MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÕES
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

sid.inpe.br/mtc-m12e/2025/08.17.22.48-TDI

A SYSTEMS ARCHITECTING PROCESS FOR SATELLITE AUTONOMOUS FORMATION FLYING - A CASE STUDY ON SMALL SATELLITES

Iván Felipe Rodríguez Barón

Doctorate Thesis of the Graduate Course in Engineering and Space Technologies, guided by Dr. Geilson Loureiro, approved in June 02, 2025.

URL of the original document:
<http://urlib.net/8JMKD2USNRW34T/4E49BQ2>

INPE
São José dos Campos
2025

PUBLISHED BY:

Instituto Nacional de Pesquisas Espaciais - INPE
Coordenação de Ensino, Pesquisa e Extensão (COEPE)
Divisão de Biblioteca (DIBIB)
CEP 12.227-010
São José dos Campos - SP - Brasil
Tel.:(012) 3208-6923/7348
E-mail: pubtc@inpe.br

BOARD OF PUBLISHING AND PRESERVATION OF INPE INTELLECTUAL PRODUCTION - CEPPII (PORTARIA Nº 176/2018/SEI-INPE):
Chairperson:
Dr. Thales Sehn Korting - Coordenação-Geral de Ciências da Terra (CGCT)
Members:
Dr. Antonio Fernando Bertachini de Almeida Prado - Conselho de Pós-Graduação (CPG)
Dr. Evandro Marconi Rocco - Coordenação-Geral de Engenharia, Tecnologia e Ciência Espaciais (CGCE)
Dr. Heyder Hey - Coordenação-Geral de Infraestrutura e Pesquisas Aplicadas (CGIP)
Simone Angélica Del Ducca Barbedo - Divisão de Biblioteca (DIBIB)
DIGITAL LIBRARY:
Dr. Gerald Jean Francis Banon
Clayton Martins Pereira - Divisão de Biblioteca (DIBIB)
DOCUMENT REVIEW:
Simone Angélica Del Ducca Barbedo - Divisão de Biblioteca (DIBIB)
André Luis Dias Fernandes - Divisão de Biblioteca (DIBIB)
ELECTRONIC EDITING:
Ivone Martins - Divisão de Biblioteca (DIBIB)
André Luis Dias Fernandes - Divisão de Biblioteca (DIBIB)

MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÕES
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

sid.inpe.br/mtc-m12e/2025/08.17.22.48-TDI

A SYSTEMS ARCHITECTING PROCESS FOR SATELLITE AUTONOMOUS FORMATION FLYING - A CASE STUDY ON SMALL SATELLITES

Iván Felipe Rodríguez Barón

Doctorate Thesis of the Graduate Course in Engineering and Space Technologies, guided by Dr. Geilson Loureiro, approved in June 02, 2025.

URL of the original document:
<http://urlib.net/8JMKD2USNRW34T/4E49BQ2>

INPE
São José dos Campos
2025

Cataloging in Publication Data

Rodríguez Barón, Iván Felipe.

R618s A systems architecting process for satellite autonomous formation flying - a case study on small satellites / Iván Felipe Rodríguez Barón. – São José dos Campos : INPE, 2025.

xx + 204 p. ; (sid.inpe.br/mtc-m12e/2025/08.17.22.48-TDI)

Thesis (Doctorate in Engineering and Space Technologies) – Instituto Nacional de Pesquisas Espaciais, São José dos Campos, 2025.

Guiding : Dr. Geilson Loureiro.

1. Autonomous satellite formation flying. 2. System of systems. 3. Systems engineering process tailoring. 4. distributed architectures. 5. Distributed spacecraft missions. I.Title.

CDU 629.782



Esta obra foi licenciada sob uma Licença Creative Commons Atribuição-NãoComercial 3.0 Não Adaptada.

This work is licensed under a Creative Commons Attribution-NonCommercial 3.0 Unported License.

MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÃO

INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS
Serviço de Pós-Graduação - SEPGR

Aluno (a): Iván Felipe Rodríguez Barón
Novo Título: "A SYSTEMS ARCHITECTING PROCESS FOR SATELLITE AUTONOMOUS FORMATION FLYING - A CASE STUDY ON SMALL SATELLITES"

Aprovado (a) pela Banca Examinadora em cumprimento ao requisito exigido para obtenção do Título Doutor (a) em Engenharia e Tecnologia Espaciais - Engenharia e Gerenciamento de Sistemas Espaciais

(assinado eletronicamente)
Dr. Walter Abrahão dos Santos – Presidente – INPE
(x) Aprovado ( ) Reprovado

(assinado eletronicamente)
Dr. Geilson Loureiro – Orientador – INPE
(x) Aprovado ( ) Reprovado

(assinado eletronicamente)
Dr. Ronan Arraes Jardim Chagas – Membro Interno – INPE
(x) Aprovado ( ) Reprovado

(assinado eletronicamente)

Dr. Jorge Enrique Espindola Diaz - Membro Externo – UPTC

(x) Aprovado ( ) Reprovado

(assinado eletronicamente)

Dr. Eduardo Escobar Bürger - Membro Externo - UFSM

(x) Aprovado ( ) Reprovado

Este trabalho foi aprovado por:

( ) maioria simples
(x) unanimidade

Declaração de aprovação do Dr. Jorge Enrique Espindola Diaz anexa ao processo.

São José dos Campos, 02 de junho 2025

Documento assinado eletronicamente por **Eduardo EScobar Burger (E)**, **Usuário Externo**, em 24/06/2025, às 14:01 (horário oficial de Brasília), com fundamento no § 3º do art. 4º do Decreto nº 10.543, de 13 de novembro de 2020.

Documento assinado eletronicamente por **Geilson Loureiro**, **Coordenador-Geral de Infraestrutura e Pesquisas Aplicadas**, em 24/06/2025, às 15:20 (horário oficial de Brasília), com fundamento no § 3º do art. 4º do Decreto nº 10.543, de 13 de novembro de 2020.

Documento assinado eletronicamente por **Walter Abrahão dos Santos**, **Tecnologista**, em 25/06/2025, às 10:20 (horário oficial de Brasília), com fundamento no § 3º do art. 4º do Decreto nº 10.543, de 13 de novembro de 2020.

Documento assinado eletronicamente por **Ronan Arraes Jardim Chagas**, **Tecnologista**, em 04/07/2025, às 14:04 (horário oficial de Brasília), com fundamento no § 3º do art. 4º do Decreto nº 10.543, de 13 de novembro de 2020.

A autenticidade deste documento pode ser conferida no site https://sei.mcti.gov.br/verifica.html, informando o código verificador **12929034** e o código CRC **402B0ABA**.

Referência: Processo nº 01340.004023/2025-61 SEI nº 12929034

I dedicate this work:

To my parents, for their unconditional love, their teachings, and the example of effort and perseverance that has guided me through every stage of my life.

To my grandmother, whose affection, wisdom, and words of encouragement have always been a refuge and an inspiration.

To my children and their mother, who, just as during my Master's, have been lights in my life, a source of hope and strength, and the inspiration that drives me to be better each day and to persevere in the pursuit of my dreams.

And to all the people who accompanied me in this process, with their support, understanding, and trust, which made it possible to complete this journey.

AGRADECIMIENTOS

I express my most sincere gratitude to my advisor, Dr. Geilson Loureiro, for his guidance, patience, and valuable contributions throughout this research process. His expertise and mentorship were fundamental to the consolidation of this work.

To the Fundación Universitaria Los Libertadores, for providing the academic environment and the tools necessary for my professional and research training.

To my colleagues and friends, whose constant support, words of encouragement, and companionship made it possible to overcome challenges and maintain motivation throughout this journey.

ABSTRACT

This research addresses SoS for autonomous formation flying missions involving small satellites. Formation flying enables advantages such as distributed sensing, increased spatial–temporal resolution, and mission level redundancy, which have heightened interest in cooperative satellite constellations. However, these benefits are accompanied by increased architectural complexity, particularly regarding inter-satellite coordination, interface definition, and autonomy management. While established SE standards such as those from NASA and the ECSS provide structured lifecycle methodologies, they do not fully accommodate the specific needs of distributed and autonomous space systems. In response, this study proposes a tailored systems architecting process, spanning from stakeholder need identification to detailed design, with adaptations to support DSM (Distributed Spacecraft Missions). Key contributions include structured requirement allocation across the formation, interface definition for both inter-satellite and ground segments, and autonomy aware decomposition of the mission architecture. The methodology is contextualised through case study references, illustrating its applicability to real-world constraints and validating its effectiveness in supporting coordination, traceability, and modular scalability. By positioning this architecting process within the broader discourse of SoS and distributed space architectures, the research extends the methodological scope of traditional SE frameworks. It establishes a process centric foundation for the design of autonomous satellite formations and contributes to the ongoing evolution of architectural practices for next generation DSM.

Keywords: Autonomous Satellite Formation Flying, System of systems, Systems Engineering process tailoring, distributed architectures, Distributed Spacecraft Missions.

PROCESSO DE ARQUITETURAÇÃO DE SISTEMAS PARA VOO EM FORMAÇÃO AUTÔNOMA DE SATÉLITES — UM ESTUDO DE CASO EM PEQUENOS SATÉLITES

RESUMO

Esta pesquisa aborda os desafios arquitetônicos associados ao desenvolvimento de sistemas de sistemas (SoS) para missões de voo em formação autônoma envolvendo pequenos satélites. O voo em formação proporciona vantagens como sensoriamento distribuído, aumento da resolução espaço-temporal e redundância em nível de missão, o que tem intensificado o interesse por constelações cooperativas de satélites. No entanto, esses benefícios também implicam maior complexidade arquitetônica, especialmente no que se refere à coordenação entre satélites, definição de interfaces e gestão da autonomia. Embora normas consolidadas de Engenharia de Sistemas (SE), como as da NASA e da ECSS, ofereçam metodologias estruturadas para o ciclo de vida, elas não contemplam completamente as necessidades específicas de sistemas espaciais distribuídos e autônomos. Como resposta, este estudo propõe um processo de arquitetura de sistemas adaptado, cobrindo desde a identificação das necessidades das partes interessadas até o projeto detalhado, com modificações específicas para apoiar missões com espaçonaves distribuídas. As principais contribuições incluem a alocação estruturada de requisitos entre os elementos da formação, a definição de interfaces intersatélites e com o segmento terrestre, além de uma decomposição arquitetônica sensível à autonomia. A metodologia é contextualizada por meio de estudos de caso, demonstrando sua aplicabilidade frente a restrições reais e validando sua eficácia no suporte à coordenação, rastreabilidade e escalabilidade modular. Ao posicionar esse processo de arquitetura dentro do escopo mais amplo dos SoS e das arquiteturas espaciais distribuídas, a pesquisa amplia o alcance metodológico das estruturas tradicionais de SE. Assim, estabelece uma base centrada em processos para o projeto de formações autônomas de satélites e contribui para a evolução das práticas arquitetônicas em missões espaciais distribuídas de próxima geração.

Palavras-chave: Voo em Formação Autônoma, Sistemas de Sistemas, Adaptação de Processos de Engenharia de Sistemas, Arquiteturas Distribuídas, Missões Espaciais Distribuídas.

LIST OF FIGURES

Page

Figure 1.1 - Intersatellite distance vs control accuracy requirements. 3
Figure 1.2 - Research structure. 7
Figure 2.1 - The systems engineering engine. 8
Figure 2.2 - Interrelationships among the System Design Processes. 9
Figure 2.3 - Total View Framework. 12
Figure 2.4 - DSM terminology Taxonomy. 14
Figure 2.5 - Overall small satellite system architecture. 15
Figure 2.6 - Basic Formation Flying Cross-Link Communications Topologies. 16
Figure 3.1 - Scientific articles published by year. 17
Figure 3.2 - Number of articles by topic of interest. 19
Figure 3.3 - SE reference models. 20
Figure 3.4 - CubeSat refence model. 21
Figure 3.5 - CubeSat refence model. 22
Figure 3.6 – Process in the lifecycle of the AOCS. 22
Figure 3.7 - Scope definition activities. 24
Figure 3.8 - System-based Collaborative Design Process. 25
Figure 3.9 - CSE approach. 26
Figure 4.1 - Tailored SE design process. 28
Figure 4.2 - FFS from NASA system design process. 29
Figure 4.3 - Flowchart of the SE Design Process for FFS. 30
Figure 4.4 – Subsystems of DSM in a mission architecture hierarchy. 41
Figure 4.5 - FFS Distributed architecture. 42
Figure 4.6 - Requirements in FFS Distributed architecture. 43
Figure 4.7 - System model relationships. 45
Figure 4.8 - System model integration points. 45
Figure 5.1 Power-Interest Grid. 62
Figure 5.2 - Systems Engineering Schedule. 64

Figure 5.3 - Life cycle development plan. 75
Figure 5.4 - DSM logical decomposition diagram. 77
Figure 5.5 - Hierarchical structure of the FACSAT-3. 78
Figure 5.6 - Distributed architecture of the FACSAT-3 mission. 79
Figure 5.7 - Distributed architecture of the FACSAT-3 mission. 81
Figure 5.8 - Model Integration. 82
Figure 5.9 - Mission Communication Hierarchy. 86
Figure 5.10 - Power–Interest Grid for TOM/TIM Stakeholders. 107
Figure 5.11 - SE Schedule. 109
Figure 5.12 - Life cycle development plan. 124
Figure 5.13 - DSM logical decomposition diagram. 126
Figure 5.14 - Hierarchical structure of the TOM/TIM mission. 128
Figure 5.15 - Distributed architecture of the TOM/TIM mission. 129
Figure 5.16 - Distributed architecture of the mission. 131
Figure 5.17 - Model Integration. 132
Figure 5.18 - Mission Communication Hierarchy. 136

LIST OF TABLES

Page

Table 2.1 - Flow of steps and typical activities of the SE process. 11
Table 2.2 - Typical lifecycle of a space mission defined by ECSS and NASA.. 13
Table 4.1 - Typical systems drivers. 35
Table 4.2 - DSM and FFS drivers. 36
Table 5.1 - Roles and responsibilities identified to accomplish the mission. 60
Table 5.2 - RACI Matrix – Systems Engineering Team Responsibilities. 61
Table 5.3 - Timeline for the identified phases. 63
Table 5.4 - Risk Matrix – FACSAT-3 Systems Engineering. 64
Table 5.5 - Interests of the stakeholders involved in the project. 65
Table 5.6 - Requirements of Stakeholders. 66
Table 5.7 - Identified DSM Taxonomy for the Mission. 67
Table 5.8 - DSM Design Drivers. 68
Table 5.9 - FFS-Specific Design Drivers. 69
Table 5.10 - Operational Environment. 70
Table 5.11 - Mission Risk Identification and Classification. 71
Table 5.12 - Functional requirements – Orbit conditions. 72
Table 5.13 - Functional requirements – Communication and control. 73
Table 5.14 - Functional requirements – Risk and Hazard. 74
Table 5.15 - Logical decomposition table. 76
Table 5.16 - Logical decomposition table. 80
Table 5.17 - ECSS Tailoring Compliance Matrix. 94
Table 5.18 - Mission Requirements Validation Matrix 95
Table 5.19 - Review Points Across Different Project Phases. 96
Table 5.20 - Evaluation Framework for System and ConOps Validation. 97
Table 5.21 - Documentation Control and Version Management 99
Table 5.22 - SE Task Roles for the TOM/TIM Formation Flying Mission. 104
Table 5.23 - RACI Matrix – Systems Engineering Team Responsibilities. 105

Table 5.24 - Power–Interest Grid – Stakeholders in the TOM/TIM FF Mission. 106
Table 5.25 - Timeline for the identified phases. 108
Table 5.26 - Risk Matrix – Systems Engineering Phases for TOM/TIM. 110
Table 5.27 - Stakeholder Interests in the TOM/TIM Project. 111
Table 5.28 - Requirements of Stakeholders. 113
Table 5.29 - Identified DSM Taxonomy for the Mission. 114
Table 5.30 - System-Level Design Drivers for TOM/TIM. 117
Table 5.31 - Implementation-Level Design Drivers for TOM/TIM. 118
Table 5.32 - FFS-Specific Design Drivers. 119
Table 5.33 - Operational Environment. 120
Table 5.34 - Mission Risk Identification and Classification. 121
Table 5.35 - Functional requirements – Orbit conditions. 122
Table 5.36 - Functional requirements – Communication and control. 123
Table 5.37 - Functional requirements – Risk and Hazard. 124
Table 5.38 - Logical decomposition table. 125
Table 5.39 - Logical decomposition table. 130
Table 5.40 - ECSS Tailoring Compliance Matrix. 145
Table 5.41 - Mission Requirements Validation Matrix. 146
Table 5.42 - Review Points Across Different Project Phases. 148
Table 5.43 - Evaluation Framework for System and ConOps Validation. 149
Table 5.44 - Documentation Control and Version Management. 151

LIST OF ACRONYMS AND ABBREVIATIONS

ACO	Advanced Concepts Office
ACS	Attitude Control System
ADCS	Attitude Determination and Control System
ADS	Attitude Determination System
BDD	Block Definition Diagram
CDGPS	Carrier-Phase Differential GPS
CE	Concurrent Engineering
CGS	Cold Gas System
ConOps	Concept of Operation
CSE	Concurrent Systems Engineering
DSM	Distributed Spacecraft Missions
ECSS	European Cooperation for Space Standardization
FDI	Fault Detection and Isolation
FDIR	Failure Detection, Isolation and Recovery
FFS	Formation Flying Systems
GNC	Guidance Navigation and Control
GSFT	Ground-based Satellite Frames Testing
HILT	Hardware in the Loop Testing
HKC	Housekeeping Computer
IBD	Internal Definition Diagram
ICS	Inter-satellite Communication System
IDS	Internal Data Storage
INPE	Instituto Nacional de Pesquisas Espaciais
IOBCs	Instrument On Board Computers
IoT	Internet of Things
ISL	Inter Satellite Link
IWSCFF	International Workshop of Satellite Constellation and Formation Flying
MAPS	Modelling Architectures and Parameterization for Spacecraft
MBSE	Model-based Systems Engineering
MRAS	Model Reference Adaptive Control
MSFC	Marshall Spaceflight Center
NASA	National Aeronautics and Space Administration
OBC	On Board Computer
OBDH	On Board Data Handling
POBC	Payload On-Board Computer

PRISMA	Prototype Research Instruments and Space Mission Technology Advancement
RPC	Reconfigurable Position Control
SAFE	Spaceborne Autonomous Formation-Flying Experiment
SAI	Satellite Industry Association
SE	Systems Engineering
SEDT	Systems Engineering Design Tool
SEE	System Engineering Environment
SoI	System of Interest
SpoC	Satellite Operation Center
SysML	Systems Modeling Language
TIM	Telematics International Mission
TT&C	Telemetry, Tracking, and Command
TTC	Time Tagged Commands
TVF	Total View Framework

TABLE OF CONTENTS

Page.

