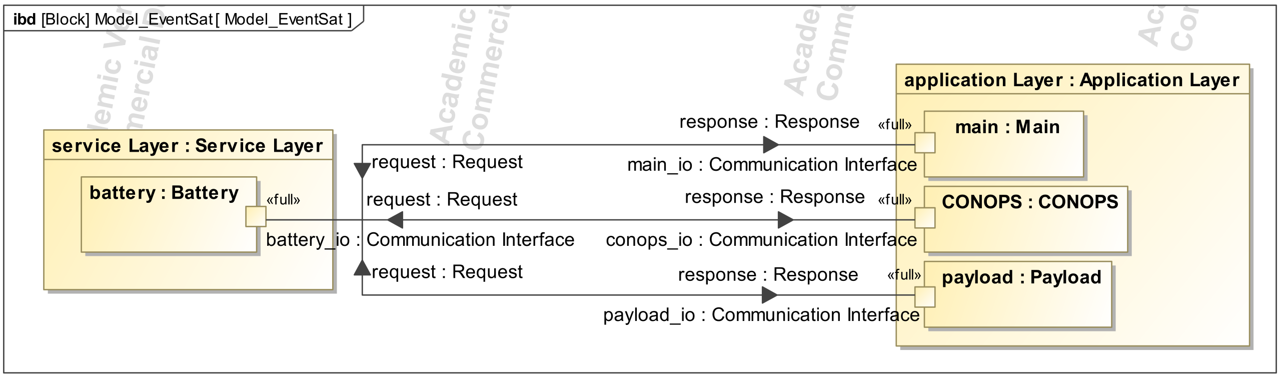

Figure 4.11 Service Module and Application Module Communication

modules abstract hardware resources or perform common functional sequences necessary for the mission. They also define ground interfaces for operator interaction. Unlike application modules, service modules can communicate with each other through the same interfaces, improving system flexibility and integration. Listing 4.1 demonstrates a battery management service module. This service module manages the battery state and operations, such as charging and power consumption. It provides critical information about the battery's status, which is essential for various operational decisions within the CubeSat. It can be reused for other missions with a battery.

Battery Service Module Example

Listing 4.1 battery.py

```
# battery.py

class Battery:
    def __init__(self, capacity_wh):
        """Initialize the battery with a given capacity in watt-hours.
           """
        self.capacity_wh = capacity_wh
        self.current_charge_wh = capacity_wh

    def consume_power(self, power_wh):
        """Consume a specified amount of power from the battery."""
        if power_wh > self.current_charge_wh:
            raise ValueError("Not␣enough␣charge␣to␣consume␣the␣power.")
        self.current_charge_wh -= power_wh

    def charge(self, charge_wh):
        """Charge the battery by a specified amount."""
        self.current_charge_wh = min(self.capacity_wh, self.
           current_charge_wh + charge_wh)

    def get_battery_level(self):
        """Return the current battery level as a percentage."""
        return (self.current_charge_wh / self.capacity_wh) * 100

    def __str__(self):
        """Return a string representation of the current battery level.
           """
        return f"Current␣battery␣level:␣{self.get_battery_level():.2f}%"
```

4.3.4 Summary

The architecture defined in this chapter addresses the key characteristics identified, ensuring a robust and effective system design:

- **Modularity:** The architecture enables the independent development and testing of different components of the Digital Twin. Components can be modified or updated without affecting others, maintaining the system's integrity.
- **Reusability:** Common components are designed for reuse across different projects, saving development time and reducing costs. The service modules provide generic functionalities that can be employed in various CubeSat missions.
- **Extensibility:** The architecture is designed to easily incorporate new features or capabilities as technologies and requirements evolve. The decoupled request and response handling facilitates the easy addition of new modules or updates to existing ones.
- **Portability:** By focusing on higher-level abstracted hardware-independent functionalities, the models and simulations can operate across different software environments. This enhances collaboration and independence from specific components and platforms.
- **Re-Configurability:** The simulation parameters can be adjusted to reflect changing mission scenarios or conditions. This flexibility ensures that the Digital Twin can adapt to different mission requirements.
- **Scalability:** The architecture is prepared to handle increased complexity and load as the CubeSat Digital Twin grows over its lifecycle. Using a priority queue and dictionary for managing requests and responses supports scalability.
- **Fault Tolerance:** The architecture ensures that simulations can handle errors or unexpected inputs, maintaining reliability even under failure conditions. The asynchronous handling of requests and responses enhances fault tolerance.

The topic of **autonomy** is not addressed in the modelling and simulation element, as the decision-making in the CubeSat Digital Twin happens in the analysis element.

4.4 Framework

The previous chapters presented a comprehensive overview of the CubeSat Digital Twin topics and showed how they could be approached and implemented, addressing the perceived intangibility of the topic in the CubeSat domain and aligning on a modular, extensible, and portable architecture to enhance future reliability of CubeSats.

Figure 4.12 presents a condensed summary of the architecture of the CubeSat Digital Twin, facilitating a wide range of applications and delivering numerous benefits for the development, production, and operation of a CubeSat.

The key components of the framework are described in a summarized manner in the following:

Digital Domain:

- Database: Stores all the necessary data required for modelling, simulation, and analysis.
- Modelling & Simulation:
  - Service Layer: Provides reusable simulation components applicable to CubeSats in general, such as data handling, event simulation, and logging.

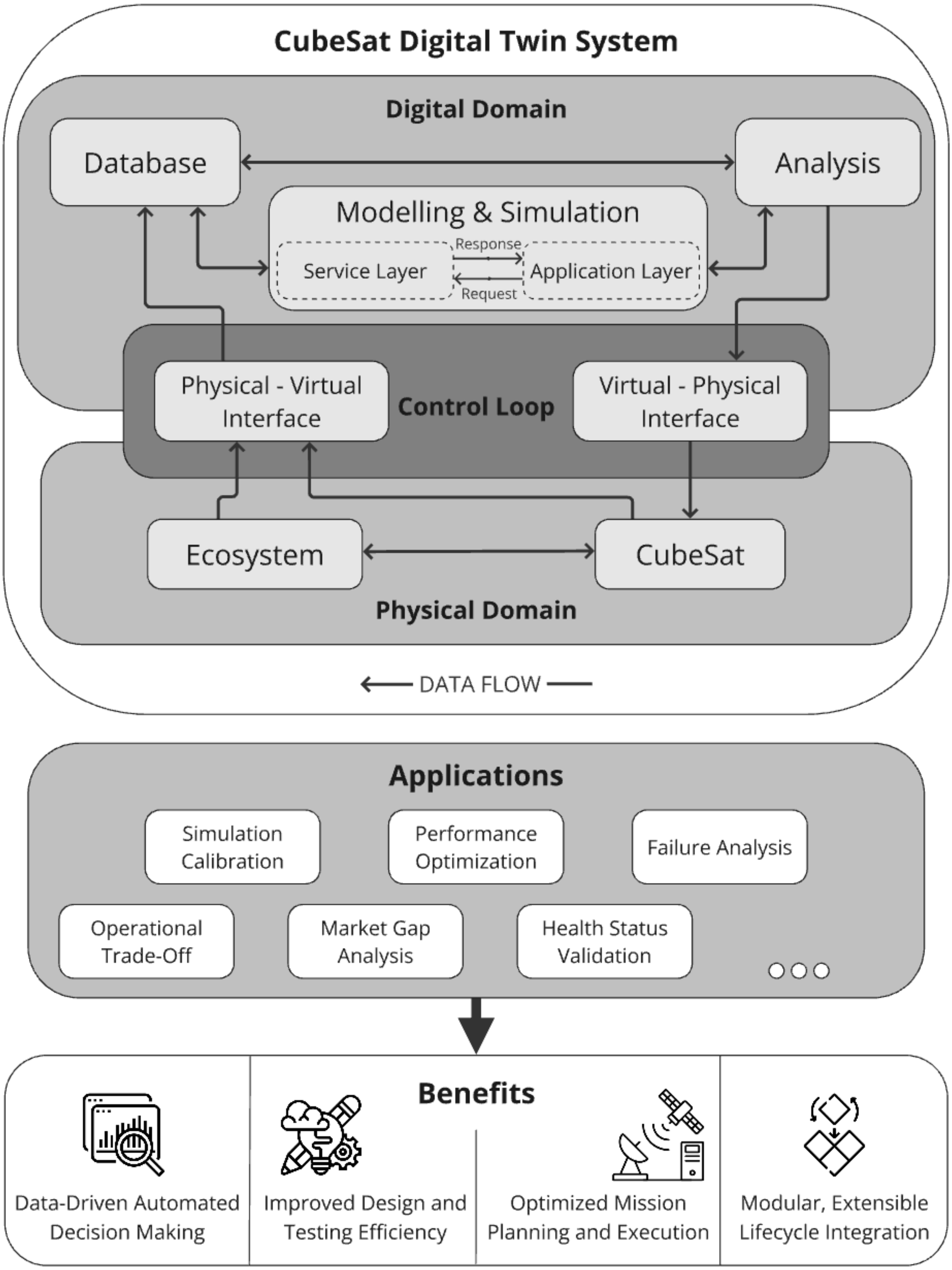

Figure 4.12 CubeSat Digital Twin Framework

  - Application Layer: Contains customizable modules developed for mission-specific simulations, including payload operations, attitude control, system health monitoring, and initialization procedures.