1 INTRODUCTION 1

1.1 Context and scope 1

1.2 Motivation 2

1.3 Research hypothesis 3

1.4 Scope of application 4

1.5 Objectives 5

1.5.1 General objective 5

1.5.2 Specific objectives 5

1.6 Methodology 5

1.7 Structure 6

2 THEORETICAL BACKGROUND 8

2.1 Systems Engineering 8

2.2 Space mission Lifecycle 12

2.3 Distributed Spacecraft Missions 13

2.4 Inter satellite communications 14

3 LITERATURE REVIEW 17

3.1 Bibliographic research 17

3.2 Approaches to systems engineering 24

4 TAILORED SYSTEMS ENGINEERING PROCESS FOR SMALL SATELLITES IN AUTONOMOUS FORMATION FLYING 27

4.1 Systems Engineering baseline 27

4.2 Steps for the tailored Systems Engineering process for FFS 30

5 APPLICATION CASES 57

5.1 FACSAT 3 57

5.2 TOM/TIM mission 101

6 DISCUSSION 155

6.1 Validation of the proposed tailoring through the TIM and TOM projects at ZfT 156

6.2 Comparison of the Tailored SE design process with theoretical backgrounds 157

6.3 Comparison of the Tailored SE design process with literature review 158
6.4 Lessons learned 159
6.5 Contributions of Tailored SE design process 160
6.6 Limitations..... 161
7 CONCLUSIONS 163
7.1 Objectives achievement..... 164
7.2 Generality, applicability, relevance, usefulness, originality 165
7.3 Future research 166
REFERENCES..... 168
APPENDIX A - AEROSPACE JOURNAL DATA 173
APPENDIX B - EVOLUTION OF AOCS IN FFS MISSIONS 175
APPENDIX C - EXTERNAL REVIEW AND FEEDBACK BY ZFT..... 198

1 INTRODUCTION

1.1 Context and scope

According to Dolgopolov et al. (2020), the global space economy experienced a growth of 1.7% between 2018 and 2019, generating revenues of USD 366 billion, with approximately 74% attributable to the satellite industry. In 2020, similar trends were reported by the Satellite Industry Association (BRYCE TECH, 2021). This growth spans various satellite missions including scientific, military surveillance, navigation, remote sensing, space observations, and both commercial and non-profit communications. Given the modern demands of telecommunications (Internet of Things - IoT), remote sensing, and meteorology, the combination of characteristics from monolithic geostationary satellites and small low-orbiting satellites enhances capability. Small satellites in multi-satellite missions or distributed spacecraft missions (DSM) can achieve objectives not possible through individual operations (BANDYOPADHYAY et al., 2016).

In this context, the objective of employing satellite constellation missions is to enhance coverage performance through the deployment of multiple satellites. Chang et al. (2007) have demonstrated that a well-designed satellite constellation can provide global continuous coverage and significantly increase coverage, meeting the demands of global communication, navigation, meteorology, positioning, space exploration, and scientific experiments (CHANG; HWANG; KANG, 2007).

Additionally, in accordance with the physical configuration characteristics of a DSM, one of these is spatial control, where different types of constellations are categorised, including Formation Flying Systems (FFS). These FFS offer unique advantages, such as the capability to observe the same target from different viewpoints simultaneously, among others. However, their requirements for precise and coherent positioning among the elements of the same FFS present challenges due to the effects and disturbances of the space environment.

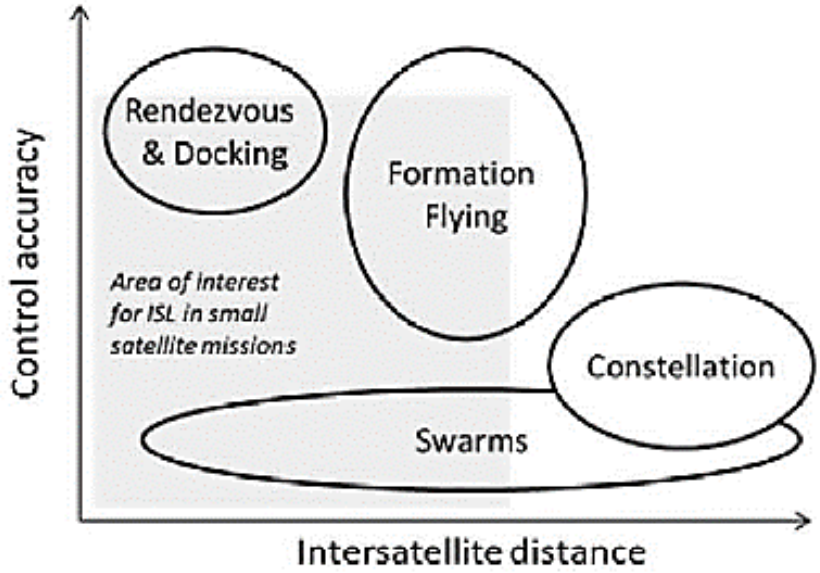
1.2 Motivation

In the case of DSM that necessitate maintaining relative distances, a FFS is essential. Le Moigne (2018) defines FFS as "two or more spacecraft conducting a mission such that the relative distances and 3D spatial relationships (i.e., distances and angles between all spacecraft) are controlled by direct detection by a spacecraft of at least one other's state." (LE MOIGNE, 2018). States are coupled using control laws. This introduces new Guidance, Navigation, and Control (GNC) functions, requiring the control of each satellite in both attitude and position for absolute reference and in relation to each other. However, FFS demands specific sensors and communication systems for relative navigation and high-precision control. It also requires highly stable positioning control and the capability to reorient in space to fulfil the mission objectives.

Additionally, as noted by D'Amico (2010), on-ground control introduces severe limitations on achievable control accuracies and may not optimize the utilization of on-board resources (D'AMICO, 2010). Conversely, onboard autonomy control ensures superior performance and prompt responses to contingencies, significantly reducing the cost of mission operations through the harmonious coordination of on-board and on-ground resources.

According to Radhakrishnan et al. (2016), there is a relationship between inter-satellite distance and control accuracy requirements. FFS allows for a relatively long inter-satellite distance; however, it necessitates medium to high control accuracy. The grey shadow in Figure 1.1 highlights the area of interest for Inter-Satellite Link (ISL) in small satellite missions. (RADHAKRISHNAN et al., 2016).

Figure 1.1 - Intersatellite distance vs control accuracy requirements.



Source: Radhakrishnan et al. (2016).

Therefore, designing architectural solutions for distributed satellite missions based on formation flying presents significant challenges—particularly concerning the coordination of subsystems, interface definition, and autonomy across multiple platforms.

1.3 Research hypothesis

As highlighted by Larson et al., the rigorous space environment, the complexity of space missions, and the minimal risk tolerance necessitate the application of Systems Engineering (SE), supported by a robust framework. This framework should facilitate the integration, interaction, analysis, and evaluation of various constraints—technical, legacy, cost, and schedule—along with design drivers. Systems Engineering is a multidisciplinary approach that identifies needs and designs solutions for real complex systems (LARSON; WERTZ, 1999). According to Wingate, establishing a solid foundation for project success and minimizing cost and schedule implications can be achieved by appropriately applying tailored Systems Engineering models with a standardized process to ensure the right amount of process is applied to project processes (WINGATE, 2019).

The architectural integration of inter-satellite communication, distributed coordination strategies, and autonomy-enabling functionalities has become

increasingly relevant in the context of formation-flying missions. Consequently, there is a growing need for tailored architecting approaches capable of addressing the systemic complexity and operational interdependence inherent to these distributed space systems.

1.4 Scope of application

Regardless of the type of space mission, it is essential to identify the appropriate level of architectural abstraction from mission level objectives down to system and subsystem design. In the context of this research, the mission is structured around a DSM architecture, where spatial control is achieved through satellite formation flying. The primary space elements are small satellites, with the architectural focus shifting from traditional subsystem-level elements to a broader system-of-systems perspective.

To support formation flying, it is necessary to define and allocate requirements at multiple levels mission, system, and element initially treating these as independent domains and subsequently integrating their roles and interfaces within a distributed architecture. Particular attention is given to inter satellite links (ISLs), coordination strategies, and autonomy enabling features, which become essential components of this integration.

The taxonomy of FF configurations, autonomy levels, and communication topologies must also be considered, as these aspects influence system decomposition and interface design. Their integration introduces additional architectural stages not addressed in traditional development processes, thus requiring new approaches to manage distributed hierarchies and spatial geometries.

Consequently, this research proposes an adapted design process that supports architectural development from early lifecycle phases starting with need identification and concept definition through to detailed design emphasising iterative system development to manage complexity, traceability, and interdependency across mission elements.

1.5 Objectives

1.5.1. General objective

Propose a systems architecting process tailored to autonomous formation flying missions using small satellites, spanning from stakeholder need identification to detailed design, and incorporating architectural adaptations required for distributed spacecraft systems.

1.5.2. Specific objectives

1. Identify key architectural design drivers relevant to monolithic satellites, DSM, and FFS, highlighting the main points of integration and divergence;
2. Define the architecting process activities needed to address autonomy, coordination, and interface design within formation flying missions;
3. Apply the proposed tailored architecting process through selected case studies involving distributed satellite systems.

1.6 Methodology

According to ISO/IEC 15288, tailoring refers to the adaptation of systems engineering processes to meet the specific needs of a given project, ensuring the appropriate level of process application (ISO/IEC, 2023). Rather than imposing a uniform approach, tailoring supports the adjustment of process rigour and scope. The practical application of SE principles is based on the process models and standards providedare by NASA and ECSS SE process.

Adcock (2005) outlines a series of activities required to implement tailoring effectively, while Mulqueen et al. (2012) provide a systems engineering tailoring model applied to space missions by NASA's Marshall Spaceflight Center. Watson et al. (2020) further propose identifying key integration points across processes to enhance coherence in multidisciplinary space projects.

Considering the focus on formation flying missions involving distributed small satellites, this thesis adopts a tailored architecting approach structured as follows:

- Identify relevant theories and conceptual foundations applicable to distributed space architectures;
- Identify reference systems engineering frameworks and analogous projects;
- For each case, map relevant processes, activities, and system interfaces;
- Characterise the System of Interest (SoI), including its operational and architectural features;
- Identify functional requirements for both monolithic and distributed elements;
- Define interdependencies and integration strategies across SoI components;
- Identify key design drivers for DSM, FFS, and relevant subsystems;
- Propose a tailored systems architecting process suitable for formation flying;
- Detail architecting activities aligned with early lifecycle phases, up to detailed design.

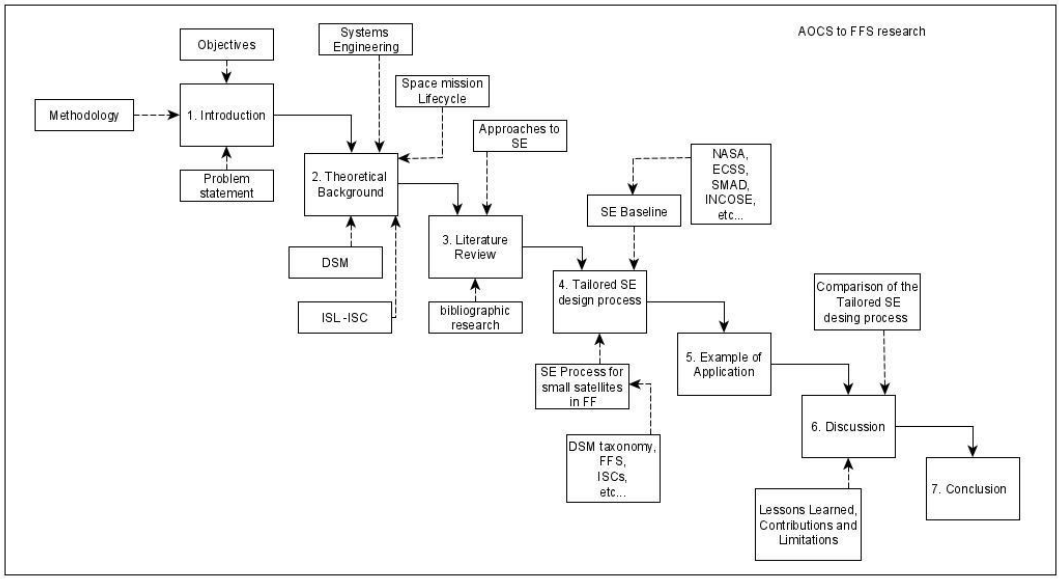
Additionally, the methodology is applied to a representative case study involving a formation of three small satellites in Low Earth Orbit (LEO), providing context for validation and fine tuning of the adapted process.

This approach does not aim to define or implement the system itself but rather to establish a structured, repeatable methodology to support system design in the context of formation flying. By aligning process activities with distributed mission needs, the tailoring supports traceability, consistency, and abstraction throughout the design lifecycle phases.

1.7 Structure

This dissertation is organized into seven chapters, as illustrated in Figure 1.2, each building progressively toward the development and application of a tailored systems architecting process for autonomous formation flying missions using small satellites.

Figure 1.2 - Research structure.



Source: Author.

Chapter 1 introduces the research, including the problem statement, objectives, and methodological approach, which is grounded in ISO/IEC 15288's tailoring principles and supported by NASA and ECSS systems engineering frameworks. Chapter 2 presents the theoretical foundations, covering essential concepts such as Systems Engineering, Systems-of-Systems (SoS), DSM, FFS, and key subsystems including. Chapter 3 provides a literature review focused on systems engineering applications across the space mission lifecycle, highlighting both established methods and their limitations within NASA, ECSS, SMAD, and INCOSE practices. Chapter 4 proposes a tailored systems architecting process for formation flying missions, detailing methodological adaptations suitable for distributed, autonomous space systems. Chapter 5 demonstrates the application of this process through a case study of a three-satellite formation in LEO, serving to contextualize and validate the methodology. Chapter 6 presents the discussion of results, including an evaluation of the proposed approach, its limitations, and contributions to the field. Finally, Chapter 7 concludes the research, summarising key findings and offering directions for future work in the architecting of distributed satellite systems.

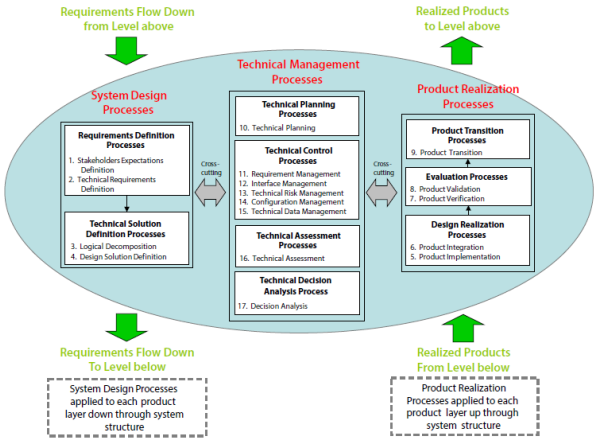
2 THEORETICAL BACKGROUND

In this section, concepts related to Systems Engineering, and the Space Mission Lifecycle are defined. Additionally, it is necessary to define and identify the characteristics DSM, Satellite Constellations, and FFS. Finally, the spacecraft systems concepts are explored, with a focus on how SoS integrates within a typical satellite structure.

2.1 Systems Engineering

NASA defines SE as “a methodical, multidisciplinary approach for the design, realization, technical management, operations, and retirement of a system.” A system is considered to be "the set of elements that function together to produce the capability required to meet a need." The application of SE from the beginning of the lifecycle of a space product contributes to meeting the functional, physical, and operational performance requirements of stakeholders, while also improving lifecycle costs and schedule adherence within the stated constraints (Figure 2.1). (NASA, 2016).

Figure 2.1 - The systems engineering engine.



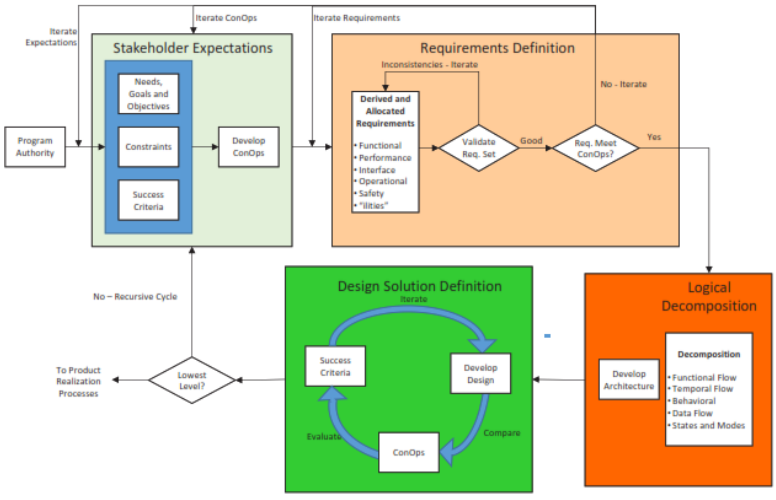
Source: NASA (2016).

Within this context, the concept of SoS becomes particularly relevant for formation flying missions, as these involve multiple independent satellites collaboratively achieving mission objectives. According to NASA, SoS are characterised by operational and managerial independence of components,

evolutionary development, geographic distribution, and emergent behaviour. These characteristics reflect the challenges of designing and coordinating autonomous satellite formations, where individual spacecraft must function both independently and cooperatively. According to Larson et. al. (2009) the space environment, the rigour in the space mission's domain and the minimum risk tolerance of the system requires the application of SE supported by a robust framework that allows the integration interaction, analysis, and evaluation of constraints technical, legacy, cost, schedule and design drivers.

Kaslow et al. (2015) note that the principal reference models for the development of space systems include the INCOSE Systems Engineering Handbook, the NASA Systems Engineering Handbook, Applied Space Systems Engineering, and Space Mission Engineering: The New SMAD. Additionally, the ECSS SE process must be considered (ECSS, 2017). All these references are based on lifecycle stages, though the purpose of each stage remains consistent. The NASA SE Handbook outlines an iterative interrelationship among the System Design Processes, highlighting the dynamic and interconnected nature of systems engineering in space missions. (NASA, 2016)

Figure 2.2 - Interrelationships among the System Design Processes.

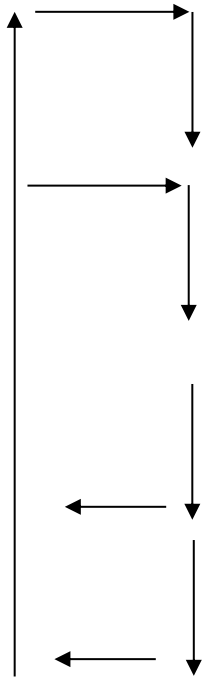


Source: NASA (2016).

Wertz et al. (2015) propose the Space Mission Engineering process as a typical flow, which is similar to the approach proposed by Larson et al. in the Applied

Space Systems Engineering Flow (LARSON et al., 2009). Both approaches to the system design process are depicted in Table 2.1.

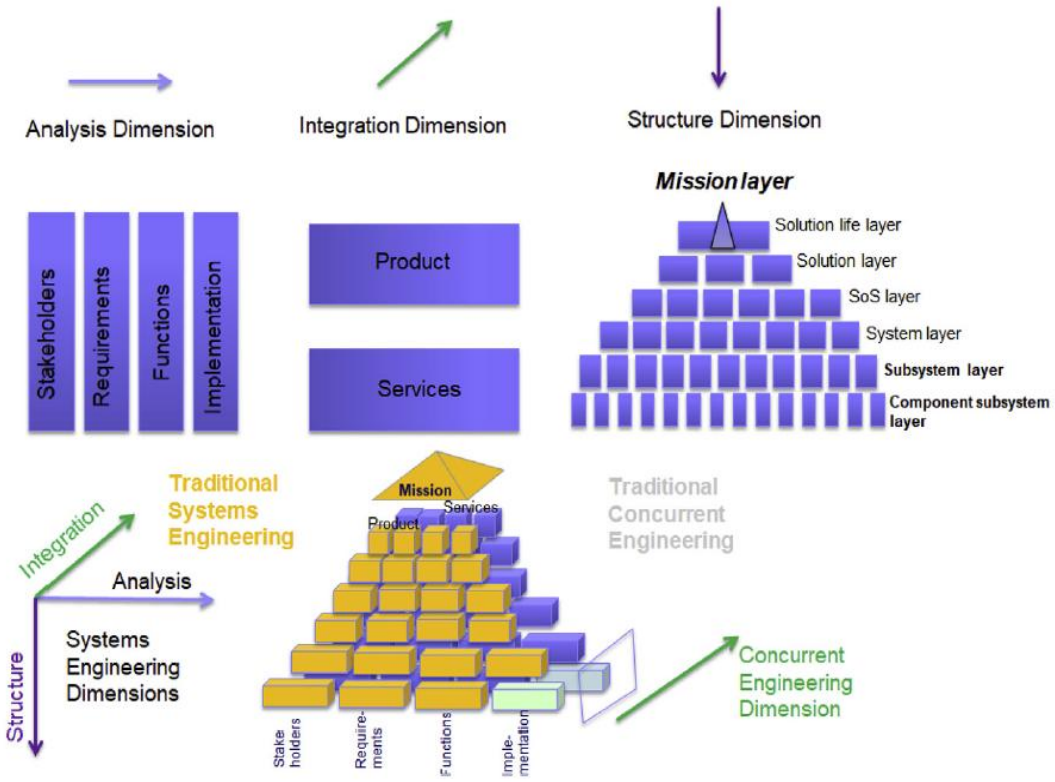
Table 2.1 - Flow of steps and typical activities of the SE process.

The Space Mission Engineering process		**The Applied Space Systems Engineering Flow**
Typical flow	Step	Activities
	Define Objectives and constraints	Define needs and stakeholder expectations
	Define Alternative Mission Concepts or Design	Generate concept of operations and operational architecture
	Evaluate the alternative mission concepts	Develop system architecture—functional and physical
	Define and allocate systems requirements	Determine technical requirements, constraints and assumptions Make decisions and conduct trade-off analyses Estimate lifecycle cost Assess technical risk

Source: Adapted from Wertz et al. (2015) and Larson et al. (2009).

On the other hand, Loureiro et al. (2018) proposed a Total View Framework (TVF), where the integration dimension encompasses both products and services. This framework considers the analysis of stakeholders, requirements, functions, and implementation, concluding with the hierarchical structure of the mission layer. This comprehensive approach aims to ensure that all aspects of the system's development are aligned and integrated, facilitating a holistic view of the mission's objectives and operational dynamics.

Figure 2.3 - Total View Framework.



Source: Loureiro (2018).

On the other hand, MBSE can be defined as the formalized application of modeling to support various system lifecycle activities such as system requirements, design, analysis, optimization, verification, and validation. This approach integrates engineering models and simulations from the very beginning of the project and continues to evolve these models throughout the system's development (KASLOW et al, 2014).

2.2 Space mission lifecycle

Based on the systems engineering philosophies of NASA and ECSS, the project encompasses extensive areas of study that require development. Both philosophies are similar, advocating for an integrated development approach to the space mission design process. This approach should encompass the entire training lifecycle, from design, development, and testing to operation, services, and eventually decommissioning of the system. Table 2.2 categorises the space

mission project lifecycle into distinct phases and outlines these phases as defined by NASA and ECSS systems engineering.

Table 2.2 - Typical lifecycle of a space mission defined by ECSS and NASA.

Phase ID		Phase name	
ECSS	NASA	ECSS	NASA
0	Pre-A	Mission analysis/needs analysis	Concept Studies
A	A	Feasibility	Concept and Technology Development
B	B	Preliminary definition	Preliminary Design and Technology Completion
C	C	Detailed definition	Final Design and Fabrication
D	D	Qualification and production	System Assembly, Integration & Test, Launch & Checkout
E	E	Operation/Utilization	Operations and Sustainment
F	F	Disposal	Closeout

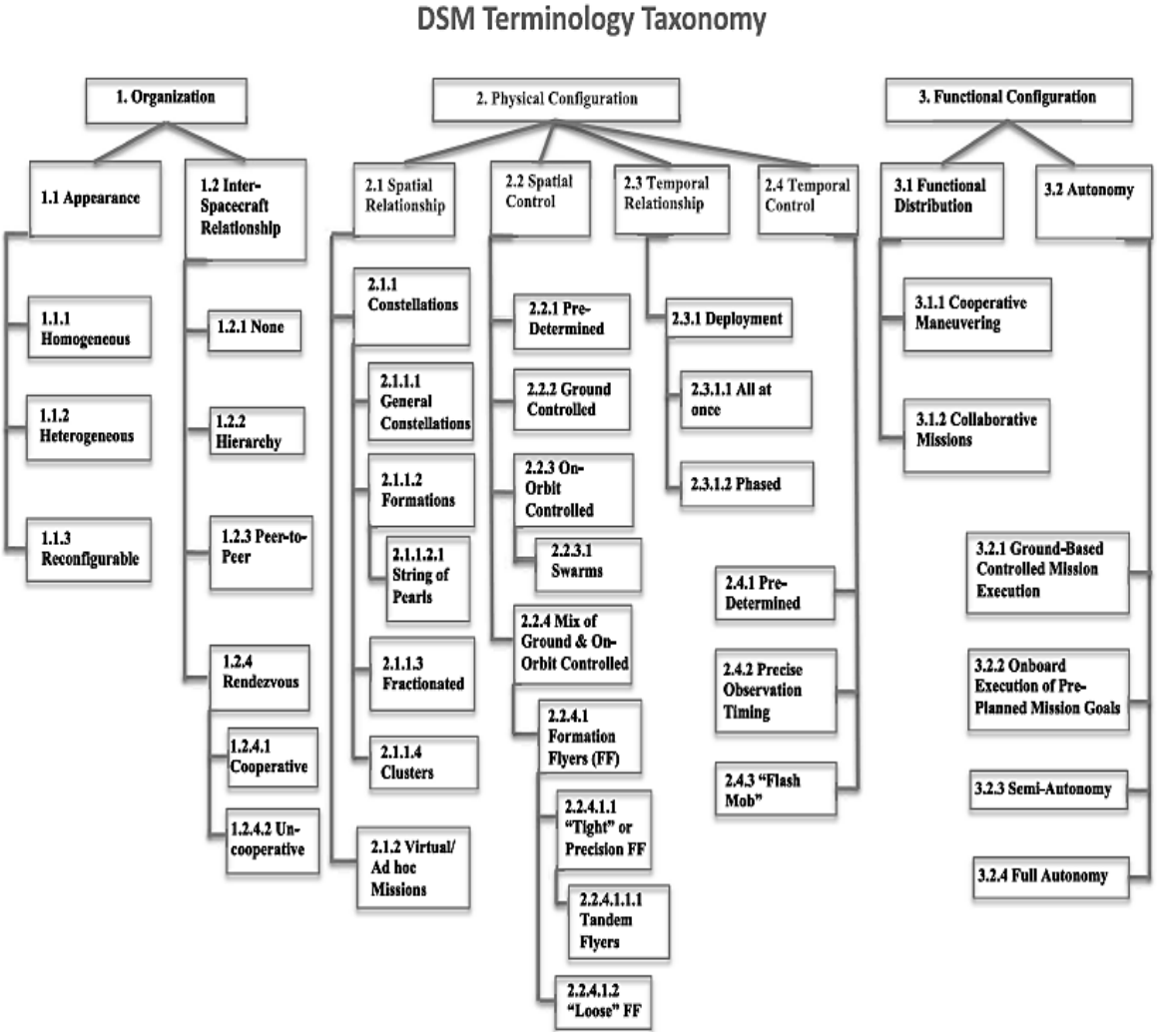
Source: Adapted from Malcolm Macdonald (2014).

2.3 Distributed Spacecraft Missions

According to Le Moigne (2018), a Distributed Spacecraft Mission (DSM) is defined as "a mission that involves multiple spacecraft to achieve one or more common goals." However, Danil Ivanov (2017) classifies DSMs into three categories: constellations, swarms, and formations.

Furthermore, Le Moigne et al. (2020) have proposed a taxonomy based on three main characteristics: "Organization," "Physical Configuration," and "Functional Organization," as illustrated in Figure 2.4.

Figure 2.4 - DSM terminology Taxonomy.



Source: Le Moigne et al. (2020).

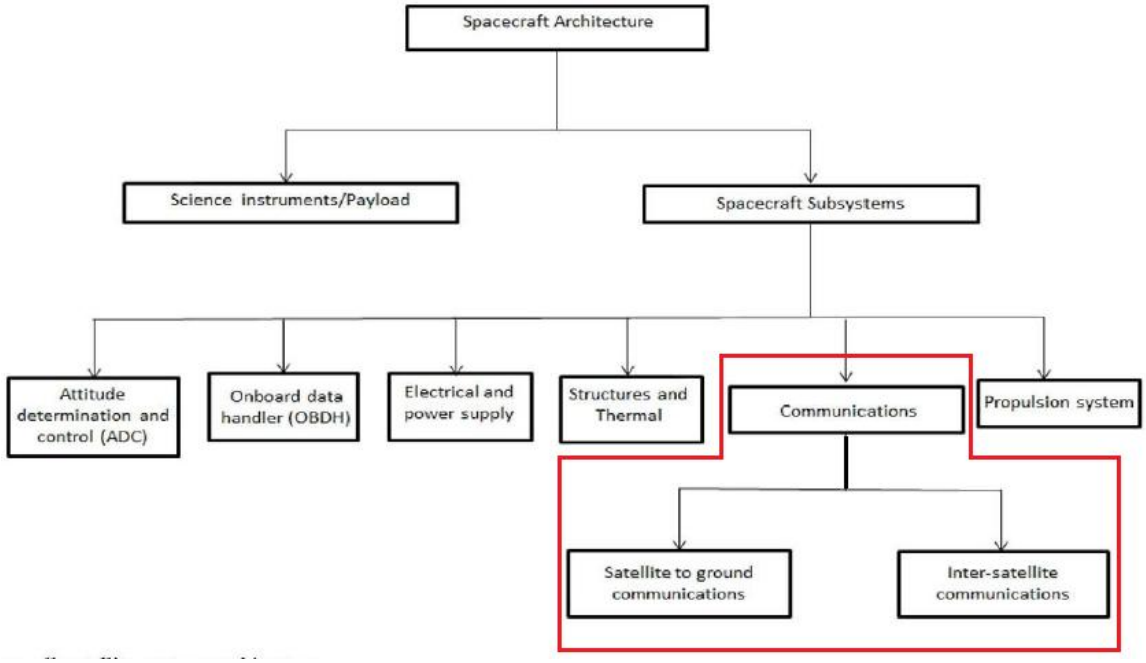
Thus, a satellite constellation is characterized by its physical configuration and spatial relationships, defined as a mission composed of multiple spacecraft with a common objective working collaboratively as a system. Based on NASA (2017), FFS are approached as two or more spacecraft maintaining mission-defined 3D relative distances.

2.4 Inter satellite communications

According to the definition of Formation Flying (FF) mentioned above, two or more satellites must maintain specific relative distances in three dimensions. To achieve this, it is necessary to know the position of each satellite within the

formation. This positioning can be managed through communication and control from the ground and/or through inter-satellite communication, as depicted in Figure 2.5.

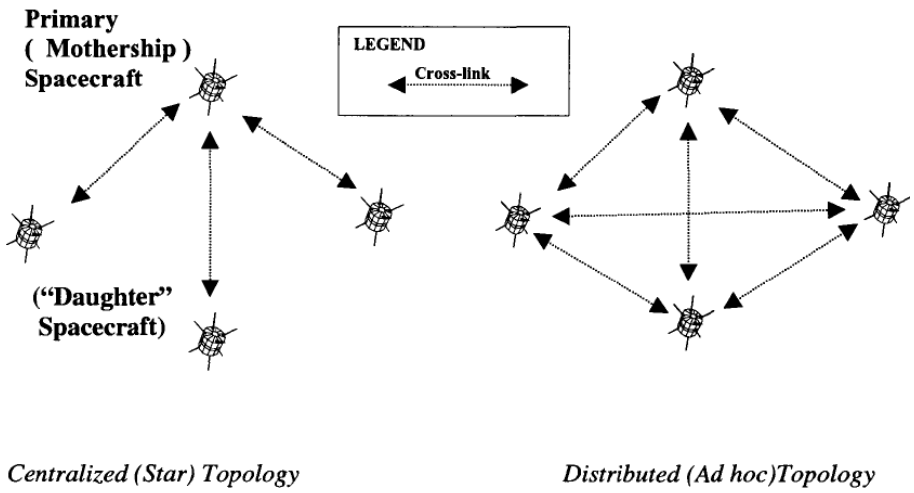
Figure 2.5 - Overall small satellite system architecture.



Source: Radhakrishnan et al. (2016).

Additionally, the communication topology for FFS cross-link communications should be considered. This mainly includes a centralized topology formed around a "mothership" and any number of "daughter" spacecraft. In this setup, the "mothership" maintains a master-to-slave relationship with each of its "daughter" spacecraft. There is also the distributed topology (as shown in Figure 2.6), where each member of the formation is equal in operations relative to every other member and is responsible for its own navigation and control determination. This is based on the assessment of collective positional data received from all other spacecraft via the cross-links (HORNE; KWADRAT; EDWARDS, 2002). A hybrid topology, combining elements of both centralized and distributed structures, may also be feasible.

Figure 2.6 - Basic Formation Flying Cross-Link Communications Topologies.



Source: Horne et al. (2002).

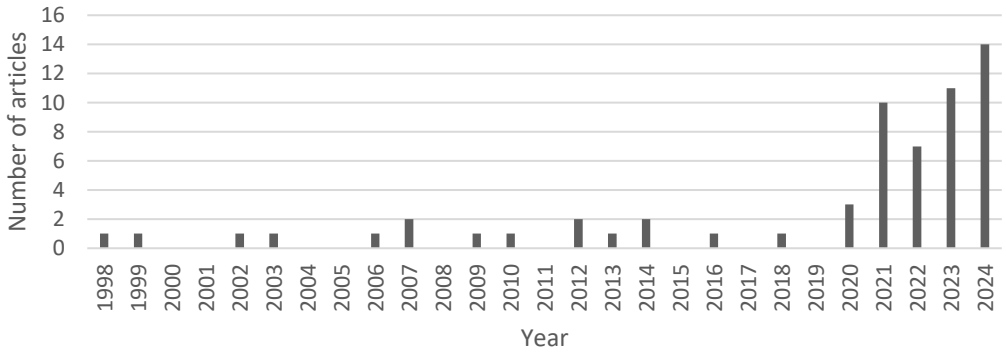
In this context, for an autonomous FFS, Cross Link communication would be implemented. The design of this system should take into account requirements such as the number of satellite members, antennas, orbit parameters, the geometry of the distribution (whether constant or changing), inter-spacecraft distances, and the flexibility of topological form, among others. (HORNE; KWADRAT; EDWARDS, 2002).

3 LITERATURE REVIEW

3.1 Bibliographic research

Through a bibliometric process focusing on high-quality scientific research, journals with a Scimago Journal & Country Rank (JCR) of 0.5 or higher were identified. The search targeted journals within the engineering subject area, specifically under the aerospace engineering category, across all regions and countries. This search yielded 40 journals, the results of which are detailed in Appendix A.1. For each of these journals, a search was conducted using four keywords: Systems Engineering, constellation of satellites flying in formation, and Systems Engineering applied to AOCS of satellites flying in formation. The search revealed documents related to topics of SE applied to space products, FFS missions, FFS Control, and SE concepts applied to FFS. The results demonstrate that these topics have experienced significant growth from 2020 to 2024. This growth is documented year by year in Figure 3.1.

Figure 3.1 - Scientific articles published by year.



Source: Author.

The scientific articles selected, as detailed in Appendix B.1, chart the evolution of control within FFS missions and the application of SE to space products.

Research topics concerning FFS and the application of SE span from 1998 to 2021. Initially, interest was shown in testing high-precision techniques for positioning and attitude in testbeds starting in 1998 and continuing through 2007. This period highlighted the proposal of two main control architectures: centralized

and decentralized. Such developments underscore the necessity of applying SE during the Assembly, Integration, and Testing (AIT) phase of FFS development. Notably, around 75% of the documents focus on implementing methods and techniques for FFS control, from Guidance, Navigation, and Control (GNC), proposing various architectures including centralized, decentralized, and reconfigurable control architectures. Such research aims to analyze the behavior and architecture of FFS services to minimize fault tolerance in these missions. Despite this focus, only 5% of the literature addresses the analysis of Fault-Tolerant Controller Design to ensure operational safety in FFS, indicating a significant area for further exploration.