- Analysis: Performs data analysis to extract valuable insights, optimize performance, and validate the health status of the CubeSat.

Physical Domain:

- Ecosystem: Represents the surrounding environment and external factors affecting the CubeSat.
- CubeSat: The actual physical satellite being monitored and controlled.

Control Loop:

- Physical-Virtual Interface: Facilitates data flow from the physical CubeSat to the virtual model in the digital domain.
- Virtual-Physical Interface: Allows updates and control commands from the virtual model to be sent back to the physical CubeSat, ensuring real-time synchronization and control.

Applications

The CubeSat Digital Twin supports various applications, including:

- Simulation Calibration: Adjusting simulation parameters to match real-world observations.
- Performance Optimization: Enhancing the operational efficiency and effectiveness of the CubeSat.
- Failure Analysis: Identifying and diagnosing faults within the system.
- Operational Trade-Off: Balancing different operational strategies to achieve optimal performance.
- Market Gap Analysis: Identifying gaps in the market to inform strategic decisions.
- Health Status Validation: Ensuring the CubeSat's systems function correctly.

Benefits

The integration offers several benefits:

- Data-Driven Automated Decision Making: Leveraging real-time data to make informed and automated decisions.
- Improved Design and Testing Efficiency: A virtual model enhances the design and testing process.
- Optimized Mission Planning and Execution: Improving mission planning and execution through accurate simulations.
- Modular, Extensible Lifecycle Integration: Ensuring that the system can be easily extended and adapted throughout the CubeSat's lifecycle.

This CubeSat Digital Twin framework creates a robust and flexible environment for developing, simulating, monitoring, and controlling a CubeSat. The system supports various applications by integrating real-world data from the physical CubeSat with advanced modelling and simulation techniques. It delivers significant benefits in decision-making, efficiency, and mission success.

5 EventSat Case Study

This chapter covers the implementation of the proposed framework on the CubeSat mission of the Chair of Spacecraft System at TUM. First, a brief overview of the mission itself is provided, then the application of the presented framework on a CubeSat under development is shown, and finally, the outcomes of the implementation are presented.

5.1 EventSat Case Study

The EventSat is the first CubeSat mission of the Chair of Spacecraft Systems at the TUM, with the mission statement:

- The mission of EventSat is to advance autonomous object detection, classification, and identification techniques in space for enhanced space situational awareness and autonomous space operations, through the technological demonstration of event cameras integrated with onboard AI

and the mission objectives:

- Study and develop AI-based autonomous object detection, classification, and identification algorithms suited to event cameras' output.
- Design, build, and test a 6U CubeSat (EventSat) with an event camera and an onboard AI PC payloads.
- Procure the launch to orbit (LEO or SSO, 400 to 600 km) and operate the CubeSat in orbit to technically demonstrate the developed hardware and software.
- Prove the techniques in orbit for nearby (<500 km) satellites and bigger objects (asteroids, comets).
- Analyze the results for future improvement and for scientific publication and dissemination.
- Decommission the satellite safely with end-of-life.

Based on these mission objectives, the following mission requirements can be derived:

Table 5.1 EventSat Mission Requirements

Code	Description
MIS01	The mission shall detect objects in space autonomously.
MIS02	The mission shall classify objects in space autonomously.
MIS03	The mission shall identify catalogued objects in space autonomously.
MIS04	The mission shall demonstrate the use of event cameras in space.
MIS05	The mission shall demonstrate the use of onboard AI for object detection, classification, and identification in space.
MIS06	The mission shall downlink detection, classification, and identification reports in regular ground station passes.
MIS07	The mission shall be able to be reconfigured by AI model update through telecommand.
MIS08	The mission's satellite shall be in the form of a 6U CubeSat.

MIS09	The mission's satellite shall operate in a LEO or SSO between 400 and 600 km.
MIS10	The mission's satellite shall not consume more than 50 W.
MIS11	The mission's satellite shall not weigh more than 12 kg.
MIS12	The mission shall comply with applicable end-of-life disposal regulations.

A first rendering of the preliminary satellite assembly is displayed in Figure 5.1.

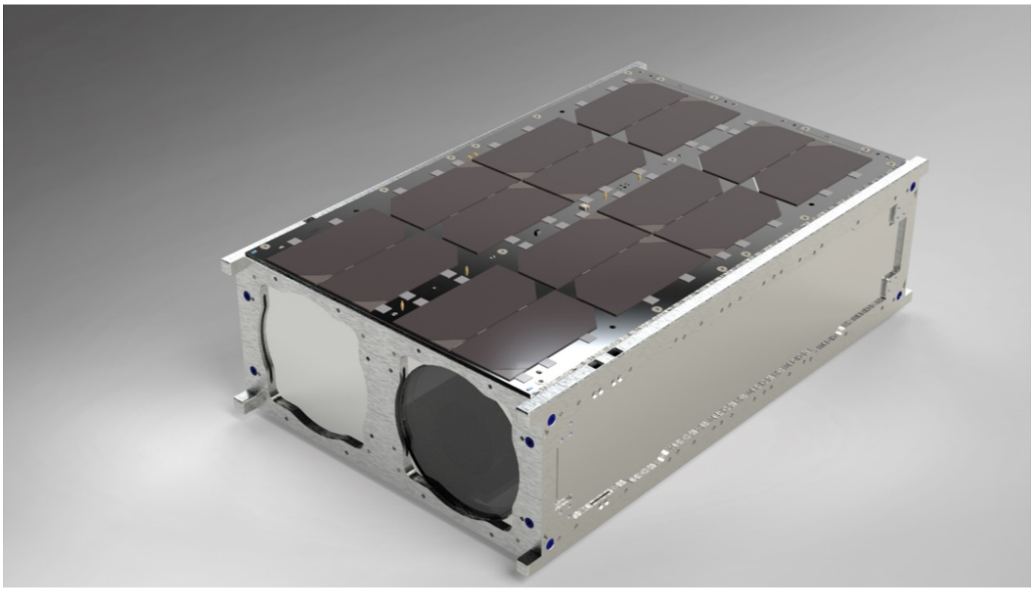

Figure 5.1 Preliminary Rendering of the EventSat CubeSat

Payload Background Information

Background information about the technology of the payload of the EventSat is provided in the following part, to understand the goals of the mission and the operation of the payload.
Event-based vision is a cutting-edge technology that integrates various engineering disciplines. Inspired by biological systems, silicon retinas or "event cameras" represent an improvement in sensor technology, providing numerous benefits over conventional frame-based cameras, including low latency, minimal power consumption, high speed, and a broad dynamic range. These features offer significant potential for advancements in computer vision [65].
Unlike traditional cameras, event cameras operate asynchronously, marking a paradigm shift in visual data acquisition. They capture light based on the dynamics of the scene rather than a fixed clock rate. This approach results in extremely high temporal resolution and low latency, both on the order of microseconds, as well as a very high dynamic range (140 dB compared to the 60 dB of standard cameras) and low power consumption [65].
Event cameras excel in challenging conditions for standard cameras, such as high-speed scenarios and environments with a wide dynamic range. Although these cameras have only been commercially available since 2008, the growing body of research and recent announcements of mass production indicate substantial commercial interest in these innovative vision sensors. However, because event cameras capture visual data differently, recording per-pixel brightness changes asynchronously instead of measuring absolute brightness at constant intervals, new processing methods are necessary to fully harness their capabilities [65].

Mission Architecture

The idea of the EventSat is to deploy an event-based camera in combination with an NVIDIA Jetson Orin Nano on board a 6U CubeSat. The spacecraft bus mainly comprises COTS components, which in the majority have already been purchased by the CubeSat component vendor EnduroSat. Additional components will be purchased later in the project or developed in-house by incorporating student theses. In such a way, the CubeSat structure has been developed.
As depicted in the following Figure 5.2, the preliminary architecture EventSat is composed of an Attitude Determination and Control System (ADCS), an Electrical Power System (EPS), an On-Board Computer (OBC), a Communication (COM) subsystem entailing two different COM modules with one antenna each for the Ultra-High-Frequency (UHF) and X-Band communication. The payload combines the event camera with an optical telescope and the high computational engine of the NVIDIA Jetson Orin Nano. The outer shell, not displayed in the figure, is equipped with solar cells without any mechanisms to reduce complexity.