Additionally, the use of SE in the development of space products was evident from 1999 onward. Proposals included the application of Classical Systems Engineering (CSE), Unified Modeling Language (UML), Systems Modeling Language (SysML), and Model-Based Systems Engineering (MBSE), along with the implementation of software and tools for SE development in space products through to 2018. However, only 5% of these studies directly apply SE to an FFS, specifically an international mission called the Telematics International Mission (TIM) composed of nine pico-satellites for Earth observation. Since 2020, a taxonomy of DSM has been proposed, emphasising three main characteristics: organisation, physical configuration, and functional configuration, with further subcategories suggested. Each configuration necessitates a detailed functional and behavioural analysis.

The case of autonomous FF in LEO, as characterised by D'Amico, exhibits a high level of multidisciplinary involvement, primarily in GNC and AOCS. This progression includes GNC for satellite rendezvous initiatives starting in 1960, GNC for FF and autonomous FF technology demonstrations such as the PRISMA mission in 2006, and the TerraSAR-X/TanDEM-X missions in 2007, culminating in a realistic demonstration of a complete GNC system for formation-flying spacecraft in LEO in 2010 (D’AMICO, 2010). In 2013, De Florio focused on "Precise Autonomous Orbit Control in Low Earth Orbit: from Design to Flight Validation", concentrating on software development (FLORIO, 2013). Moreover, the application of SE in space systems has been broadly addressed by NASA

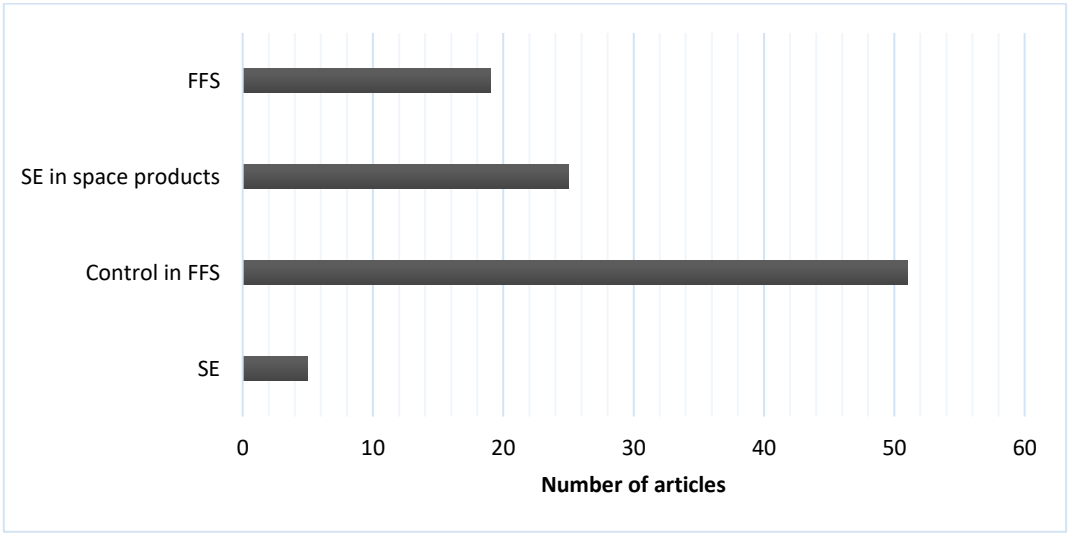
(NASA, 2016) and the European Cooperation for Space Standardisation (ECSS, 2017) which have proposed handbooks outlining the development process of space systems. However, this process predominantly covers only monolithic, small satellites.

SE applied to FFS is also explored, as in the case of Subramanian et al. in 2015, with a Systems Engineering study of a Formation Flying Demonstration Mission using CubeSats (SUBRAMANIAN et al., 2015). Additionally, the Classical Systems Engineering application for the conception of AOCS was approached by De Souza et al. (2011), proposing a systematic process to develop systems according to stakeholders' expectations. (DE SOUZA et al., 2011).

It is crucial to emphasise that since 2021, there has been considerable growth in interest in the development of DSMs targeting the exploration of planets, the Moon, and the Sun. Similarly, significant interest and expansion are evident in the development of mega constellations and the application of artificial intelligence for the autonomous control of satellites.

According to the bibliometric process conducted, various relationships between FFS, SE, and AOCS were identified. The research highlights a primary interest in SE applied to space product development and, in particular, in the control of FFS (Figure 3.2).

Figure 3.2 - Number of articles by topic of interest.

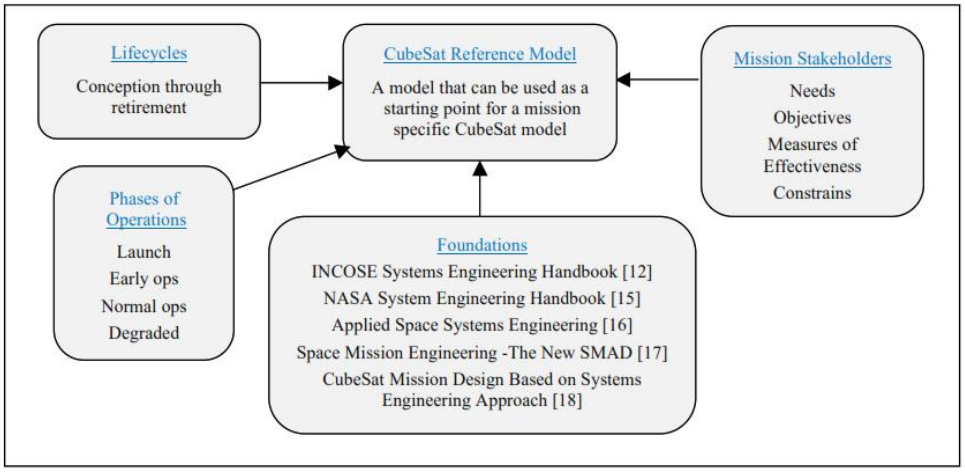


Source: Author.

In this manner, Systems Engineering applied to space products accounts for nearly 25% and 5% to Systems Engineering in Formation Flying Systems. Although interest in control within Formation Flying Systems stands at 51%, these types of research are primarily approached from perspectives of testing, validation, and control precision, as detailed in Appendix B.1.

Regarding Systems Engineering for small satellites, this aspect is addressed as depicted in Figure 3.3 (KASLOW et al., 2015) king into consideration SE reference models.

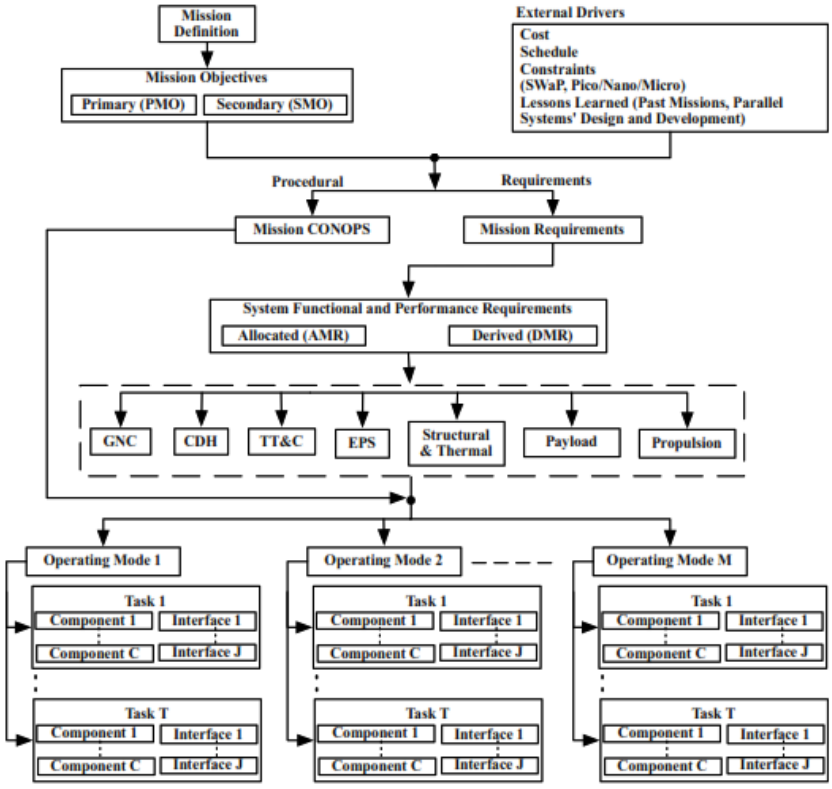
Figure 3.3 - SE reference models.



Source: Kaslow et al. (2015).

Additionally, "Enterprise Modeling for CubeSats" (ANDERSON et al., 2014) and the systems design and development processes for CubeSats are proposed. These are focused on CubeSat mission design, underpinned by Systems Engineering principles as illustrated in Figure 3.4. (ASUNDI; FITZ-COY, 2013).

Figure 3.4 - CubeSat refence model.

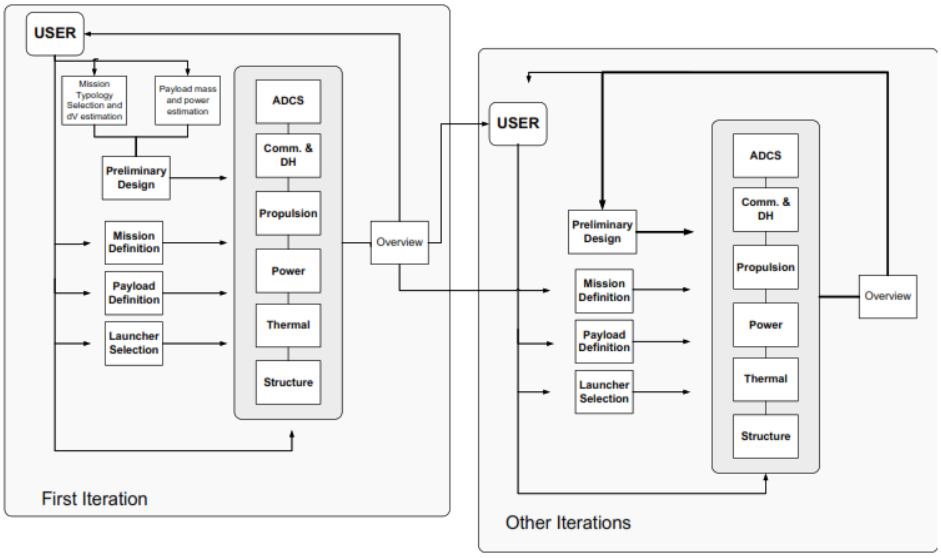


Source: Asundi and Fitz-Coy (2013).

The development process of small satellites' Systems Engineering (SE) can be informed by traditional SE reference models. However, specific requirements must be considered; these are discussed by Larson and Wertz (1999) as systems drivers. (LARSON; WERTZ, 1999)

Furthermore, in addition to system design, the subsystem design must also be considered during the design process. This involves providing subsystems with inputs and constraints and interacting with the payload definition and mission definition model on a bilateral basis, as proposed by Ridolfi et al. (2009) in Figure 3.5. (RIDOLFI; MOOIJ; CORPINO, 2009)

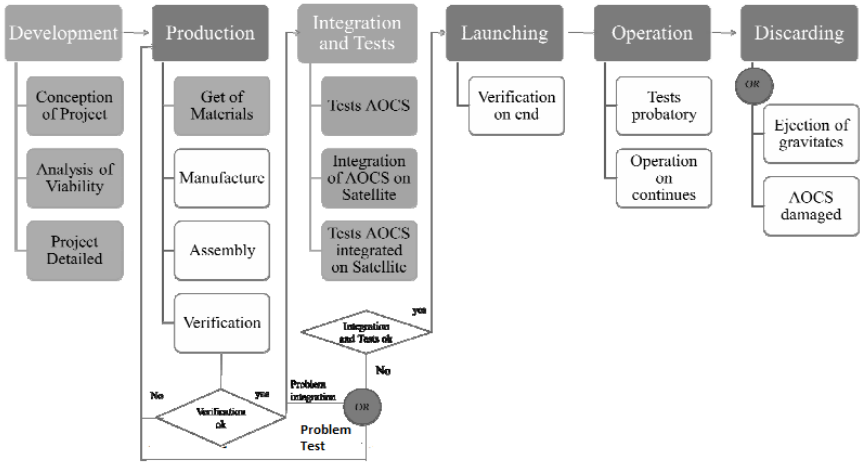
Figure 3.5 - CubeSat refence model.



Source: Ridolfi et al. (2009).

In the case of AOCS, De Souza et al. (2011) proposed "systems concurrent engineering for the conception of an attitude and orbit control system." This approach considers the AOCS throughout the lifecycle process, as illustrated in Figure 3.6 (DE SOUZA et al., 2011).

Figure 3.6 – Process in the lifecycle of the AOCS.



Source: De Souza et al. (2011).

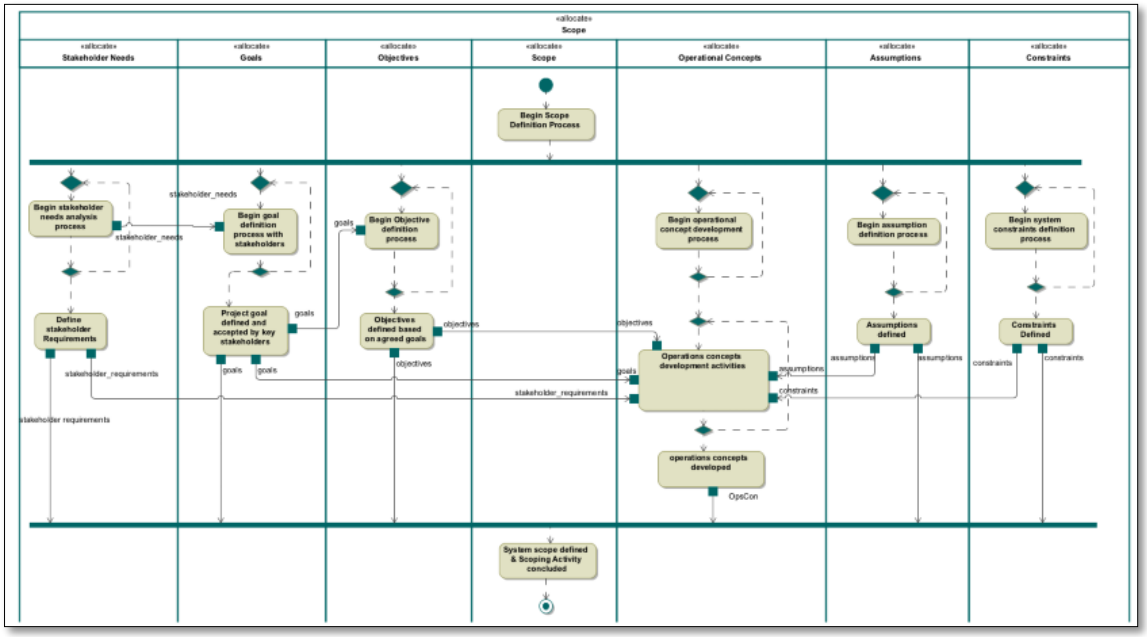
However, all above SE application was addressed to monolithic satellites, thus, approaching DSM, specifically FFS, Loureiro et al. (2018) presented a System

Concurrent Engineering (SCE) applied in the Telematic International Mission (TIM), contributing to the derivation of the requirements of each satellite and other concepts of the life cycle process such as the Production Concept and System Production Architecture, the Test Concept and System Test Architecture, the Launch Concept and Architecture System Launch, the System Service and Service Architecture Concept, and the System Decommissioning and Decommissioning architecture Concept. (LOUREIRO; PANADES; SILVA, 2018)

Regarding autonomous FFS, PhD theses and scientific articles address autonomous and precise formation flying validation in LEO (FLORIO, 2013), Specifically, the PRISMA mission explores autonomous formation flying based on GPS technology (D'AMICO, 2010). In the case of PRISMA, it approaches the flight of an Autonomous formation flying based on GPS (DE FLORIO; D'AMICO; ARDAENS, 2010). Additionally, research on autonomous control and manoeuvring of CubeSats and nanosatellites was conducted in 2014 by Grocott et. Al. (GROCOTT et al., 2014) and Underwood et. al. (UNDERWOOD et al., 2014) By 2019, Tiraplegui et al. highlighted the "Challenges and Needs for Sub-Millimetre Autonomous Formation Flying", particularly in the context of the Proba-3 mission, which faced challenges related to the power budget due to the small size of the satellites. (TIRAPLEGUI et al., 2019)

In this context, it is essential to address the design of the inter-satellite communication (ISC) subsystem. Anyanhun and Edmonson (2018) proposed a MBSE process for the development of ISC, beginning with scope definition activities as shown in Figure 3.7.

Figure 3.7 - Scope definition activities.



Source: Anyanhun and Edmonson (2018).

In summary, based on the state of the art discussed above, research on systems engineering applied to various aspects includes: 1) space products, small satellites, and FFS; 2) autonomous FFS precision and validation; and 3) the ISC as a separate system from the AOCS.

Consequently, the integrated systems development process for autonomous formation flying missions using small satellites particularly considering ISC, distributed autonomy, and formation coordination—remains underexplored. While SE models have been extensively applied in traditional, monolithic space missions, their application to SoS architectures such as FFS demands further investigation. Specifically, adapting SE models to support the orchestration of distributed nodes, interface control, autonomy aware decomposition, and synchronisation of mission elements across multiple spacecraft continues to pose both a technical and methodological challenge.

3.2 Approaches to systems engineering

Kaslow et al. (2015) identify the primary reference models for the development of space systems as the INCOSE Systems Engineering Handbook (WALDEN,

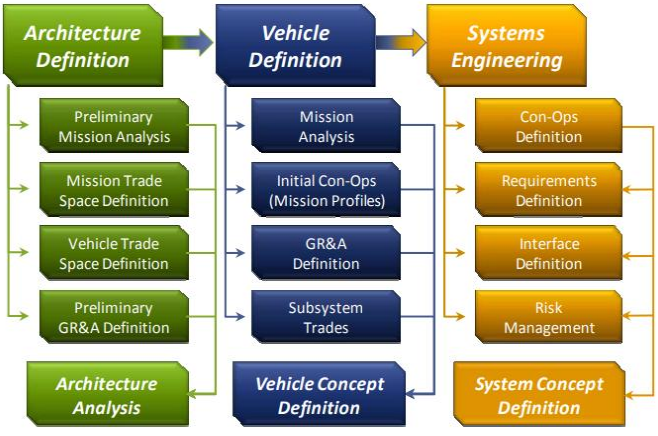
ROEDLER; FORSBERG, 2015), NASA Systems Engineering Handbook, Applied Space Systems Engineering (LARSON et al., 2009), and Space Mission Engineering - The New SMAD (WERTZ; EVERETT; PUSCHELL, 2015).

Additionally, the ECSS SE process must also be considered. All the aforementioned SE approaches are based on lifecycle stages, from system conceptual design to system decommissioning, although the purpose of each stage remains similar. Wertz et al. propose the Space Mission Engineering process as a typical flow (WERTZ; EVERETT; PUSCHELL, 2015), while Larson et al. propose the Applied Space Systems Engineering Flow (LARSON; WERTZ, 1999).

According to the NASA SE Handbook, an iterative interrelationship among the System Design Processes is advocated, addressing four main stages: stakeholders' expectations, requirements definition, logical decomposition, and design solution definition (NASA, 2016).

Furthermore, the collaborative design process outlined by Mulqueen et al. should be taken into account, which consists of sequential systems analysis starting with mission and system functional analysis to identify higher-level mission and objectives requirements. This progresses through three iterative and parallel processes: mission definition, vehicle and system engineering (MULQUEEN; MAPLES; FABISINSKI, 2012).

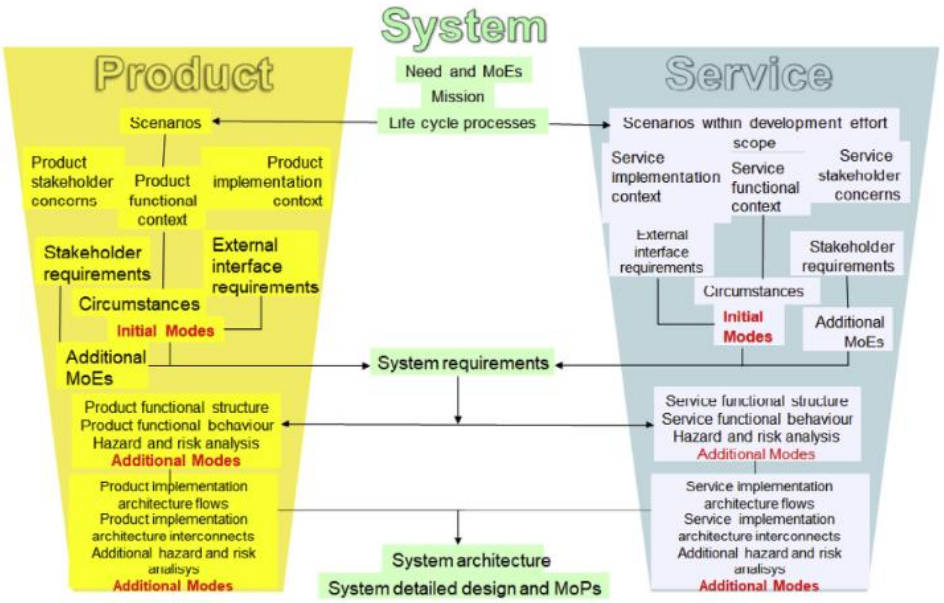
Figure 3.8 - System-based Collaborative Design Process.



Source: Mulqueen; Maples and Fabisinsk (2012).

According to Loureiro et al., for problems that involve solutions encompassing multiple spacecraft, it is essential to model all lifecycle concepts and architectures of the solution, not just the operational aspects. In this context, when considering Concurrent Systems Engineering (CSE), the integration dimension includes both products and services, as shown in Figure 3.9.

Figure 3.9 - CSE approach.



Source: Loureiro; Panades and Silva (2018).

These products and services represent the compilation of methods, people, and tools that are employed to implement lifecycle processes. (LOUREIRO; PANADES; SILVA, 2018).

In addition to SE, CSE, and collaborative processes, it is crucial to include the analysis and development of each solution within the mission. This should consider the integration of products and services related to both the mission itself and the distributed systems and satellite subsystems.

4 TAILORED SYSTEMS ENGINEERING PROCESS FOR SMALL SATELLITES IN AUTONOMOUS FORMATION FLYING

This chapter presents a tailored systems architecting process for distributed space missions involving autonomous formation flying with small satellites. As DSM depart from the paradigm of single-satellite design, they introduce new architectural challenges particularly in system decomposition, interface coordination, and autonomy-aware allocation of functionality. Additionally, generalises the process to encompass formation flying systems as a whole. It recognises the need for synchronisation between multiple space elements, shared infrastructure, and ground support, requiring the coordination of ISL, ground data segments, and user interfaces.

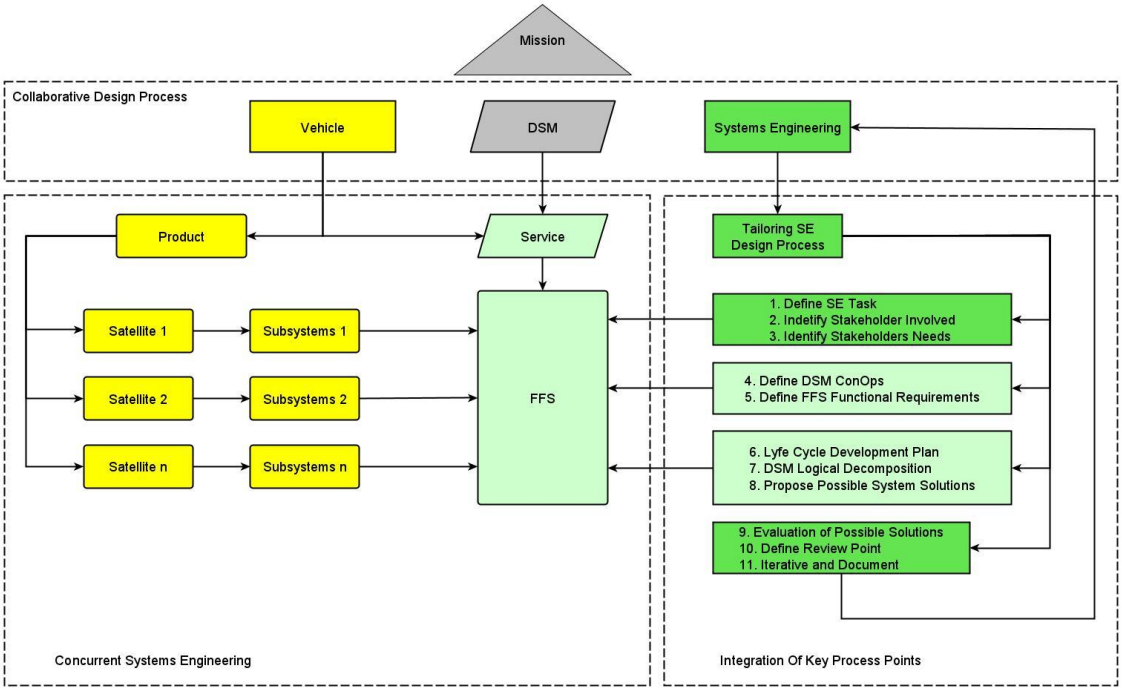
Key integration points and abstraction layers are defined to support decision-making from early need identification to detailed design. Special attention is given to distributed requirements allocation and modular system interfaces, enabling coherent development across a mission composed of multiple coordinated spacecraft.

4.1 Systems Engineering baseline

Beginning with the collaborative design process, attention is simultaneously directed towards SE and the development of both the satellite's product and service components. However, as Loureiro et al. (2018) emphasize, it is crucial to conceptualize the design from the perspective of a mass production architecture, which differs significantly from the production of a single satellite. In this regard, considering the mission as the ultimate objective and highest level of development, an initial proposal is made for a collaborative design process for the SE, DSM, and the vehicle. However, vehicle development should be approached as the integration of service and product based on CSE, where the product involves the development of individual satellites and their collective arrangement (as a medium level of abstraction). Likewise, the application of SE progresses in parallel, based on a Tailoring SE design process, taking into account the proposed activities as depicted in Figure 4.1. At this juncture, it is

essential to consider the key integration points of the selected processes and models.

Figure 4.1 - Tailored SE design process.

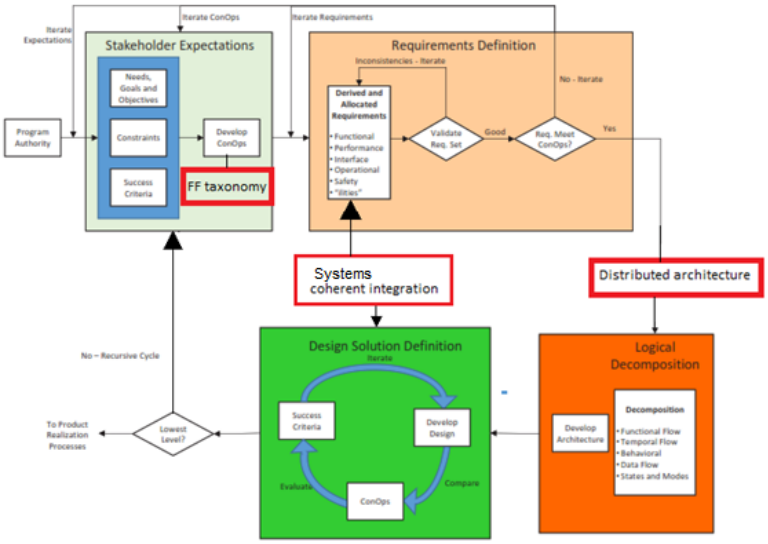


Source: Author.

The design process for DSM needs to incorporate the DSM taxonomy to accurately define stakeholders' expectations, accommodate the distributed architecture associated with multiple spacecraft involved in the mission, and ensure coherent integration of the ISC system in line with DSM requirements.

Figure 4.2 illustrates a DSM approach adapted from NASA's system design process. Here, the addition of the DSM taxonomy analysis is shown in the stakeholders' expectations, thus proposing a Concept of Operations (ConOps) based on the characteristics of the DSM and defining the system requirements. Subsequently, a distributed system architecture is proposed, taking into account the architecture of each satellite, which are part of a larger architecture composed of the individual architectures.

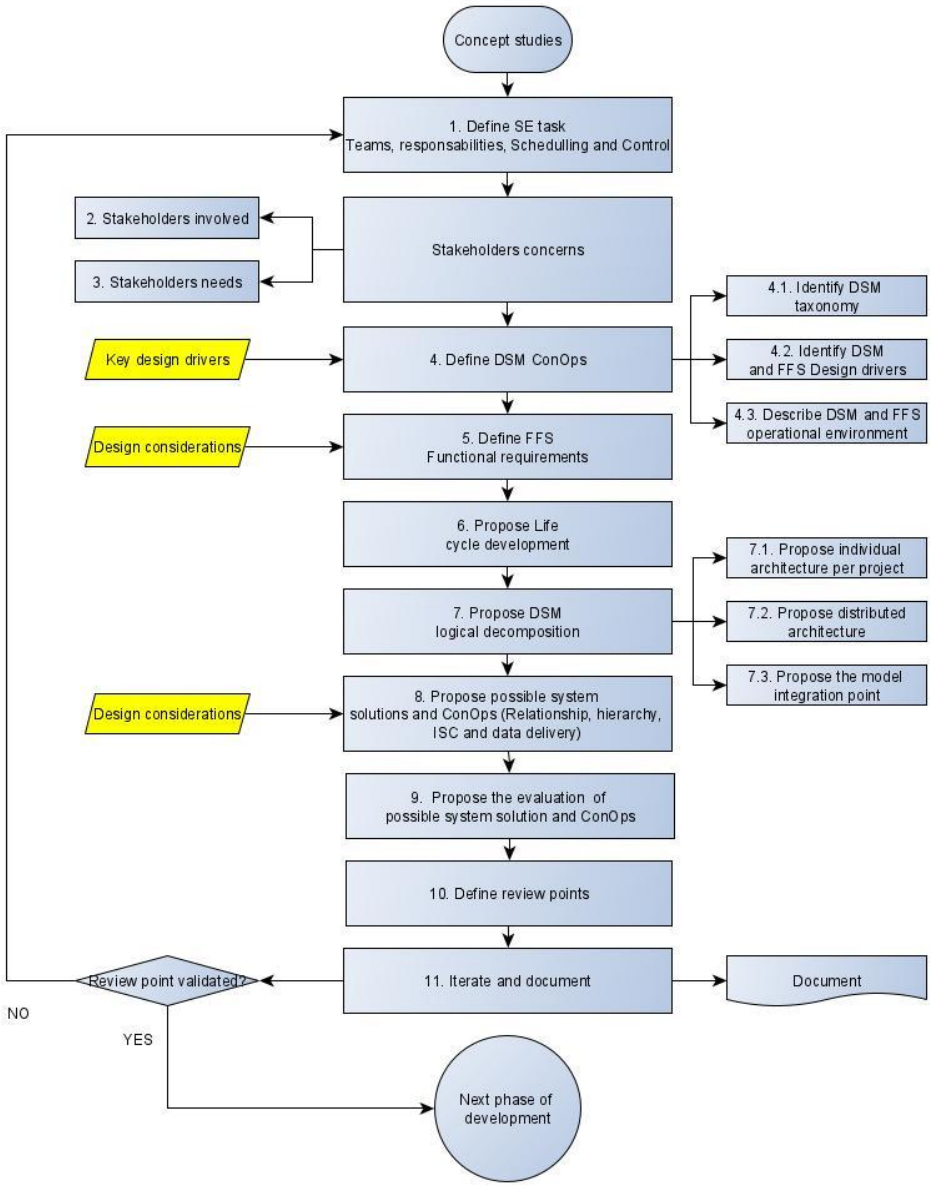
Figure 4.2 - FFS from NASA system design process.



Source: Adapted from NASA (2016).

According to NASA (2016), ECSS (2017), Larson and Wertz (1999), and Wertz et al. (2015), the development of a Concept of Operations (ConOps) within Systems Engineering (SE) requires the early definition of mission statements that capture stakeholder needs and high-level expectations. In the context of FF missions, it is equally important to integrate key design drivers and mission specific considerations into the architecting process. These elements directly influence the decomposition and allocation of functionality across the distributed system. As illustrated in Figure 4.3, these drivers are introduced in Activity 4 of the proposed process, guiding the selection of DSM taxonomy, formation structure, and operational environment. Furthermore, the design considerations introduced in Activities 5 and 8, enable the potential Concept of Operations. These stages collectively provide a structured foundation for tailoring systems engineering activities to the unique demands of autonomous formation flying using small satellites.

Figure 4.3 - Flowchart of the SE Design Process for FFS.



Source: Author.

Based on SE models and DSM requirements for space systems, a tailored SE design process along with design drivers and activities is proposed.

4.2 Steps for the tailored Systems Engineering process for FFS

Here are the initial steps, which incorporate traditional SE activities while emphasizing the need for collaborative and concurrent processes to ensure

comprehensive integration across the SE framework, vehicle, mission, and scenarios:

1. Define Systems Engineering task

By completing this step, it is expected to obtain a detailed SE task description, which includes clearly defined SE team roles and responsibilities, scheduling, and control mechanisms to manage technical risks and ensure project alignment with objectives. This description can be presented as a list or an organisational chart categorised by responsibilities and tasks. Additionally, it is necessary to establish a schedule and control matrix related to the tasks, objectives, and scope of the project.

When managing projects, there are numerous alternatives to the traditional Gantt chart that can be employed, depending on the project's complexity and the level of detail required. For instance, network diagrams (such as PERT or CPM) are particularly useful for visualising the sequence of activities and identifying critical paths and slack times. Timeline charts, on the other hand, are simpler tools that effectively highlight key events or milestones along a linear timeline, making them ideal for communicating overall progress in a clear and concise manner.

For projects requiring a more detailed breakdown of sequential activities, waterfall charts are an excellent choice, as they clearly illustrate transitions between stages. Similarly, stacked bar charts offer a way to represent tasks with subtasks or resource allocation, providing a multi-dimensional view of progress.

In agile environments, Kanban boards and Scrum boards are highly effective for tracking the status of tasks, allowing teams to organise work into categories such as "pending," "in progress," or "completed." For monitoring work progress over time, burn-down and burn-up charts are invaluable, especially for understanding whether teams are on track to meet deadlines or project goals.

For resource management, a task vs. resource chart can be employed to clearly allocate responsibilities, while a RACI matrix defines roles and responsibilities, ensuring all stakeholders are informed and accountable. Additionally, workflow

diagrams and process maps are effective tools for visualising and analysing the procedural flow of tasks, helping to optimise efficiency.

When focusing on project phases, milestone charts offer a high-level overview of critical dates and stages, while progress heatmaps use colour coding to visually track task completion. Finally, for prioritisation and time management, tools such as the time management matrix are particularly useful for categorising tasks by urgency and importance.

By leveraging these tools, project managers can tailor their approach to suit specific project requirements, ensuring clarity, efficiency, and effective communication across all stakeholders.

1.1. Define SE team

Forming a systems engineering team tailored to project requirements, including a diverse range of experts from various engineering disciplines.

Defining the responsibilities of the Systems Engineering team involves creating a structured framework that clearly delineates tasks and roles. This can be achieved through tools such as a responsibility matrix (YANG; CHEN, 2009), which outlines key activities like subsystem integration, risk assessment, and stakeholder communication.

A commonly used approach is the RACI (Responsible, Accountable, Consulted, Informed) matrix, which provides a detailed breakdown of who is responsible for, accountable for, or involved in tasks such as testing, design reviews, and system validation (YANG; CHEN, 2009).

1.2. Define SE team responsibilities

Identifying key participants in the SE team requires a structured approach to categorising individuals and entities based on their level of influence and interest in the project. A Power-Interest Grid can be employed to enhance this analysis, providing a clear framework for prioritising engagement, decision-making, and communication strategies within the team.

The Power-Interest Grid classifies SE team members into four distinct categories. Those with high power and high interest include mission-critical decision-makers, such as system architects, and project managers, among others, who must be actively engaged in all project phases. Members with high power but low interest, such as regulatory bodies and funding agencies, require periodic updates to ensure compliance without excessive involvement in day-to-day operations.