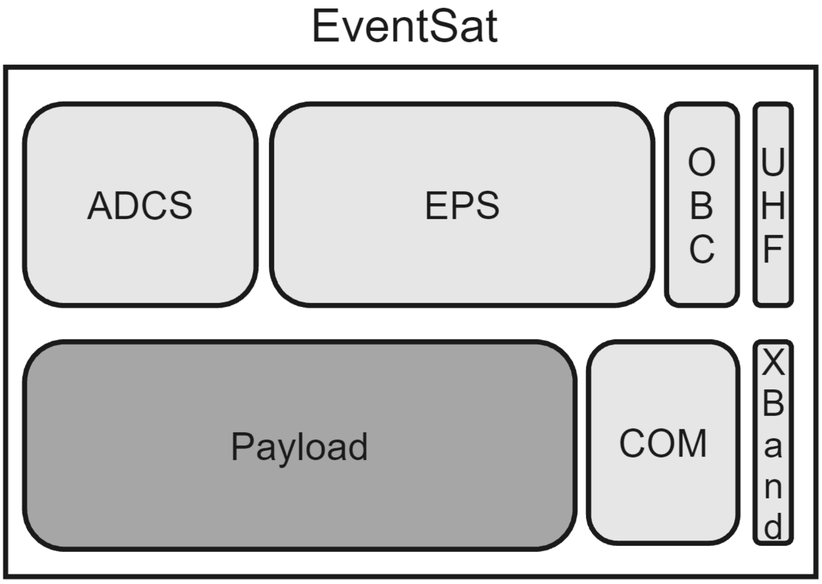

Figure 5.2 EventSat Preliminary Architecture

Mission Status

The status of the mission can be classified as preliminary design and technology development, as especially the payload requires further investigation into the technology constraints and abilities to achieve the mission objectives. Preliminary budget calculations have shown that the amount of data produced by the payload can be very high rate, up to a max of 1.6 Gbps, and thus require advanced COM X-Band downlink capabilities. The data flow from the camera is received by the NVIDIA Jetson Orin Nano through USB 3.0, processed through filters and ranked with machine learning algorithms, transferred through the PC104 interface to the X-Band module, and then downlinked through the patch antenna [66].

The CubeSat and, notably, the payload will undergo further development cycles to identify the limits and challenges of the system, with a combined approach of theoretical studies to define the optical characteristics maximizing the outcome of the mission in space and experimental test setups to predetermine the expected data rate and power consumption in more detail.

5.2 Application of Methodology

The goal of applying the proposed methodology to a real-world scenario offers the possibility to verify the approach against the initial requirements, checking for the correctness of the framework and validating if the implementation fulfills its intended purpose and meets the end user's needs.

5.2.1 Scenario Description

To assess if the CubeSat's design and configuration meet the payload's needs, an early-stage analysis has been conducted in the software tool Valispace [67], accessing the first power and mass budgets. The power budget for different modes and an additional calculation in the project showed that the power consumption of the payload based on the given data sheets revealed relatively high power consumption values while operating the payload. This resulted in a very low average operation time of the payload per day of 60 minutes, as the cycle to charge the battery would be very long with the restricted area of the solar panel of 20 x 30cm and the high power consumption of the payload discharging the battery over a timeframe of only 210 minutes. This would not disrespect the initial mission requirements, as the mission is aimed at technology demonstration. This would drastically lower the probability of detecting objects in space, as no long-term operation can be executed while operating the CubeSat.

The investigation of the payload of a CubeSat offers the possibility of refining the operation of this component and drastically increasing the scientific value of a mission, as with more operation time, more scientific data can be gathered. The payload is, in most cases, the first investigated technology, as the CubeSat bus is built to serve the needs of the primary payload to ensure mission success. This is why the payload is usually the first subsystem for which prototypes are available to test the design and its behavior under different conditions.

Regarding the CubeSat Digital Twin, this offers an early implementation with the payload to improve the selection of the correct spacecraft bus COTS components to enhance later mission success and show the possible application of a power budget verification. Therefore, the power budget investigation is chosen as a use case for the CubeSat Digital Twin. This use case can then be used throughout the remaining lifecycle of the mission and can be connected to the other hardware components, investigated under different scenarios and conditions to get an in-depth understanding of the power consumed while operating, estimate an accurate payload operation time before launch and enhance mission planning while in operation.

5.2.2 Implementation Setup

Currently, the hardware of the payload available at the university consists of development kits, as the payload is still under investigation. Therefore, this early iteration of the payload is chosen for implementing the CubeSat Digital Twin. This will result in values different from those of the actual satellite, but it gives a baseline understanding of the behavior and the opportunity to refine the simulation throughout its lifetime. Through the step-by-step connection to more hardware and the investigation of different algorithms and software operating the payload, a demand-based model update frequency is aimed at in this early investigation.

Figure 5.3 shows the setup to investigate this implementation. It is set up in the laboratory of the Chair of Spacecraft Systems with the available resources of the Chair and the author. This assembly is only temporal and has been currently used only for the investigation of the thesis work because the different components are used in other investigations as well. In the following, a more detailed assignment of the different elements of the CubeSat Digital Twin to the EventSat and the other hardware used is presented:

Physical Domain

The physical domain covers the ecosystem and the target entity. The ecosystem is, on the one hand, the complete laboratory environment that surrounds the target entity and influences its behavior, e.g., if the temperature inside the laboratory rises, a rise in the temperature of the components is seen. For this early investigation of the

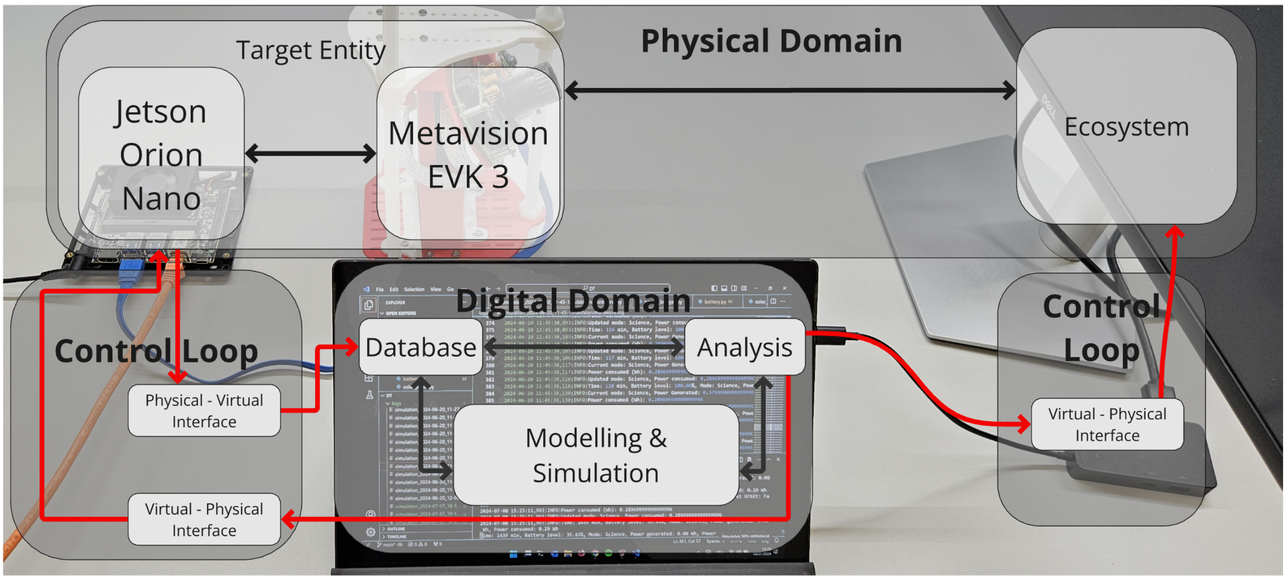

Figure 5.3 Setup of the CubeSat Digital Twin for the EventSat - Black Lines Depict the Internal Connections of the Elements and Red Lines Depict the Connections among the Elements

behavior of the target entity, there has been no aim to control the environment in detail, as this would have resulted in an increase in necessary resources, which could have led to an abort of the operation of the Digital Twin as it raises the entry barrier. An additional expense has been taken regarding the visual recognition of the target entity. Therefore the field of view, which is covered by the EventCamera, has been covered by a screen on which videos or pictures can be displayed to enhance further comparability between different modes of the target entity during the different sessions.

The target entity comprises the NVIDIA Jetson Orin Nano Developer Kit and the Metavision Evaluation Kit 3 (EVK-3)-HD; both are not optimized for space operation currently but rather for early development, evaluation, and on-ground testing. For the NVIDIA Jetson Orin Nano Developer Kit, the biggest indication for this can be seen in the fan operating above the Central Processing Unit (CPU), as well as all the hardware surrounding the CPU to support the development of various projects. It is powered by an external power source to ensure safe and reliable operation. As an operation system, it currently has Ubuntu 20.04.6 LTS installed. For further development and access to the board, a screen and other peripherals like a keyboard and mouse can be connected via USB. In the test setup, the NVIDIA Jetson Orin Nano Developer Kit offers 4 GB of RAM and up to six CPUs and one Graphics Processor Unit (GPU). It also offers different predefined modes to switch between and adjust the computational power usage to the project's needs. For this version of the AI computer, three different modes are available: 7W CPU, 7W AI, and 10W. As already indicated by the naming of the modes, the power consumption differs between these modes, which is achieved by restricting the number of online CPU cores and the GPU and the CPU frequencies. Regarding the use case of the power budget, it is important to mention that the NVIDIA Jetson Orin Nano is equipped with an internal power measuring unit, and the values are available to access via different tools [66]. Via USB 3.0, the Metavision EVK-3 is connected to the AI computer. This evaluation kit is ideal for early hands-on, cost-efficient evaluation of developments, equipped with an SONY IMX 636 sensor, which is already integrated on a Printed Circuit Board (PCB), equipped with various mounting and data interfaces. The Jetson uses the open-source-based architecture provided by Metavision "OpenEB" to access the functions of the Camera and can record and save event-based videos.