Team members with low power but high interest, including researchers, analysts, and subsystem specialists, play a crucial role in contributing expertise but do not make high-level decisions. Lastly, individuals with low power and low interest, such as external consultants and supporting staff, may be involved selectively based on specific project needs.

1.3. Define systems engineering scheduling and control

Effective management of timelines and resources includes detailed planning and monitoring of engineering activities to align with the project's scope and objectives.

Developing a project schedule is essential for effective time and resource management. This schedule should include detailed milestones, such as major reviews like the Preliminary Design Review (PDR), Critical Design Review (CDR), and Mission Concept Review (MCR). Additionally, it should incorporate risk management plans to address potential challenges proactively.

2. Identify all stakeholders involved

A structured approach to identifying and categorising stakeholders is essential for ensuring comprehensive engagement, efficient communication, and alignment with project objectives. At a high level, a SIPOC (Suppliers, Inputs, Process, Outputs, and Customers) diagram provides a clear framework for mapping external interactions and stakeholder relationships (UTAMA; ABIRFATIN, 2023). This method systematically defines key project contributors, including regulatory agencies as suppliers, mission data and funding as inputs, satellite integration as core processes, operational satellites and sensor data as

outputs, and government agencies, research institutions, and commercial users as customers (UTAMA; ABIRFATIN, 2023).

For detailed subsystem coordination a Business Process Model and Notation (BPMN) diagram is effective. BPMN visually represents workflow dependencies, decision points, and system interactions, ensuring precise coordination within subsystems. It is particularly useful for illustrating sensor data processing, formation control adjustments, and command and telemetry exchanges between satellites and ground stations (LIMA et al., 2025).

3. Identify stakeholders needs

The identification of needs involves the detailed collection of concerns from all stakeholders to ensure that the system functions as required under given restrictions and expectations. These needs are gathered to articulate the mission, goals, and objectives. It is recommended to create a table where each need is identified and related, to maintain traceability.

Identifying stakeholders' needs involves collecting and documenting their concerns and expectations to ensure the system meets all requirements under given constraints. This step produces a traceable table that links each stakeholder's needs to corresponding system requirements, prioritising them based on feasibility and mission constraints.

4. Define baseline DSM ConOps, identifying and classifying risk

This section aims to define the type of DSM and the design controllers, considering the size of the satellites (small satellites) and their FFS. Additionally, based on the operational environment, it is necessary to perform a hazard and risk analysis. Tools such as fault injection and Markov models can be utilised for this purpose (GU; WANG; ZHANG, 2025).

4.1. Identify DSM taxonomy

Based on DSM taxonomy and FFS definition described by Le Moigne (2018), presented in Chapter 2, Section 2.3 categorize the mission by characteristics such as Organization, Physical configuration, Functional Configuration. The

spatial control within the physical configuration determines the FFS, while the organization and functional configuration refine the type of FFS.

4.2. Identify DSM and FFS design drivers

Pinpoint key system drivers within the mission, product, and service to address system requirements effectively. As Murali (2006) proposed, system drivers are the principal mission parameters or characteristics critical for small satellite missions, which are documented in Table 4.1.

Table 4.1 - Typical systems drivers.

Driver	What limits driver	What driver limits
Size	Available weight	Payload size
On-orbit weight	Altitude, inclination, launch vehicle	Payload weight, survivability, design and manufacturing cost
Power	Size, weight	Payload and bus design, on-orbit life
Data rate	Storage, processing, antenna sizes, limits of existing systems	Information sent to the user, demand for onboard processing
Communications	Coverage, availability of ground stations or relay satellites	Coverage, timeliness, ability to command
Pointing	Cost, weight	Resolution, geolocation, and system accuracy, increase spacecraft cost
Number of spacecrafts	Cost	Coverage, frequency, and overlap
Altitude	Performance demands, weight	Performance, survivability, coverage and communications
Coverage	Orbit, scheduling, payload field of view and observation time	Data frequency and continuity
Scheduling	Timeline and operations, decision making, communications	Coverage, responsiveness, mission utility
Operations	Cost, communications	Frequently, the principal cost driver, principal error source

Source: Murali (2006).

The design drivers of DSM and FFS can be analysed using the taxonomy proposed by Le Moigne et al., which classifies DSMs into organisational, physical, and functional configurations. The organisational aspect defines the control structure among spacecraft (centralised or decentralised), influencing autonomy and coordination. The physical configuration focuses on the spatial arrangement and distances between satellites, affecting propulsion and communication needs. The functional configuration addresses how mission tasks are distributed or

shared across satellites. (LE MOIGNE; ADAMS; NAG, 2020) as shown in Table 4.2.

Table 4.2 - DSM and FFS drivers.

DSM Drivers		
Driver	**What limits driver**	**What driver limits**
Appearance	bus, payload, and operational characteristics	Member characteristics
Inter-Spacecraft Relationship	degree of capability, manoeuvres	Focal point for the communication, control and command, rendezvous and docking.
Spatial relationship	Common result of the missions	Mission Design Layout
Spatial control	Mission control characteristics	Control mission degree
Temporal relationship	Temporal deployment	Number of members deployment at the same time
Temporal Control	Control determination time	Control Accuracy Time
Functional distribution	Mission functionalities	Mission compatibility and cooperative capabilities
Autonomy	System control autonomy	control distribution
Formation Flying System Drivers		
Spatial relationship	Spacecrafts distribution	Position and relative distance in orbit between satellites.
Spatial control	AOCS capabilities	degree of precision and accuracy of control
Autonomy	System autonomy capacity	Degree of operation independently of external control.
Communication	Data transfer type, data transfer time, spatial perspective, relationship between segments, satellites hierarchy.	Connection format between satellites, data transfer schedule, Distance between satellite and line of sight, Communication between satellites and the ground station, number of satellites that collect information and communicate with the ground station.
OnBoard Data Handling (OBDH)	Software, task distribution	Spacecraft telemetry, storage and execution of application software, operating system, data processing time.

Source: Author.

4.3. Describe DSM operational environment

Based on key design drivers, the following mission considerations are proposed:

- Time of operation phases: This term refers to the distinct stages of a spacecraft's mission, each marked by specific goals and operational requirements. These phases typically include launch, orbit insertion, operational lifespan, and decommissioning;

- Precision degree of the operational ranges: This pertains to the required accuracy within operational parameters such as altitude, orbit, and position for spacecraft;
- Multiple spacecraft operation: This involves the simultaneous management of more than one spacecraft. Tasks may include FF, constellation management, or coordinated observations, necessitating efficient management to ensure data integrity and maximize output from the mission;
- Individual spacecraft operational characteristics are analysed in order to define the DSM appearance;
- On-orbit spacecraft hierarchical layout. This refers to the organisational structure and role assignment among multiple spacecraft within a fleet or constellation. A hierarchical layout may designate lead and subordinate spacecraft with specific responsibilities such as data collection, relay functions, and command execution, among others;
- Real-time decision-making degree: This indicates the capacity of the spacecraft or its ground control to make immediate decisions based on real-time data. Such capability is vital for missions that require adaptive responses to dynamic conditions or unforeseen events;
- On-orbit spacecraft control decision-making degree: This focuses on the autonomy level of the spacecraft in making operational decisions independently of ground intervention;
- Number of members deployment at the same time: This refers to the quantity of spacecraft or modules deployed simultaneously during a mission phase. This is particularly relevant during the deployment of satellite constellations, where multiple units might be launched from a single vehicle;
- On-orbit cooperative manoeuvrings degree between spacecrafts: This measures the complexity and frequency of coordinated manoeuvres between spacecraft, which could include activities such as docking, FF, or coordinated trajectory adjustments.

5. Define FFS functional requirements

The FFS must consider also DSM design drivers and based on Leitner (LEITNER, 2007), Underwood (2014) and Tiraplegui (2019). Some relevant needs that should be considered for the design of a system capable of performing formation flying activities (TIRAPLEGUI et al., 2019), a series of FFS design considerations can be proposed as follows:

On-orbit Considerations

- On-orbit Position and Relative Distance of Satellites: This pertains to the specified locations and inter-satellite spacing within a constellation or FFS in orbit;
- On-orbit Satellite Task Distribution and Execution: This refers to the allocation and performance of tasks among satellites in orbit;
- Activities Execution Per Orbit: This denotes the specific tasks that satellites undertake with each orbital completion, encompassing data collection, repositioning, or maintenance checks;
- Consider the Eclipse (Shadow) Projected Between Spacecrafts: This concerns the management of intervals when one spacecraft casts a shadow upon another, impacting solar power generation and thermal conditions.

Communication and control considerations

- Communication Format Data Transfer Schedule Between Satellites and Ground Station: This involves the established protocols and timing for data exchanges between the satellites and the terrestrial control station;
- Degree of Precision and Accuracy of Control: This concept describes the exactitude with which satellites maintain their prescribed orbits and positions, alongside the execution of manoeuvres;
- Degree of Operation Independently of External Control: This measures the extent to FFS can function autonomously, absent direct inputs from terrestrial control stations;

- Coupled Dynamics Capabilities to Simultaneously Managing Position and Attitude: This capability of multiple satellites to concurrently control both their position in orbit and their attitude, in a cohesive manner;
- Synchronization Capabilities to Simultaneously Managing Position and Attitude: This refers to the ability of multiple satellites to synchronise their positional and attitudinal adjustments to operate in a cohesive manner;
- Flexibility of Adjusting the Relative and Absolute Position of Satellites: This describes the capability of satellites to modify their positions relative to one another and their absolute positions in orbit.

Risk and Hazard considerations

- Level of Regional Disturbances During the Operation: This term addresses the impact of environmental factors such as gravitational forces, solar radiation, and atmospheric drag on the operations of satellites;
- Consider the Collision Risk Management: This involves the implementation of strategies to avert collisions with other satellites, debris, or meteoroids, including proactive manoeuvres and the deployment of collision prediction software.

At this point, a list of functional requirements for the FFS must be defined based on the information obtained in the previous steps. These requirements should be clearly identified for traceability and should consider alongside the constraints. In step 9, the requirements for the subsystems will be defined.

6. Propose life cycle development plan

The life cycle of an autonomous formation flying system follows a structured systems architecting process aligned with the early phases from the identification of stakeholder needs to detailed system design. Given the distributed and collaborative nature of these missions, the life cycle must account for the coordinated development and integration of multiple small satellites, each contributing to a shared operational objective.

The concept development phase defines the mission rationale, assesses the feasibility of distributed architectures, and establishes the foundational concepts that guide subsequent architectural choices. This phase includes the identification of key design drivers and constraints associated with formation dynamics, autonomy levels, and SoS interactions.

The system design phase elaborates the global architecture, decomposes the system into functional and physical segments, and allocates requirements to individual spacecraft, ground segments, ISL, and user interfaces. This decomposition is informed by the mission's taxonomy particularly the DSM and FFS classification and incorporates consideration for autonomy aware interfaces and subsystem interdependencies.

During the detailed design phase, subsystem specifications and interface control documents are finalised. This phase emphasises the integration of communication, control, and autonomy capabilities across distributed nodes, ensuring system coherence under decentralised operation. The result is a harmonised system baseline ready for implementation and integration planning.

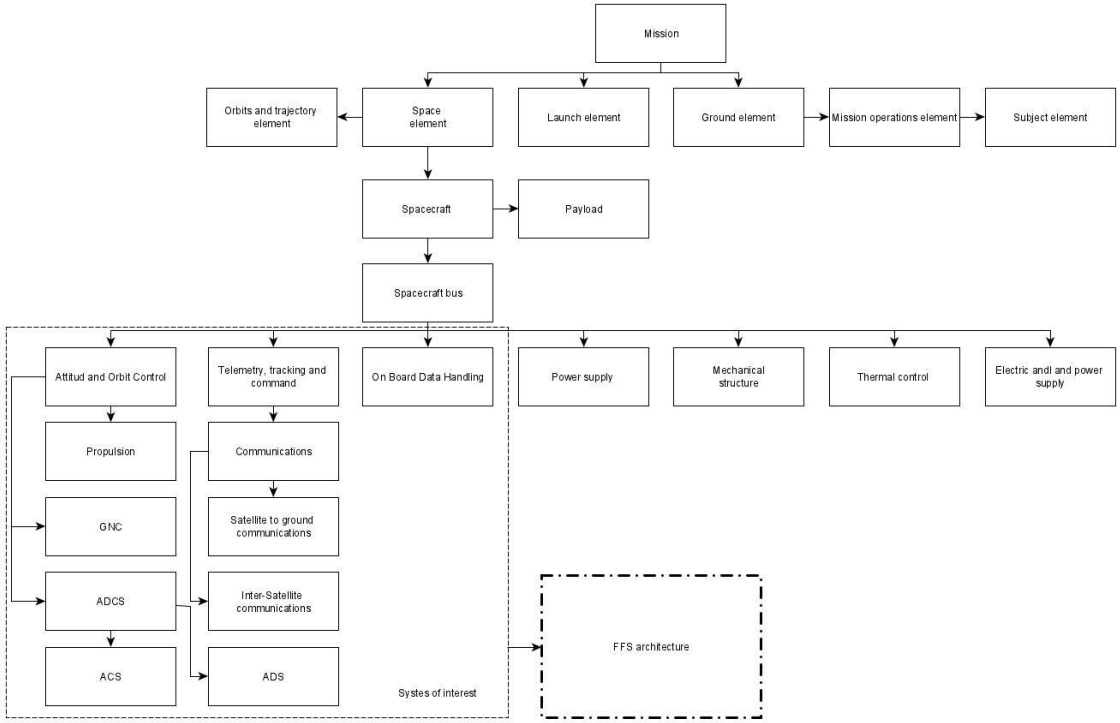
7. Propose DSM logical decomposition

This step must define the hierarchical architecture of the mission, including the architecture of each satellite and subsystems, in alignment with the requirements of the FFS. It should consider the concept of the ISL as a point of harmonisation for the requirements of the ISC of each satellite within the FFS. This analysis must be approached from a model of integration points, generating a logical decomposition of the mission, the FFS, ISL, and subsystems of ISC, and GNC.

7.1. Propose individual architectures per project

Irrespective of the intended mission, the breakdown of a typical space mission considers at least the space element, the launch element, and the ground elements. The subsystems are elements of the spacecraft bus in a typical space mission architecture. Figure 4.4 shows some relevant subsystems of DSM in a mission architecture hierarchy.

Figure 4.4 – Subsystems of DSM in a mission architecture hierarchy.



Source: Author.

The subsystems within the dashed box, marked as systems of interest, must be aligned with the needs of the FFS. This alignment serves as the integration point between the satellites. The outputs of this step include a detailed architectural diagram of the mission, encompassing the space element, launch element, and ground element.

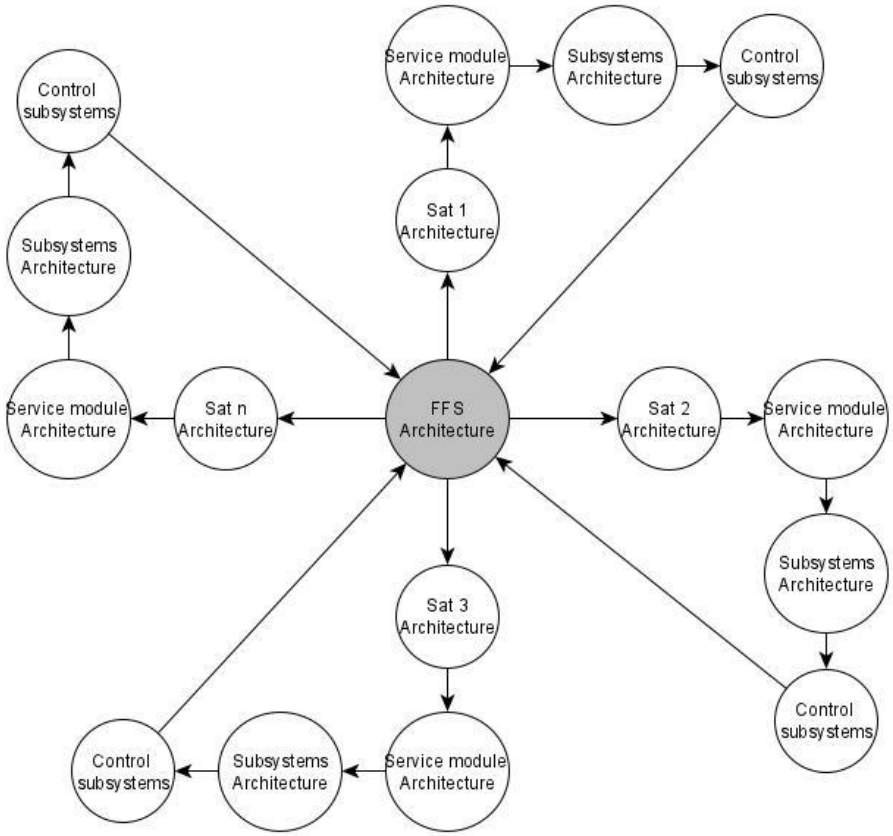
To achieve these outputs, programming languages such as SysML (HAN et al., 2025; HERZIG et al., 2013) and tools such as MagicDraw, or Cameo Systems Modeler can be employed to model the system architecture (BATALEBLU et al., 2024; HERZIG et al., 2013; STANCEK et al., 2024).

Diagramming tools such as Microsoft Vision or Lucidchart can also be used for visual representation. For example, a hierarchical diagram can illustrate the mission architecture, clearly marking subsystems. Integration points, such as "Communication subsystem aligned with FFS data exchange requirements," can be detailed in a supporting table.

7.2. Propose distributed architecture

As shown in Figure 4.5, the FFS has its own architecture, taking into account that it consists of other architectures, such as those of each satellite that composes it. In each of these satellites, the architecture of the service module and its subsystems.

Figure 4.5 - FFS Distributed architecture.



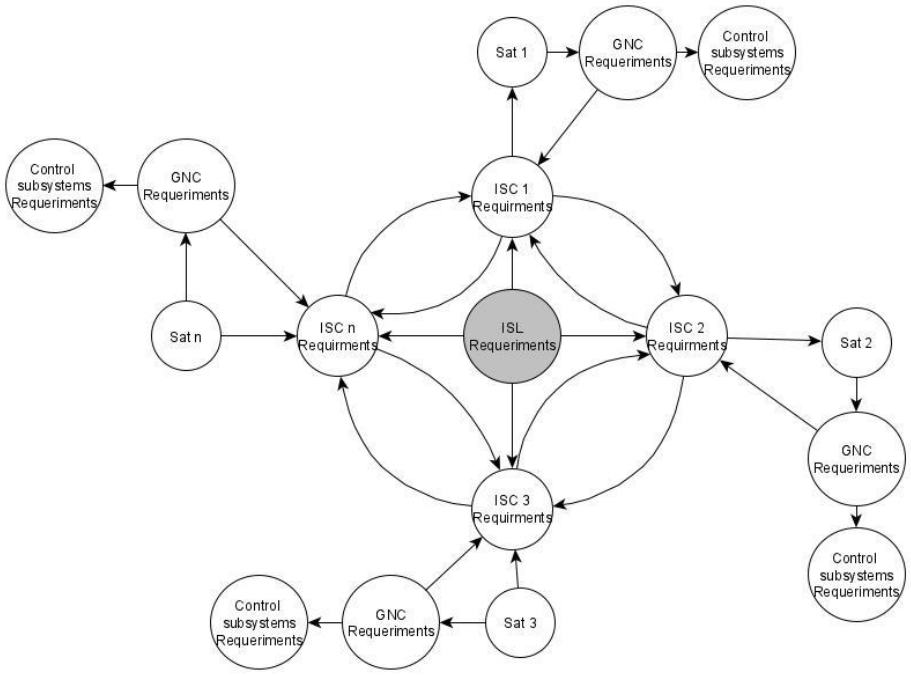
Source: Author.

In this case, the FFS architecture establishes the operational criteria for the satellites, which in turn determine the architecture of the service module, the subsystems of interest, which will be responsible for maintaining the operational characteristics of the FFS.

- Consider the specific points of harmonization.

At this juncture, it is important to note that each satellite may have its own specific features; therefore, they must converge at specific points of harmonization, such as the ISC and ISL requirements. The approach to developing the DSM should be tackled from the perspective of the individual characteristics of each element (satellites) and the overall type of DSM. Figure 4.6 illustrates the relationship between the development of systems and subsystems in isolation and their integration at a point of harmonization, as exemplified by the ISC of each satellite within the context of the ISL concept.

Figure 4.6 - Requirements in FFS Distributed architecture.



Source: Author.

Thus, it is imperative to consider the requirements of the ISC in adherence to the stipulations of the GNC and satellite, taking into account the communication needs and ISC requirements of the other satellites within the FFS.

In this case, the link requirements between the satellites must determine the communication system requirements, considering the key design drivers and constraints of the satellites, which also define the requirements for GNC.

Additionally, the requirements of the ISC for each satellite must be coordinated and aligned with the ISC requirements of the other satellites in the FFS.

The outputs of this step include a distributed architecture diagram that defines the individual service modules and subsystems of each satellite. Additionally, specific points of harmonisation, such as ISL and ISC requirements, are established to align the satellite architectures within the FFS.

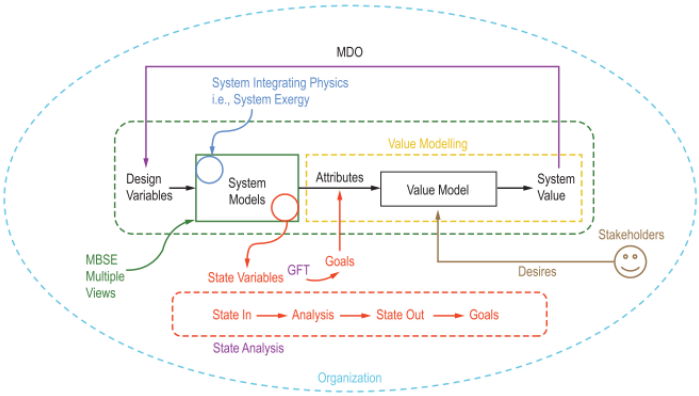
7.3. Propose the model integration points

A reference SE model should be selected as the basic approach. The model proposed by the research is modified throughout its development according to the experience, results, and needs encountered. In this case, a framework of space mission development models can be considered, which can be integrated at key integration points.

- Model integration points

According to Watson et. al. (2020) it is necessary to approach the high level relationships between different system models. These models offer various perspectives on the system, assisting in understanding and decision making. Within this model set, key system characteristics such as integrating physics, state variables, system value, and other attributes are identified. Some attributes are directly linked and state analysis methods. Specifically, attributes within the design variables box in the Figure 4.7. align with the objectives of these approaches and feed into the value model. (WATSON; MESMER; FARRINGTON, 2020).

Figure 4.7 - System model relationships.

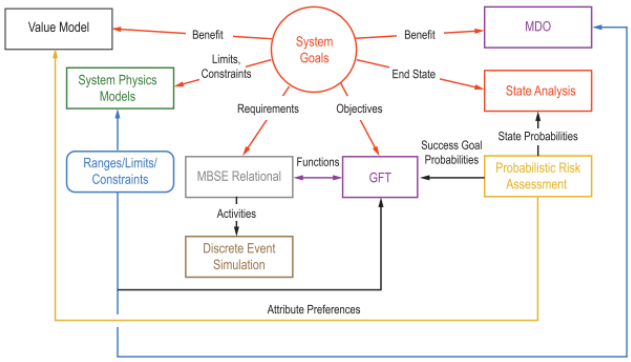


Source: Watson et al. (2020).

Additionally, as illustrated in Figure 4.8, the central connecting factor among these models is the system goals. Engineered systems are created to fulfill specific objectives; thus, the models employed in designing and constructing these systems are inherently linked to the intended goals of their stakeholders.

Figure 4.8 - System model integration points.

.



Source: Watson et al. (2020).

In this case, considering a distributed architectures model, the integration points correspond to the concept of ISL and ISC, where each satellite and its subsystems have their own architecture but are part of the overall FFS architecture. This step results in a reference SE model that identifies key integration points and a system model relationship diagram illustrating the high-level links between system goals and design attributes. The integration of

individual satellite architectures into the overall FFS architecture is also addressed within this framework.

Simulation tools like Simulink can support the analysis and validation of the model. For example, a system model relationship diagram can depict the connections between the ISL concept, ISC requirements, and the overall FFS architecture. Key attributes influencing synchronisation and communication, such as positional adjustments and inter-satellite data flow, can be highlighted in a supporting table to demonstrate alignment with mission objectives.

8. Propose possible system solutions and ConOps

After defining the distributed architecture, it is expected to propose a concept of operations (ConOps) as a system solution, considering the hierarchy and relationships between the satellites. This includes defining the characteristics of the ISC and the data delivery process, including the type of software and its architecture.

With the distributed architecture defined, it is essential to develop a ConOps that establishes the functional and operational framework of the system. This involves defining the satellite relationships, hierarchy, ISC system, and data delivery process, ensuring efficient coordination and control of the FFS.

The proposed ConOps should clearly differentiate the current operational state (“as-is”) from the expected system performance (“as-it-would-be”), highlighting improvements in autonomy, communication, and synchronisation between satellites.

8.1. Identify satellite relationship

All spacecrafts shall consider according to FFS drivers:

- Support themselves during operation;
- Collaborate to accomplish the mission;
- Keep their position and distance between satellites according to degree of precision and accuracy of control required by the FFS;

- Reconfigure their position and distance between satellites according to degree of precision and accuracy of control required by the FFS;
- Contribute to the required degree of autonomy independent of external control;
- Independent free-flight capability;
- Established size for satellite;
- ISL capability.

On the other hand, at least one spacecraft shall communicate with ground station.

The success of an FFS depends on the ability of its satellites to interact seamlessly while maintaining autonomy. Each spacecraft must be capable of self-sustaining operation, collaboration, and precise positioning, ensuring the required level of control accuracy and adaptability. These relationships define how satellites maintain formation, respond to disturbances, and support the overall mission.

A critical aspect is the ISL, enabling real-time communication and coordination. At least one spacecraft must be designated to establish a direct connection with the ground station, serving as a communication gateway for the constellation.

8.2. Define satellite hierarchy

Choose the type of hierarchy based on the number of lead satellites; there can be one, several, or none with higher hierarchy than the others. In any case, it is also necessary to consider the type of communication, mission architecture, levels and types of hierarchy between satellites. (Horne; Kwadrat; Edwards, 2002)

The organisational structure of the constellation must be established by defining the satellite hierarchy, which dictates decision making processes and communication protocols. Depending on the mission architecture, satellites can operate under a single-leader, multi-leader, or fully decentralised structure.

In a hierarchical configuration, leading satellites manage coordination and synchronisation, whereas in decentralised systems, all satellites share decision-

making responsibilities. The chosen structure must balance autonomy, efficiency, and resilience, ensuring that no single point of failure compromises mission success.

8.3. Define ISC system

According to Anyanhun and Edmonson an Inter-satellite communication system (ICS) could mitigate the Size, Weight and power, among other constraints of this group of spacecrafts (ANYANHUN; EDMONSON, 2017). Also, ICS design of DSM has a huge impact on performance of FFS, according to Underwood requirements about ICS in DSM must consider (UNDERWOOD et al., 2014):

- Frequency allocations established by regulatory body;
- Altitude operation;
- DSM global coverage;
- Space environment;
- Viewing geometry;
- User-to-user delay;
- Power system capacity;
- Offered communication services;
- Physical interactions;
- Satellite time in darkness;
- Effect of space-based routing (user-sat-user);
- Ground-based routing (user-sat-ground station-wire-user).

Considering Sun et al., because of the restricted distribution of facilities, some system administrators are unable to track satellites throughout their entire operation and ISL are needed for transmission of telemetry or telecommand in time and effective ranging (SUN et al., 2018). In this way, according to Leitner (LEITNER, 2007) for each satellite ISC is necessary to consider:

- Hardware available;
- Network and protocols;
- Software required for implementation;

- Robustness of the communication;
- Distance between spacecraft;
- Potentially tight power constraints.
- Ability to continuously measure the coarse range between the vehicles.

Finally, based on Horne et al. it is first necessary to identify cross-link communications requirements common to a cross-section of proposed missions considering internal cross-link networking operations and external networking interface operations (HORNE; KWADRAT; EDWARDS, 2002). In this way, it is necessary to added Cross-Link Communications considerations as follow

- Cross-link communications;
- Internal cross-link networking operations;
- External networking interface operations.

A robust ISC is fundamental to coordinating activities and ensuring mission continuity. The design must take into account frequency allocations, altitude-dependent communication constraints, global coverage, and power efficiency. Additionally, the system should support both direct inter-satellite links and relay-based communication through ground stations.

To optimise efficiency, ISC must also consider the impact of physical interactions, satellite distance, and space-based versus ground-based data routing. These factors influence data transmission reliability and latency, directly affecting operational performance.

Ensuring network stability and fault tolerance is a priority, requiring advanced communication protocols that enhance signal robustness and system redundancy. The design must also facilitate seamless integration with existing space communication networks to enhance interoperability.

8.4. Define data delivery process

According to Subramanian et al., understanding the interconnectedness of subsystems is crucial. In the context of On-Board Data Handling (OBDH), the On-

Board Computing (OBC) system, specifically, plays a vital role by managing temperature data monitoring, receiving ground station commands, and processing energy and data for the control subsystem. Similarly, in the case of FFS, the Controls subsystem relies on data from other satellites through communications (SUBRA-MANIAN et al., 2015).

Based on Grocott et al., in FFS the OBC architecture of each spacecraft is part of a distributed system architecture. However, each spacecraft depends on at least a Housekeeping Computer (HKC), overcurrent protection, and the execution of Time Tagged Commands (TTC). Additionally, it includes a Payload On-Board Computer (POBC), Instrument On-Board Computers (IOBCs), Internal Data Storage (IDS), and an Attitude Determination and Control Computer (ADCC) responsible for all related tasks (GROCOTT et al., 2014). In this way, some design considerations about OBDH can be proposed as follows:

- Onboard Attitude System Software flight code of each spacecraft;
- On-orbit execution tasks time;
- Control commands from ground station;
- Autonomous control degree;
- Pre-established tasks from the ground control according to autonomous control degree;
- On-orbit decision making according to autonomous control degree;
- Satellite hierarchy;
- Common software among spacecrafts.

Based on Blanquart et al. design considerations about software (BLANQUART et al., 2019) can be approached as follow:

- Code generation from ground;
- Onboard automatic code generation;
- Common language;
- Evolutions implementation life-cycle time;
- Manual coding faults by automatization;
- Tools for embedded software;

- Assure the feasibility and availability of every representative operation.

Regarding the control system software, it is essential to consider the trend towards using Artificial Intelligence (AI) (THANGAVEL et al., 2024) and the concepts of intelligent DSM (BURRONI et al., 2024) and intelligent satellites (DAI et al., 2020).

Well-structured data delivery process is essential for synchronising operations, managing onboard resources, and ensuring continuous data exchange. The OBDH system must efficiently process commands, telemetry, and sensor data while maintaining real-time communication between satellites and the ground station.

Each spacecraft's OBC system plays a pivotal role in managing essential tasks such as temperature monitoring, power regulation, and control command execution. To ensure reliability, the software architecture must support automated updates, onboard fault detection, and system-wide synchronisation. The increasing role of AI in spacecraft operations presents new opportunities for autonomous decision-making and adaptive control strategies.

9. Propose the evaluation of possible system solutions and ConOps

It is advisable to use a characteristic measurement matrix to compare the feasibility of each option. This process is expected to yield a list of options and their measurable characteristics, propose a comparative table or matrix, and provide a justification for the decision making based on the results.

The evaluation of possible system solutions and the ConOps is a fundamental step in ensuring that the selected approach aligns with the mission requirements, operational constraints, and performance expectations of the FFS. This evaluation must be conducted using a structured and data-driven approach, allowing for an objective comparison of alternative designs and operational strategies.

To achieve this, a characteristic measurement matrix is recommended as a quantitative assessment tool. This matrix enables a systematic evaluation of

multiple design options by defining measurable criteria such as formation-keeping accuracy, communication latency, power efficiency, and system autonomy. By applying this method, decision-making is grounded in objective data rather than subjective interpretation, ensuring that trade-offs are transparent and justifiable. The outcome of this evaluation should provide a comparative analysis of system alternatives based on quantifiable performance metrics, along with a well-founded justification for the selected solution supported by clear evaluation criteria. Additionally, it should establish a structured decision-making framework that enhances transparency, traceability, and alignment with the mission objectives.

9.1. Define compliance measures

Based on the tailoring matrix for "Space Product Types" from ECSS (2017), consider the FFS requirements and define a tailored compliance measures matrix.

To ensure that the FFS aligns with its specific mission requirements, it could be beneficial to establish a structured set of compliance measures. These measures could be based on the ECSS (2017) tailoring matrix for Space Product Types, while also considering the unique constraints associated with small satellites operating in formation.

9.2. Define decision making model

According to Larson et al. (2009), it is essential to implement a structured approach for decision-making in technical issues. This involves establishing guidelines to identify which technical matters need formal analysis or evaluation and defining the criteria for evaluating potential solutions. Subsequently, solutions must be identified and evaluated using selected methods and tools. Based on these evaluations, the most suitable solutions are chosen, and the results are reported along with recommendations, anticipated effects, and corrective actions. Finally, it is crucial to document the work products from the decision analysis process.

A structured decision-making framework could be a valuable tool for systematically selecting the most effective system solution for the formation flying system. Given the complexity of coordinating multiple small satellites, a well-defined methodology could help ensure that all design alternatives are evaluated objectively, consistently, and transparently. Following an established decision-making process could facilitate informed choices that align with mission objectives while balancing technical constraints and operational feasibility.

One approach to structured decision-making could involve first identifying key technical issues that require formal evaluation. These may include factors such as formation-keeping accuracy, propulsion efficiency, communication reliability, and system autonomy. By clearly defining these critical aspects, it becomes easier to establish measurable parameters that serve as the foundation for assessing different solutions. Once the key evaluation criteria are defined, a range of assessment methods could be applied, such as multi-criteria decision analysis, trade-off studies, or cost-benefit analysis, to compare alternative system configurations systematically.

After evaluating potential solutions, the next step could involve selecting the optimal system architecture based on a structured comparison. A decision matrix could be a useful tool in this process, allowing each system alternative to be assessed based on quantifiable factors such as performance efficiency, energy consumption, resilience to faults, and cost-effectiveness. Assigning priority weights to these factors could further refine the selection process, ensuring that decisions are data-driven rather than subjective.

Finally, documenting the entire decision-making process could be essential for maintaining transparency and traceability. By keeping records of the evaluation criteria, trade-offs considered, and the rationale for selecting the final system configuration, the decision framework could serve as a reference for future project phases, including integration, testing, and operational deployment. Through this structured approach, the formation flying system development process could benefit from a more robust, efficient, and mission-aligned decision strategy, ultimately contributing to the success of the formation-flying mission.

10. Define the review point for the validation of the systems solution and ConOps

According to NASA (2016) The aim of this section is to offer an overview of the Decision Analysis Process. Decision Analysis serves as a framework where various types of analyses are utilized to formulate and characterize decision alternatives, ensuring they align with the decision-maker's priorities based on their current knowledge. In these cases, is necessary to approach Mission Concept Review (MCR), System Requirements Review (SRR), Mission Definition Review (MDR) and System Definition Review (SDR).

Through exhaustive reviews of the project phases after each key review point, it is expected to obtain the observations and recommendations necessary for the project to continue. It is essential to generate a descriptive document outlining the results of each review.

At each review point, a comprehensive analysis of the project phase, system performance, and compliance measures is carried out to assess progress and identify potential areas for refinement. These evaluations serve as critical checkpoints, ensuring that the system development aligns with mission requirements and technical expectations. The feedback obtained from these reviews provides valuable insights, guiding necessary adjustments and improvements to enhance overall system reliability and efficiency.

The results of each review should be thoroughly documented in a descriptive report that outlines the evaluation criteria, identified issues, recommended modifications, and justifications for decisions. This structured documentation process ensures traceability, enabling clear tracking of design changes and their rationale throughout the system’s development. Additionally, maintaining detailed records allows for informed decision-making in future iterations, facilitating continuous improvement and risk mitigation.

By systematically conducting these validation reviews, the project maintains technical integrity, operational feasibility, and stakeholder confidence. This structured approach enhances the credibility of the development process, ensuring that all critical aspects are reviewed and optimized. Ultimately, this

iterative evaluation framework contributes to the success of the formation flying system, guaranteeing that it meets both performance and operational requirements before deployment.

11. Iterate and document

Finally, it is necessary to iterate the process until a solution is defined. After each review and validation of compliance measures, feedback must be provided to the process to implement the observations obtained. Each review must include a return point until the proposed needs, goals, objectives, and requirements are met. The iteration will end when all the concerns and expectations of the stakeholders are satisfied. As a result, a comprehensive descriptive document of the process and the development of each proposed step must be generated.