Digital Domain

The digital domain is operated on a Windows Surface Pro 7, with 8 GB of RAM and eight logical CPU cores, running Windows 11 Home. The database is represented by the installed Solid State Drive (SSD) with up to 256 GB of storage available. The modelling simulation and analysis elements work in a Python environment operated with Visual Studio Code Version 1.91.0. All of the different layers, the corresponding scripts, and the diagrams are saved in the same folder and connected to a GitLab repository for easier implementation.

Control Loop

As shown in Figure 5.3, the control loop is separated into two different elements in the application to access the Ecosystem and the target entity with different connections. The virtual-physical interface from the digital domain to the ecosystem is realized as an HDMI connection, connecting the screen to the personal computer and displaying the videos or pictures for the camera to record. The other side of the control loop reflects the interfaces between the target entity and the digital domain. The digital domain is connected to the university's local WLAN network via a Virtual Private Network, and the NVIDIA Jetson Orin Nano is connected to the university network via the orange LAN cable with a fixed IP address. The communication of these two elements works with the Secure Shell Protocol (SSH) for a secure network service operation.

5.2.3 Software Architecture

This section gives a defined overview of all the components involved in the implementation. However, a further look at the software architecture is necessary as the CubeSat Digital Twin mainly interacts and operates through software components. All the scripts discussed and used for the thesis can be found in the thesis's GitLab[1] repository.

As already briefly introduced, the "OpenEB" architecture is running on the operating system Ubuntu 20.04.6 LTS of the NVIDIA Jetson Orin Nano to access the Metavision EVK-3 event-based camera. The "OpenEB" architecture comes with samples that enable easy access to the camera and a possible visualization. For the implementation, there is no visualization required, but the availability should be given to review these event recordings later in the process to validate the actual recording. Thus, the script of the "metavision_simple_recorder.py" is modified in a way that it does not visualize the output while recording, and the storage directory is chosen differently. Thereby, it can be assured that the EVK-3 resembles the operation of the payload in space. To measure the power of the NVIDIA Jetson Orin Nano accurately, the inbuilt power measuring devices of the different lines are used, and through a second Python script using the jetson-stats package, the system values of the AI computer are accessed [68]. These two Python scripts reproduce the operation of the payload in space. For parallel execution and easier operability, these scripts are executed via a bash script, defining the environment values, opening the two scripts, and taking care of the proper closure procedure of the script execution in case of any interruption or if the simulation is finished.

The digital domain is realized on the personal computer. This implementation focuses on the modelling and simulation elements. Therefore, less effort has been put into implementing the database, and no graphical data visualization has been implemented. Only a textual output has been provided. The architecture of the modelling and simulation element is displayed in the SysML Block Definition Diagram 5.4. This also implies the first part of the modelling and simulation element. To show the abstract behavior of the simulation and the communication interactions between the different layers, it has been modeled in SysML to enable an easier understanding and faster simulation implementation. The model is not actively connected with the simulation or the target entity. It solely serves as an abstraction of the implementation to understand the structure easier and faster.

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[1] https://gitlab.lrz.de/leonhard.kessler/leonhard-kessler-master-thesis

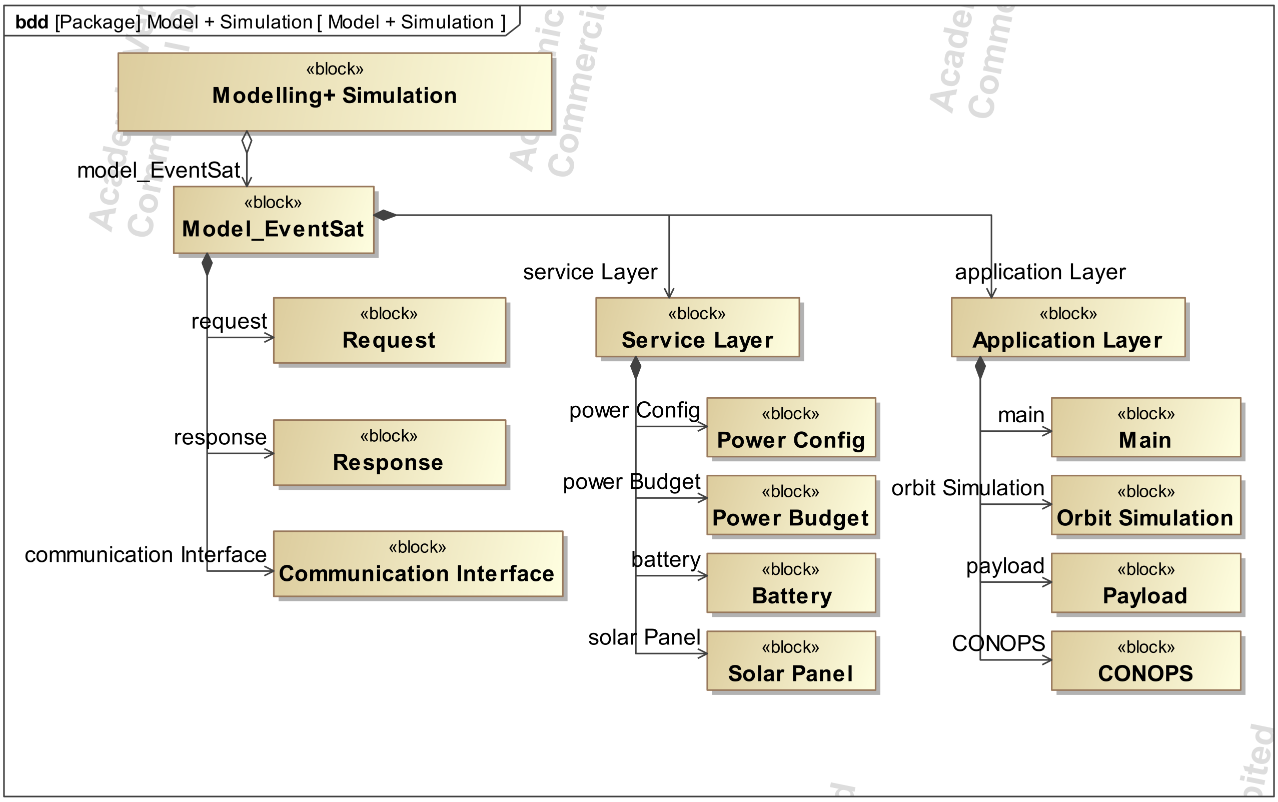

Figure 5.4 Block Definition Diagram of the Modelling and Simulation Element of the CubeSat Digital Twin System

The simulation is designed to model the operations of a satellite's power and payload management over multiple orbits. It consists of three primary layers: the Application Layer, the Service Layer, and the Communication Interface. Each layer contains modules that perform specific tasks, working together to simulate various operational scenarios:

- Application Layer:
  - `main.py`: Orchestrates the overall simulation.
  - `orbitsimulation.py`: Runs detailed simulation scenarios.
  - `payload.py`: Manages payload operations.
  - `conops.py`: Defines operations concepts and scenarios.
- Service Layer:
  - `power_config`: Acts as a single source of truth for power values.
  - `power_budget`: Defines calculations for a power budget.
  - `battery`: Defines simplified battery functions, including charge and discharge.
  - `solar_panel`: Simulates the charging phases.
- Request-Response Interaction:
  - `request_and_response`: Used to encapsulate command details and results.
  - `Communication Interface`: Manages the sending, handling, and receiving of requests and responses.

The state machine in Figure 5.5 for the Concept of Operations (ConOps) illustrates the transitions between satellite operational modes based on battery levels and other conditions.

- **Idle**: Default mode when the satellite is powered on. Transitions to this state if it recovers from a failure or is not in another specific mode.
- **Science**: Activated when the battery level is above a certain threshold, allowing the satellite to perform scientific operations.
- **Communication**: Engaged during ground contact windows if the battery level is sufficient. Exits this mode when the ground contact window ends.
- **Safe**: Entered during a failure or when the battery level is critically low, ensuring minimal power consumption to prevent complete power loss.
- **Off**: End-of-life state when the satellite ceases operations permanently.

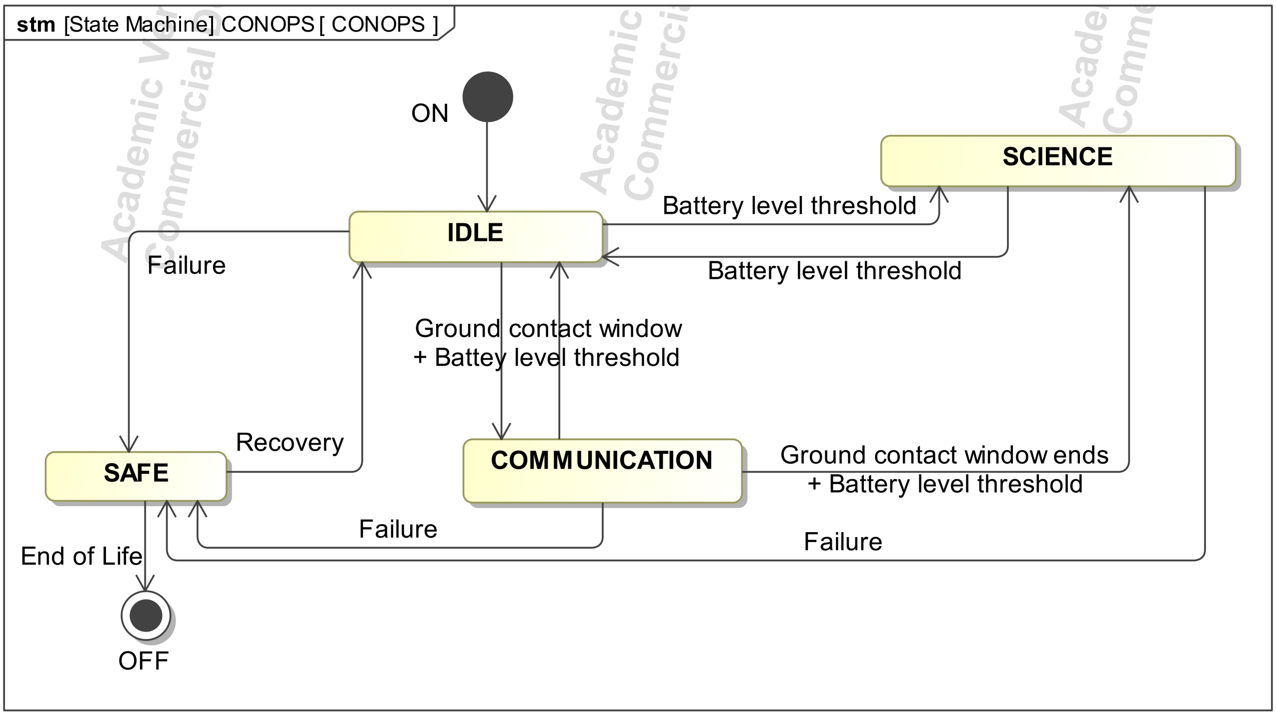

Figure 5.5 State Machine - ConOps

The operator initiates the simulation via the main.py command and then it follows this high-level interaction flow between the different modules in the simulation:

1. **Initialization**:
    - `main.py` initializes the battery, solar panel, and communication interface.
    - `conops.py` sets the operational thresholds.
2. **Simulation Loop**:
    - `orbit_simulation.py` runs the main simulation loop.
    - Alternates between sunlight and eclipse phases.

3. **Mode Management**:
    - `conops.py` determines the satellite's operational mode (Idle, Science, Communication, Safe) based on battery levels and current conditions.
4. **Power Management**:
    - `battery.py` manages charging and discharging.
    - `solar_panel.py` simulates power generation during sunlight periods.
5. **Payload Interaction**:
    - `payload.py` handles recording operations and fetches power data from the Jetson device.
6. **Communication**:
    - `communication_interface.py` manages requests and responses between modules.

Additionally, this sequence diagram in Figure 5.6 illustrates the detailed data-gathering process from the payload and its importance in correlating simulation values. It shows the critical steps and interactions required to correlate hardware data with simulation values. The precise implementation of these steps ensures accurate simulation and analysis, highlighting the importance of integrating hardware interactions in the simulation workflow.

1. **Initialize ConOps**: `main.py` initializes the ConOps.
2. **Check Hardware Connection**: `conops.py` checks if the hardware is connected.
3. **Simulate Phase**: `conops.py` simulates a phase.
4. **Check Battery Level**: The battery level is checked.
5. **Connect Jetson**: If the battery level is sufficient for Science mode, the Jetson device is connected.
    - SSH connection is established.
6. **Start Recording**: Starts the recording on the Jetson device.
    - Executes the start command.
7. **Confirm Recording Started**: Confirms that recording has started.
8. **Fetch Power Data**: While in Science mode, power data is periodically fetched.
    - Fetches power data from the Jetson device.
9. **Return Power Data**: The fetched power data is returned.
10. **Update Power Configuration**: Updates the power configuration based on the fetched data.
11. **Log Power Data**: Logs the power data.
12. **Stop Recording**: Stops the recording when exiting Science mode.
    - Executes the stop command.
13. **Confirm Recording Stopped**: Confirms that recording has stopped.
14. **Disconnect Jetson**: Disconnects the Jetson device.
    - SSH connection is closed.
15. **Switch to Idle Mode**: Switches back to Idle mode if necessary.
16. **Log Simulation Status**: Logs the current status of the simulation.

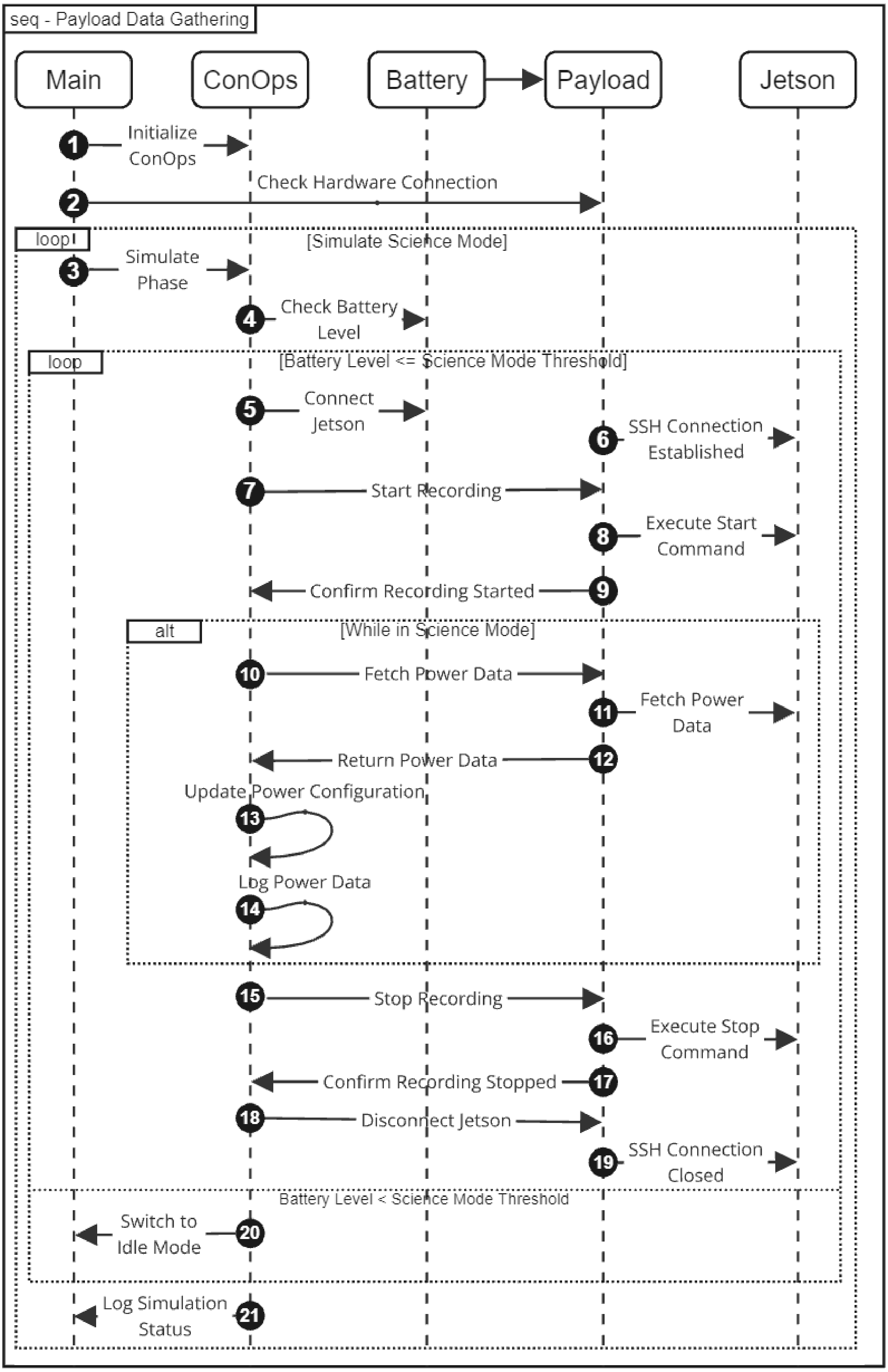

Figure 5.6 Sequence Diagram - Payload Data Gathering

The simulation connects to the hardware once when it can establish contact. Then, the operation on the Jetson is initialized. While this script is operating, the simulation runs at the clock time of the PC to reflect one minute in the orbit as one minute for the payload and fetches the power data of the payload every 10 seconds. After one minute of operation, the average of this value is taken to update the simulation long-term, and the payload is disconnected again. This is a tradeoff of payload availability, simulation time, and accuracy. If the simulation keeps running in this slow mode, a long-term prediction would be unfeasible, and the payload would not be available for other operators at this time. As this implementation serves only as a demonstration of this thesis, this trade-off has been accepted. After the disconnection, the simulation keeps running until the set limit of orbits is reached. During the whole simulation, the data and the debug output of the simulation, respectively, the power values with a corresponding timestamp, are saved in a log file as well as in a CSV-Format file. This ensures proper documentation of the simulation over the lifecycle and enables manual analysis later on. The GitLab repository ensures the scripts have version control, which can then be aligned to the specific simulation that was running at this time.

Once the simulation is finished, the data will be handed over to the analysis element. There is only one script in this element, the analysis.py script. It evaluates the performance of different operational modes, specifically focusing on the Science mode. It calculates the percentage of time spent in each mode, gives out the current status, and evaluates if a mode change is required by comparing the result to a threshold defined by the operator. If the hardware requires a change, the analysis script connects to the target entity via SSH, changes the hardware, and re-runs the simulation again, comparing the results at the end of the different simulations. This hardware configuration changes the NVIDIA Jetson Orin Nano mode from the 10W to the 7W CPU mode.

5.3 Results

The implementation of the case study showed the application in a real-world scenario, ensuring the approach is valid for usage as a CubeSat Digital Twin concept. The approach highlights the incorporation of the payload as the main valuable component of a CubeSat and the imperative design of a CubeSat Digital Twin. The satellite bus subsystems have not been involved in the simulation, but a better understanding of the payload has been accomplished through simulating their values and behavior throughout the mission.

The simulation for the has only been an example for the CubeSat Digital Twin, therefore some assumptions and considerations have been taken. This assumption mainly considered the amounts of events logged, the computation algorithms operated on the NVIDIA Jetson Nano, and the orbit characteristics. The focus point for the operation of the camera's event logging has been set on comparability, which the setup of the environment has achieved. The computation of the AI computer has been reduced to operating the event camera and logging the power as no ready-to-use algorithms have been available. For the orbital considerations, a simplified sun-synchronous orbit has been taken as a baseline for the simulation: 90 minutes of orbit time, 60 minutes in the sunlight, and 30 minutes in the eclipse. This has been validated with a separate computation in orbit mechanics software. The communication window has been selected in a way that it communicates while operating in the sun to reduce the risk of a fallback in the safe mode. It has been decided to initiate the simulation for one orbit to be able to observe the correct functionality of the simulation before the hardware connects automatically. The different modes' thresholds and safety factors have been selected from the early mission power budget calculations. The component values of the satellite bus have been used from the mission's Valispace. The EventSat satellite team selected this configuration with the corresponding values. All of the values can be changed very easily in the simulation due to the architecture simulation based on the methodology.
This approach mainly stems from the early lifecycle stage of the mission, which is still finishing itself in the preliminary design and technology completion stage. A lot of information, especially about the payload, is missing. Therefore, no design decisions can be made without risking success. The outcome of the payload, its optimal operation, and especially the incorporation of the machine learning and AI algorithm are still subject to various studies and will be examined. As an example, the exact amount of objects the sensor can detect as events is unclear, which can have a serious impact on the data and power budget of the mission, as only if

objects are recognized as events, the payload needs to transfer data and the NVIDIA Jetson Orin Nano needs to compute the filtering and detection algorithms.

The simulation operated for 170 orbits, as a trade-off between time to wait until the simulation finishes and giving the behavior of the component enough time to see a trend in operation. In Table 5.2, the output values of the operations in the different modes of the Jetson and the simulation operating without the hardware are displayed. These outputs indicate the correlation of the simulation to the input of the payload and additionally show the difference in the simulation data indicated by the mode change through the analysis.py script.

Table 5.2 Percentage Distribution of Different Mode Operations

Mode	**10W**	**7W**	**No Hardware**
Idle	13.11	0.59	42.78
Science	85.51	98.03	55.84
Communication	1.38	1.38	1.38

This gives insights into the difference in the performance of the different modes and how this affects the mission operation overall. This coupled loop of data gathering, correlating the simulation, and updating the hardware as a reaction to the simulation impacted the development of the CubeSat tremendously in various ways and demonstrates the successful implementation of the CubeSat Digital Twin according to the presented framework:

- **Improved Performance**: The analysis ensures enhanced performance by monitoring and adjusting the satellite's operational modes, particularly for critical tasks like scientific data collection.
- **Real-Time Adaptation**: The system can quickly respond to suboptimal conditions, adapting hardware configurations without manual intervention.
- **Enhanced Simulation Accuracy**: Integrating feedback from physical hardware into the simulation enhances the accuracy and reliability of the Digital Twin.
- **Data-Driven Decisions**: The analysis leverages data collected during simulations to make informed decisions, improving the overall mission success rate.

6 Future Work and Conclusions

6.1 Conclusion

This research aimed to optimize the methodology of Digital Twins tailored for the needs of CubeSats, particularly focusing on a 6U CubeSat with an optical payload. Three key research questions guided the study:

> **What are the key challenges and system requirements for developing a Digital Twin for a satellite? How can these be derived and tailored for nanosatellites focusing on a 6U CubeSat with an optical payload? How do these requirements differ regarding the level of detail of the various subsystems and their prioritization?**

The research identified that the primary challenges in developing a Digital Twin for CubeSats include a lack of literature in the space sector and general standardized frameworks that could be transferred from other domains. The knowledge of implementation processes is insufficiently covered in other research applications for a Digital Twin. High costs are associated with the concept of Digital Twin, as noted in both the literature and the industry survey, though detailed cost analyses have been unavailable due to nondisclosure agreements. The challenges have been addressed by clarifying definitions and summarizing requirements for a Digital Twin. CubeSat requirements were derived from non-functional requirements specific to CubeSats and tailored to create a combined set for a CubeSat Digital Twin. These requirements balance feasibility, fidelity, modularity, reusability, and iterative improvement. Prioritization is given to the payload due to its critical role in mission success. For a 6U CubeSat with an optical payload, the focus can be identified on enhancing pointing accuracy and optimizing data handling and power management for increased science time and reliability. However, only power management was demonstrated in the case study due to resource constraints.

> **How can the architecture and configuration of a Digital Twin be optimized to enhance efficiency, accuracy, and performance in supporting CubeSat development and operations in the new space domain?**

The architecture of the CubeSat Digital Twin has been optimized by adopting a modular and scalable approach. The architecture has been designed to be flexible, allowing for incremental implementation and gradual enhancement. The architectural element terms have been specified in detail, while the naming has been aligned with standards to ensure maintainability. To orient the implementation of the CubeSat Digital Twin close to other Digital Twins and thus to enhance the transferability of other tools used for Digital Twin technology to the domain of CubeSats, the general architecture presented in the work does not differ from other Digital Twins. A detailed description of the CubeSat Digital Twins throughout the lifecycle has been presented. This can guide developers through the process, showing potential application possibilities and enhancing implementation through identified benefits. Key characteristics identified for optimization include alignment with CubeSat characteristics, use of common tools and platforms, and robust data handling and analysis processes. Reusable service modules have been developed and stored in a library for future missions. These modules have been created in the context of the case study implementation. Therefore, no general code snippets have been created as standard templates, but specific scripts have been developed for each module. The case study shows a potential application beneficial for many CubeSat domain actors, as power management often presents significant challenges.

> **What are the implementation strategies, limitations, and potential areas for improvement of Digital Twins for CubeSats, considering the industry's evolving needs and technological advancements?**

The implementation strategy followed a systematic approach, beginning with an overview of the CubeSat system and identifying the actors and components involved in the CubeSat Digital Twin from the CubeSat side, as well as specifying the coverage of the Digital Twin beforehand. The subsequent steps focused on developing simulations based on datasheet parameters, correlating simulation data with real-world data, and establishing an automated control loop to adapt the behavior of the target entity according to analysis outcomes. This follows the discussed approach of Digital Model, Digital shadow, and then Digital Twin. Several limitations have been identified during this process. First, early simulations depend heavily on datasheet parameters, which may not always be accurate or could represent only the maximum values of components. This dependency poses a challenge for precise modeling. Correlating real-world data requires additional validation to ensure repeatability in simulations, which can be labor-intensive and may necessitate further research on the components used. Additionally, customers often have real-time simulation objectives, which can be difficult to meet. Addressing this through the lifecycle evolution offers a potential framework for this issue and communicates expectations clearly. Early lifecycle stages may only have development hardware available, limiting the reliability of values for later applications when the target entity design evolves. This has been the case in the case study, which aimed to demonstrate practical implementation strategies and highlighted some limitations. For instance, using an advanced AI computer with onboard sensors to measure power consumption revealed discrepancies due to peripherals like the event camera but enabled easier implementation. This highlighted the need for qualified measuring tools to ensure value reliability in future implementations. Additionally, if a computer with an accessible operating system is unavailable, alternative data acquisition methods are necessary, which could limit application modularity. The industry survey and expert interviews revealed that while the industry sees potential in Digital Twin technologies, specific needs, and technological advancements could not be fully identified due to the low number of interviews. Future research should aim to engage more industry stakeholders to gather comprehensive insights.

The methodology developed in this research was implemented in a 6U CubeSat project at the Technical University of Munich. The case study demonstrated the practical application of the Digital Twin, showcasing how real-world data can be correlated with simulations to optimize payload operations. This implementation highlighted the benefits of early lifecycle data correlation, improving the understanding of satellite behavior and enabling early configuration optimization to enhance the operational time of scientific missions. This research fills a gap in the literature by presenting a novel methodology for CubeSat Digital Twins, integrating industry perspectives, and addressing the unique challenges of CubeSat development. The study contributes to the field by proposing a systematic approach to Digital Twin implementation, summarized in a framework, emphasizing modularity, reusability, and scalability. The findings suggest that a well-designed Digital Twin can significantly enhance CubeSat development and operations, offering a promising solution to the industry's growing demand for efficient, reliable, and cost-effective satellite missions.

6.2 Future Work

This section presents an outlook for possible future developments and proposes a potential way forward for the different aspects of the thesis. Future research should focus on refining the proposed framework and conducting more extensive industry evaluations to validate the findings. Further studies should also explore integrating advanced technologies, such as artificial intelligence and machine learning, to enhance the predictive capabilities of Digital Twins.

Further implementation of the CubeSat Digital Twin in CubeSat projects is crucial. Validate the methodology presented for the design stages that are yet to come for the EventSat, as these could not be implemented in the current study. Refining the methodology should focus on the modeling and simulation element, building a library of service and application modules, and ensuring the portability of these modules. Incorporate more experts with deep software knowledge to enhance the system's robustness. It's essential to bring more stakeholders to the table to discuss the uniqueness of CubeSats and their potential for Digital Twins. Refining the questionnaire and collecting more comprehensive results to engage more experts for an interview, particularly those who have already implemented a Digital Twin for CubeSats, will help identify the challenges and opportunities in this domain.

Potential areas for improvement include leveraging more already-deployed technologies, such as the AAS, to deliver data about components upon purchase. Encouraging vendors to incorporate this technology into their systems will make data entry more seamless, reducing the reliance on manual input from datasheets and having parameters and behavior on a common exchange platform. Utilizing IoT technologies to connect facilities and components of the target entity to the digital domain will also be beneficial. Incorporating tools to facilitate the support and simplification of the connection and management of Digital Twins could enable faster implementation and would require less technical knowledge.

Finally, the most important aspect of future work is to continue helping people understand the concept of Digital Twins. Foster the usage of a common definition and terms, as language is crucial. The Digital Twin needs to move from being a technology promoted by various individuals to one that is widely understood and consistently applied across the industry.

A Appendix

A.1 Adopted Digital Twin Maturity Model for Satellites

The following page contains the Digital Twin adopted Maturity Model for Satellites, the original for aerspace OEM has been provided courtesy of Medina et al. [28].

Table A.1 Maturity Model Digital Twin Adopted to Space/Satellite

Dimensions	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Analytical Capability	Monitoring Describing and analyzing what happened	Diagnostics Analyzing why did it happen	Prediction Prediction what will happen	Prescription Recommends operational adjustments to achieve intended action
Model Update Frequency	Weeks Frequency ≥ 1 week	Days Frequency < 1 week	Hours Frequency < 1 day	Minutes Frequency < 1 hour
Data Collection Frequency	Irregular Incident driven collection	Scheduled Flight history is sent bundled during overpass	Continuous Data sent through multiple ground stations	Real-Time Continuous data with negligible latency through relay constellation
Modelling Scope	Parts Individual parts	Subsystems Self-contained for specific purpose	Complete Product Complete payload or satellite	Product Environment Modelling exceeds individual product
Decision Implementation	No Consideration of DT Data DT input data not considered in decision-making	Human in the Loop DT input data initiates human acting on product	Hybrid Combination of Human in the Loop and automated actions	Automated Connection DT triggers automated actions on product
Lifecycle Integration	Single Stage DT is integrated in one lifecycle stage	Two Stages DT is integrated in two lifecycle stages	Three stages DT is integrated in three lifecycle stages	Full integration DT is integrated along the whole lifecycle
Level of DT Individualization	As-operated Satellite operational data used to update DT data and model	As-launched Level 1 + Launch and deployment data used to update DT data and model	As-built Level 2 + Assembly data to update DT data and model	As-manufactured Level 3 + Manufacturing data to update DT data and model
Business Level Affected	Process Change of company processes due to DT usage	Design Product adjusted due to DT implementation	Business Model DT causes changes of the companies BM	/*
Operational Data Accessibility	Conditional Access Subject to certain conditions or incidents	Restricted Access Contractual secured access	Full Access Co-owner of the data	Sole ownership OEM is sole owner of data
Stage of Implementation	Conceptual Until proof-of-concept got conducted	Development Until prototype trials got conducted	Deployment Digital twin complete and qualified	Deployed Commercial success in operational environment

A.2 Questionnaire Satellite Digital Twin

Enclosed herein is the full print version of the questionnaire for the satellite Digital Twin carried out during this study.

Questionnaire Satellite Digital Twin

1 This study researches the usage of Digital Twins in the satellite domain, recognizes the differences in their operation, and explores the current state of development in the industry. This questionnaire is intended for experts and persons in contact with digital twins in the context of satellites.
The study asks for your personal experience and opinion on the topic. There is no right or wrong way of answering the questions. All answers are treated fully anonymously and serve purely scientific purposes.
Thank you a lot for participating in this research!

2 How familiar are you with the concept of Digital Twins in the context of satellite technology?

- A Not at all familiar
- B Somewhat familiar
- C Moderately familiar
- D Very familiar
- E Expert

3 How interested is your company/organization in the topic of Digital Twins for satellites?

4 Please select the three most fitting terms for your definition of a Digital Twin:

- A Product instance
- B Multiphysics simulation
- C Real world entity
- D Dynamic digital representation
- E Connectivity mechanism
- F Environment emulation
- G Integrated simulation
- H Lifecycle coverage
- I Real time data
- J Predictive modeling
- K Behavior mirroring

5 Please order the satellite's lifecycle stages based on your interest in modeling or simulating them in the context of a Digital Twin:

1 most interested - 5 least interested

- A Concept and Technology Development
- B Preliminary Design and Technology Completion
- C Final Design and Fabrication
- D System Assembly, Integration and Test, Launch
- E Operations and Sustainment

6 How likely do you expect the use of digital twin technology to be in the aerospace sector over the next five years?

7 Which satellites classified by their purpose have the most potential advantages of implementing Digital Twin technology?

- A Communication satellites
- B Earth observation satellites
- C Navigation satellites
- D Scientific research satellites
- E Military satellites
- F Space exploration satellites

8 Which satellites classified by their mass have the most potential advantages of implementing Digital Twin technology?

- A Large spacecraft ≥1000kg
- B Medium spacecraft ≥500kg and <1000kg
- C Small spacecraft ≥180kg and <500kg
- D Mini spacecraft ≥100kg and <180kg
- E Micro spacecraft ≥10kg and <100kg
- F Nano spacecraft ≥1kg and <10kg
- G Pico spacecraft ≥0.01kg and <1kg
- H Femto ≤0.01kg

9 Have you implemented a Digital Twin in your organization?*

Yes

No

```
If this = true:
  Jump to 10
If this = false:
  Jump to 20
```

10 Rate the Analytical Capability of your Digital Twin:

A Level 1: Monitoring: Describing and analyzing what happened

B Level 2: Diagnostics: Analyzing why did it happen

C Level 3: Prediction: Prediction what will happen

D Level 4: Prescription: Recommends operational adjustments to achieve intended action

11 Rate the Model Update Frequency of your Digital Twin:

A Level 1: Weeks: Frequency ≥ 1 week

B Level 2: Days: Frequency < 1 weeks

C Level 3: Hours: Frequency < 1 day

D Level 4: Minutes: Frequency < 1 hour

12 Rate the Data Collection Frequency of your Digital Twin:

A Level 1: Irregular: Incident driven collection

B Level 2: Scheduled: Flight history is sent bundled during overpass

C Level 3: Continuous: Data sent through multiple ground stations

D Level 4: Real-Time: Continuous data with negligible latency through relay constellation

13 Rate the Modelling Scope of your Digital Twin:

A Level 1: Parts: Individual parts

B Level 2: Subsystems: Self-contained for specific purpose

C Level 3: Complete Product: complete payload or satellite

D Level 4: Product environment: Modelling exceeds individual product

14 Rate the Decision Implementation of your Digital Twin:

A Level 1: No Consideration of DT Data: DT input data not considered in decision-making

B Level 2: Human in the Loop: DT input data initiates human acting on product

C Level 3: Hybrid: Combination of Human in the Loop and Automated Actions

D Level 4: Automated Connection: DT triggers automated actions on product

15 Rate the Lifecycle Integration of your Digital Twin:

A Level 1: Single Stage: DT is integrated in one lifecycle stage

B Level 2: Two Stages: DT is integrated in two lifecycle stages

C Level 3: Three stages: DT is integrated in three lifecycle stages

D Level 4: Full integration: DT is integrated along the whole lifecycle

16 Rate the Level of your Digital Twin Individualization:

A Level 1: As-operated: Satellite operational data used to update DT data and model

B Level 2: As-launched: Level 1 + Launch and deployment data used to update DT data and model

C

Level 3: As-built: Level 2 + assembly data to update DT data and model

D Level 4: As-manufactured: Level 3 + manufacturing data to update DT data and model

17 Rate the Business Level Affected of your Digital Twin:

A Level 1: Process: Change of company processes due to DT usage

B Level 2: Design: Product adjusted due to DT implementation

C Level 3: Business Model: DT causes changes of the companies BM

18 Rate the Effect of your Digital Twin on the Operational Data Accessibility:

A Level 1: Conditional Access: Subject to certain conditions or incidents

B Level 2: Restricted Access: Contractual secured access

C Level 3: Full Access: Co-owner of the data

D Level 4: Sole ownership: OEM is sole owner of data

19 Rate the Stage of Implementation of your Digital Twin:

A Level 1: Conceptual: until proof-of-concept got conducted

`Always:`
`Jump to 30`

B Level 2: Development: Until prototype trials got conducted

C Level 3: Deployment: DT complete and qualified

D Level 4: Deployed: Commercial success in operational environment

20 Assess the Analytical Capability of your envisioned Digital Twin:

A Level 1: Monitoring: Describing and analyzing what happened

B Level 2: Diagnostics: Analyzing why did it happen

C Level 3: Prediction: Prediction what will happen

D Level 4: Prescription: Recommends operational adjustments to achieve intended action

21 Assess the Model Update Frequency of your envisioned Digital Twin:

A Level 1: Weeks: Frequency ≥ 1 week

B Level 2: Days: Frequency < 1 weeks

C Level 3: Hours: Frequency < 1 day

D Level 4: Minutes: Frequency < 1 hour

22 Assess the Data Collection Frequency of your envisioned Digital Twin:

A Level 1: Irregular: Incident driven collection

B Level 2: Scheduled: Flight history is sent bundled during overpass

C Level 3: Continuous: Data sent through multiple ground stations

D Level 4: Real-Time: Continuous data with negligible latency through relay constellation

23 Assess the Modelling Scope of your envisioned Digital Twin:

A Level 1: Parts: Individual parts

B Level 2: Subsystems: Self-contained for specific purpose

C Level 3: Complete Product: complete payload or satellite

D Level 4: Product environment: Modelling exceeds individual product

24 Assess the Decision Implementation of your envisioned Digital Twin:

A Level 1: No Consideration of DT Data: DT input data not considered in decision-making

B Level 2: Human in the Loop: DT input data initiates human acting on product

C Level 3: Hybrid: Combination of Human in the Loop and Automated Actions

D Level 4: Automated Connection: DT triggers automated actions on product

25 Assess the Lifecycle Integration of your envisioned Digital Twin:

A Level 1: Single Stage: DT is integrated in one lifecycle stage

B Level 2: Two Stages: DT is integrated in two lifecycle stages

C Level 3: Three stages: DT is integrated in three lifecycle stages

D Level 4: Full integration: DT is integrated along the whole lifecycle

26 Assess the Level of your envisioned Digital Twin Individualization:

A Level 1: As-operated: Satellite operational data used to update DT data and model

B Level 2: As-launched: Level 1 + Launch and deployment data used to update DT data and model

C Level 3: As-built: Level 2 + Assembly data to update DT data and model

D Level 4: As-manufactured: Level 3 + Manufacturing data to update DT data and model

27 Assess the Business Level Affected of your envisioned Digital Twin:

A Level 1: Process: Change of company processes due to DT usage

B Level 2: Design: Product adjusted due to DT implementation

C Level 3: Business Model: DT causes changes of the companies BM

28 Assess the Effect of your envisioned Digital Twin on the Operational Data Accessibility:

A Level 1: Conditional Access: Subject to certain conditions or incidents

B Level 2: Restricted Access: Contractual secured access

C Level 3: Full Access: Co-owner of the data

D Level 4: Sole ownership: OEM is sole owner of data

29 Assess the Stage of Implementation of your envisioned Digital Twin:

A Level 1: Conceptual: until proof-of-concept got conducted

B Level 2: Development: Until prototype trials got conducted

C Level 3: Deployment: DT complete and qualified

D Level 4: Deployed: Commercial success in operational environment

30 What best describes your department's primary focus in the satellite sector?

A Communication satellites
B Earth observation satellites
C Navigation satellites
D Scientific research satellites
E Military satellites
F Space exploration satellites
G Academic
H Other

31 What is your role within the company?

- A Managment/Leadership
- B Engineering/Technical
- C Specialist (Hardware/Software)
- D Support/Operations

32 What is your educational background?

- A Natural Sciences
- B Engineering
- C Computer Science
- D Social Science
- E Humanities and Arts
- F Business/Managment
- G Health Sciences

33 How much years of experience do you have in the aerospace industry?

34 Could you please provide three additional contacts who may be interested in participating in this survey?*

Yes

No

```
If this = true:
  Jump to 35
If this = false:
  Jump to 36
```

35 Please write your contacts here: Thank you for helping to spread this questionnaire!

36 Would you be interested in a further interview to talk about this topic in more detail? Please insert your email, and I will get in contact with you.

The interview will be semi-structured and can be conducted via phone, online, or in person. It is estimated to take about 30 minutes.

37 Please feel free to share any additional thoughts, suggestions, or comments here:

A.3 Expert Interview Guideline

The following pages include the question guide for the semi-structured interview with an expert with a Digital Twin and without a Digital Twin in the satellite domain, which has been used for conducting the interviews.

Semi-structured Interview with an Expert with a DT in the Satellite Domain

Introduction

- Briefly introduce yourself
- Goal: Collect stories and voices about implemented Digital Twins in the satellite domain.

Section 1: Biographic Information

- Can you please share a brief overview of your background?
- What is your current position and your role in relation to Digital Twins?
- Do you have experience in working with CubeSats?

Section 2: Describe Your Digital Twin

- Can you describe the Digital Twin you are working with or have implemented?
  - What physical and digital assets does it cover? How is the connection realized?
  - How is the structure of your Digital Twin organized?
  - Which kind of simulation model is integrated into your Digital Twin?
  - What data analytical techniques are utilized in your Digital Twin?

Section 3: Strategy Towards the Digital Twin

- Can you describe the integration strategy of the Digital Twin?
  - What was your research strategy?
  - Can you describe your practical implementation strategy?
- What are the key success factors for your Digital Twin projects?
- What major challenges have you faced while developing and implementing the Digital Twin?

Section 4: Potential Benefits and Opportunities

- What are your primary benefits and values of implementing a Digital Twin?
- What is your opinion on the need for consistent guidelines for Digital Twin development and implementation? If yes, how could they impact the field of DTs?
- What are the key differences between developing a Digital Twin for CubeSats compared to other types of satellites?
- Are there unique challenges or advantages specific to CubeSat Digital Twins?
- What future plans do you have for your Digital Twin projects?

Conclusion

- Thank the interviewee for their time and insights.
- Offer to share the final results or findings from the study if they are interested.

Semi-structured interview with an Expert without a DT in the Satellite Domain

Introduction

- Briefly introduce yourself
- Goal: Collect stories and voices about the absence of Digital Twins in the satellite domain and understand the challenges and opportunities.

Section 1: Biographic Information

- Can you please share a brief overview of your background?
- What is your current position and your role in relation to Digital Twins?
- Do you have experience in working with CubeSats?

Section 2: Current Practices in Satellite Development

- Can you describe your current practices and methods in managing, developing, and operating satellite systems?
    - What are your Digital engineering approaches?
    - Which simulation, data analysis, and asset management tools do you use?

Section 3: Understanding the Absence of a Digital Twin

- Have you considered implementing a Digital Twin for your satellite?
    - What were the main considerations or reasons for not proceeding?
    - What challenges or barriers have you encountered that have prevented the implementation of a Digital Twin?
    - Are specific technical, financial, or organizational constraints influencing this decision?

Section 4: Potential Benefits and Opportunities

- What could be the primary benefits and values of implementing a Digital Twin?
- What is your opinion on the need for consistent guidelines for Digital Twin development and implementation? If yes, how could they impact the field of DTs?
- What are the key differences between developing a Digital Twin for CubeSats compared to other types of satellites?
- Are there unique challenges or advantages specific to CubeSat Digital Twins?
- What future plans do you have for your project in regards to Digital Twins?

Conclusion

- Thank the interviewee for their time and insights.
- Offer to share the final results or findings from the study if they are interested.

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