A structured iterative process is essential to ensuring that the FFS development progresses systematically, aligning with mission objectives and technical feasibility. By defining expected outcomes and clear stopping criteria, each iteration refines system requirements, optimizes design performance, and validates operational feasibility before deployment.

11.1. Expected Outcomes of Each Iteration

Each iteration produces specific deliverables that verify progress and guide refinements. The following key phases define the iterative process:

1. Requirements Validation: Ensures system requirements align with mission objectives and constraints.
    - Deliverables: Updated System Requirements Document (SRD), compliance assessment;
    - Stop Condition: All requirements are validated, documented, and traceable.
2. Design Refinement: Optimizes system architecture, interfaces, and operational strategy.
    - Deliverables: Revised system architecture, trade-off analysis;

- Stop Condition: The design is stable, with no unresolved trade-offs.

3. System Integration: Ensures proper integration of all subsystems, including communication, propulsion, and onboard processing.
    - Deliverables: System integration report;
    - Stop Condition: Subsystems function as expected, with no major integration issues.
4. Final Validation and Review: Confirms the system is fully compliant and mission-ready.
    - Deliverables: Final system verification report, launch readiness assessment;
    - Stop Condition: All requirements, constraints, and performance benchmarks are satisfied.

11.2. Stopping Criteria for Iterations

Iterations continue only until all defined objectives are met. The process stops when:

- The system meets all functional, operational, and performance requirements;
- Compliance measures have been validated;
- Stakeholder concerns and risks have been addressed;
- Test results confirm expected system behavior, with no major discrepancies;
- Trade-off decisions reach a stable configuration.

If inconsistencies arise, the phase must be iterated until resolved. Each iteration must be documented to ensure transparency, traceability, and alignment with mission objectives, reinforcing the reliability and success of the FFS development process.

5 APPLICATION CASES

The examples presented in this research were developed based on publicly available information regarding real missions. These case studies are not intended to fully replicate the original designs, but rather to illustrate how the proposed architecting process can be applied in representative contexts. The selection of these missions is grounded in their relevance to distributed systems and formation flying, as well as the accessibility of technical and operational data that support the conceptual validity of the developed methodology.

5.1 FACSAT 3

The mission aims to design, develop, and operate a constellation of three nanosatellites entirely manufactured in Colombia, with the primary objective of conducting high-frequency Earth observation to support environmental monitoring, territorial security, natural resource management, and emergency response.

The constellation will operate in LEO, enabling revisit times of less than 12 hours over strategic areas of the national territory. Each satellite will be equipped with optical and multispectral sensors capable of capturing high-resolution imagery to detect land-use changes, monitor hydrological and atmospheric conditions, and identify environmental degradation processes.

The system architecture follows a SoS approach, in which the constellation is seamlessly integrated with national ground stations, the Satellite Operations Center (SpOC), and data processing centers. This integration ensures interoperability, modularity, and scalability within the national space infrastructure.

The satellites will incorporate advanced subsystems, inter-satellite synchronization protocols, and onboard data processing capabilities, enabling increased autonomy and reducing reliance on the ground segment. Additionally, each satellite will be equipped with a deorbiting mechanism to ensure controlled disposal at the end of its operational life, in compliance with international space debris mitigation guidelines.

Goals

To address the operational and strategic needs identified by key stakeholders, the FACSAT-3 mission establishes the following overarching goals:

- Provide reliable, high-frequency Earth observation data in support of national environmental and security priorities;
- Enable autonomous and coordinated operation of the constellation under a distributed system-of-systems approach;
- Strengthen national capabilities in the design, integration, testing, launch, and operation of satellite systems;
- Promote the local development of advanced space technologies and geospatial data processing capabilities;
- Implement sustainable space operations through responsible management of the orbital lifecycle, including deorbiting strategies at the end of the mission.

Objectives

To ensure the fulfillment of the mission and its goals, the following specific and measurable objectives have been established:

- High-frequency observation: Achieve a temporal resolution of less than 12 hours over critical areas by distributing orbital phases among the constellation satellites;
- Sensor performance: Equip the satellites with optical sensors capable of achieving a spatial resolution equal to or better than 5 m/pixel, including multispectral capabilities for environmental analysis;
- Formation coordination: Ensure coordinated operations among satellites through synchronized scheduling for optimal coverage and image overlap;
- Integration with the ground segment: Guarantee full interoperability with the SpOC and ground stations by implementing standardized communication protocols;
- Data latency: Ensure data delivery from the satellite to processing centers with a maximum latency of 2 hours under nominal conditions;

- Operational autonomy: Implement onboard event detection with intelligent data prioritization to optimize bandwidth usage and reduce human intervention;
- Sustainability: Incorporate a passive or semi-passive deorbiting system that ensures the controlled disposal of satellites within no more than 5 years after mission completion.

Needs Identification from a System-of-Systems (SoS) Perspective

Colombia requires a high-frequency, reliable Earth observation system due to limited environmental monitoring amidst climate variability and rapid land-use changes. A nanosatellite constellation can address this need by enabling frequent monitoring of climate variables, air and water quality, land-use dynamics, and resource management.

Given the country's limited geospatial capabilities, the development of a national constellation strengthens technological sovereignty, fosters local design and operations, and builds critical infrastructure and expertise.

Strategically, the mission supports surveillance, territorial management, disaster response, and food security through real-time monitoring and geospatial intelligence.

A SoS architecture ensures that satellites operate cohesively in a modular, scalable framework, requiring adaptive systems engineering and continuous cross-validation to maintain system-wide integration.

FACSAT-3 Architecture from a System-of-Systems Perspective

- Space Segment: Three autonomous LEO nanosatellites built in Colombia with optical and multispectral sensors, operating collaboratively to capture multi-angle imagery and generate 3D models;
- Ground Control Segment: Managed by the Colombian Aerospace Force, this segment oversees mission operations, orbital control, and real-time monitoring;

- Data Processing Segment: Converts satellite data into geospatial products using AI to support sectors like defence, agriculture, and disaster response;
- Institutional and End-User Segment: A national network that uses satellite data for policy, research, and operations, ensuring continuous feedback for mission adaptability.

Step 1. Define the SE Task

The Table 5.1 outlines the SE tasks defined for the FACSAT-3 formation flying case study. These tasks ensure alignment with mission objectives by establishing a structured workflow, clarifying responsibilities, and providing scheduling for each activity. The tasks are tailored to the context of formation flying and small satellite systems, as described in the referenced technical and stakeholder analysis documents.

Table 5.1 - Roles and responsibilities identified to accomplish the mission.

Role	Responsibilities
Systems Engineering Team	Coordinates system design, integration, requirements traceability, and performance evaluation.
Mission Architecture Team	Defines mission objectives, system-of-systems architecture, risk assessments, and reporting.
AOCS Engineering Team	Develops the attitude and orbit control system to ensure stability and formation alignment.
Orbital Analysis Team	Analyzes orbital mechanics, constellation stability, and trajectory optimization.
Communication Team	Designs and implements the communication system between satellites and with ground stations.
Power System Team	Develops efficient energy and propulsion subsystems.
Software Team	Creates autonomous navigation algorithms, real-time control strategies, and fault detection mechanisms.
Integration & Testing Team	Assembles, validates, and verifies all subsystems and the complete system.

Source: Author.

Step 2. Define SE team responsibilities

To ensure effective coordination across engineering domains, a structured responsibility matrix has been developed for the Systems Engineering (SE) activities associated with the FACSAT-3 formation flying mission. This matrix follows the RACI model, Responsible (R), Accountable (A), Consulted (C), and Informed (I); which provides a clear delineation of roles among participating teams. It ensures that each engineering group, from system architects to integration and testing personnel, understands its level of involvement in key tasks such as requirements definition, subsystem integration, risk management, and system validation. This matrix is shown in Table 5.2.

Table 5.2 - RACI Matrix – Systems Engineering Team Responsibilities.

Activity	Systems Engineering	Mission Architecture	AOCS Eng.	Orbital Analysis	Comms	Power	Software	Integration & Testing
Requirements Elicitation & Definition	A/R	C	C	C	C	C	C	I
Architecture Definition	R	A/R	C	C	C	C	C	I
Subsystem Interface Control	A/R	C	R	C	C	C	C	C
Risk Identification & Mitigation	R	C	C	R	C	C	C	I
Configuration Management	A/R	I	I	I	I	I	I	C
Test & Validation Planning	R	I	C	C	C	C	C	A/R
Integration Coordination	C	I	C	C	C	C	C	A/R
Stakeholder Communicatio n	R	C	I	I	I	I	I	I

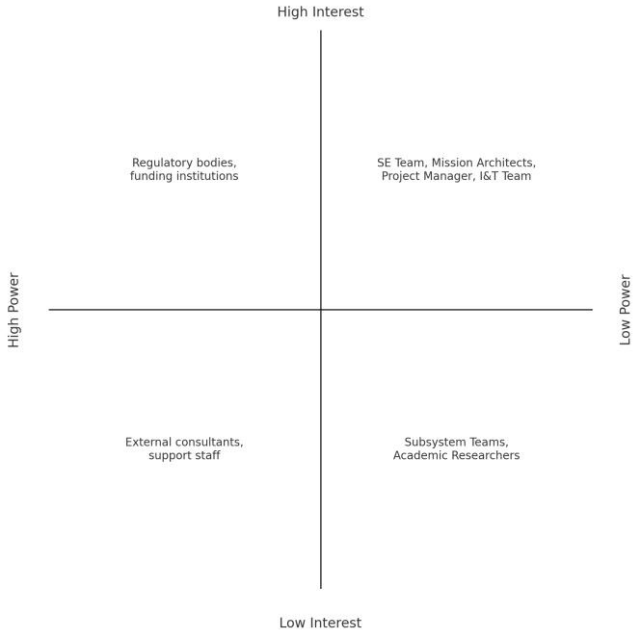
Source: Author.

By explicitly assigning responsibilities, the RACI matrix facilitates traceability, enhances inter-team communication, and minimises ambiguity in task ownership. It also supports project governance by clarifying decision-making authority and

consultative relationships, which are critical in a distributed satellite architecture involving tightly coupled subsystems.

Defining the responsibilities within the SE team for the FACSAT-3 mission involves identifying key participants and categorizing them according to their degree of influence and interest in the project. This structured approach supports targeted engagement and ensures that communication and decision-making efforts are optimized throughout the system life cycle. To support this classification, a Power-Interest Grid has been developed (Figure 5.1), allowing for the strategic alignment of roles and responsibilities within the SE framework.

Figure 5.1 Power-Interest Grid.



Source: Author.

Define systems engineering scheduling and control

To successfully accomplish the mission, it is necessary to implement controls over the different teams and monitor overall progress. The mission is divided into six phases, expected to be completed over 35 months. Table 5.3 presents the key objectives of each phase along with its estimated duration.

Table 5.3 - Timeline for the identified phases.

Phase	Phase	Duration	Key Objective
1	**Requirements Definition**	5 months	Establish mission objectives, technical requirements, and operational constraints.
2	**System Design and Analysis**	5 months	Develop the constellation architecture and key subsystems
3	**Prototyping and Partial Validation**	7 months	Validate formation control algorithms and subsystem performance through prototypes.
4	**Final Prototype Development**	5 months	Assemble engineering models and integrate subsystems for functional verification.
5	**Testing and Full Validation**	6 months	Conduct environmental, functional, and full-system testing.
6	**Launch and Operations**	7 months	Final integration, pre-launch validations, and mission deployment.

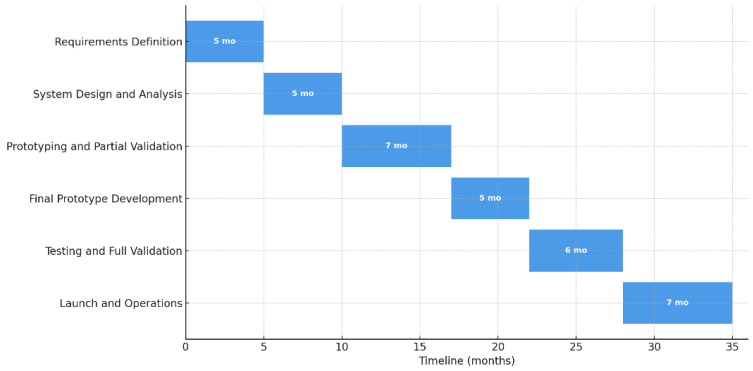
Source: Author.

Each phase must include control mechanisms to ensure its successful execution, guaranteeing that the mission is carried out with high efficiency and accuracy. The following is a list of mechanisms that will be used to control the mission.

- PERT/CPM Diagrams: To identify critical paths and optimize scheduling;
- Kanban Board: For agile task management and team coordination;
- RACI Matrix: To clearly define roles and responsibilities;
- Milestone Chart: To monitor progress at key project checkpoints;
- Progress Heatmaps: To visualize performance trends and address bottlenecks;
- Time Management Matrices: To prioritize tasks effectively and allocate resources efficiently.

The management of time and resources within the FACSAT-3 formation flying mission requires a structured approach to planning, scheduling, and controlling engineering activities. This approach enables effective oversight of all project phases. By using a Gantt-style chart, it becomes possible to manage each stage, estimate the mission's development timeline, and ensure a more rigorous control over the progress and completion of each phase, as can be observed in the Figure 5. 2.

Figure 5.2 - Systems Engineering Schedule.



Source: Author.

To proactively address potential technical and programmatic challenges throughout the system lifecycle, a structured risk assessment was conducted for each phase of the FACSAT-3 systems engineering process. The following table identifies key risks, assesses their likelihood and potential impact, and proposes mitigation strategies tailored to each development stage.

Table 5.4 - Risk Matrix – FACSAT-3 Systems Engineering.

Phase	Risk Description	Probability	Impact	Mitigation Strategy
Requirements Definition	Incomplete or conflicting stakeholder requirements	Medium	High	Conduct early stakeholder workshops and validation cycles
System Design and Analysis	Architecture inconsistencies or interface misalignment	High	High	Apply MBSE tools and interface control documents (ICDs)
Prototyping and Partial Validation	Algorithm instability or insufficient hardware performance	High	Medium	Implement incremental testing and simulations with prototypes
Final Prototype Development	Subsystem incompatibility during integration	Medium	High	Perform integration readiness reviews and subsystem pre-tests
Testing and Full Validation	System failure in environmental or functional testing	Medium	High	Execute system-level test plans with fault injection
Launch and Operations	Launch delay or orbital deployment anomaly	Low	High	Develop contingency launch plans and pre-deployment rehearsals

Source: Author.

Step 2. Identify all stakeholders involved

In the context of the mission, a structured identification of stakeholders ensures alignment with strategic objectives and supports the coordination of distributed capabilities within a SoS framework. Using a high-level SIPOC approach, the main stakeholders and their roles can be categorized as follows:

Table 5.5 - Interests of the stakeholders involved in the project.

Category	Stakeholders
Suppliers	Ministry of National Defense, National Military Industry and Technology Partners, Space Component Suppliers
Inputs	Government funding, National and international regulations, Commercial Off-The-Shelf (COTS) technologies, Existing ground station infrastructure
Process	Development and integration of satellite platforms, Subsystem coordination and mission protocol definition, Assembly, testing and validation, Launch and orbital deployment
Outputs	Fully operational satellites, High-resolution Earth observation data, Contribution to national space capabilities, Support for security, environmental monitoring, and urban planning
Customers	Colombian Aerospace Force (FAC), Office of the Presidency and government entities, Research centers and universities, Commercial users of geospatial data, Risk management and environmental agencies

Source: Author.

To address subsystem coordination and its role within FFS, a BPMN (Business Process Model and Notation) model would identify interactions among:

- Satellite engineering teams, responsible for control algorithm development and sensor calibration;
- Mission operation centers, which interpret sensor data and send orbital adjustment commands;
- Ground segment operators, who handle telemetry, tracking, and command (TT&C);
- Data processing units, responsible for payload data extraction and delivery to users;
- Regulatory entities, ensuring compliance with national/international space policy.

This internal coordination ensures traceability and performance of formation behaviors, particularly in missions involving multiple spacecraft or evolving toward constellation architectures.

Step 3. Identify Stakeholders Needs

The mission addresses a diverse set of needs from national, institutional, and technological stakeholders. The distributed constellation enhances national autonomy, boosts scientific and technological development, and contributes to

improved decision-making in areas such as environmental monitoring and defense. Table 5.6 summarizes these stakeholder requirements and their corresponding systems.

Table 5.6 - Requirements of Stakeholders.

Stakeholder Need	Description	Corresponding System
National sovereignty and autonomy	Strengthening Colombia's capabilities to independently monitor its territory and reduce dependence on foreign satellite systems.	National satellite constellation with autonomous operations, secure data handling, and domestic ground control infrastructure.
Defense and security	Detection and monitoring of illicit activities, border surveillance, and strategic situational awareness.	High-resolution optical payloads, secure real-time communication, and integration with national defense networks.
Environmental management	Observation of forest cover, illegal mining, and hydrological patterns for informed policymaking and risk management.	Multispectral imaging payloads, cloud-penetrating sensors, periodic revisit capabilities.
Disaster response and resilience	Early detection and assessment of floods, landslides, and fires to support emergency response and humanitarian missions.	Rapid tasking satellite architecture, high-frequency overpasses, and image analytics with AI-assisted interpretation.
Scientific and technological development	Strengthening academic-industry collaboration and enhancing national capabilities in areas like formation flying and onboard processing.	Implementation of distributed orbital architectures, and standardized interfaces for academic access.
Economic and industrial growth	Promotion of local aerospace industry, generation of skilled jobs, and potential commercial applications of Earth observation data.	Modular satellite bus design, interoperability protocols, and public-private development platforms.

Source: Author.

Step 4. Define baseline DSM ConOps and Identify Risks

Identify DSM Taxonomy

The DSM taxonomy is applied to classify the system along three key dimensions: organizational, physical, and functional. These elements help define how the spacecraft will interact, share tasks, and maintain formation in orbit. As can be observed in the Table 5.7.

Table 5.7 - Identified DSM Taxonomy for the Mission.

Taxonomy Element	FACSAT-3 Classification
Organizational Configuration	Decentralized hybrid: Each satellite has onboard autonomy for navigation and data acquisition but relies on periodic coordination with the ground segment and peer spacecraft.
Physical Configuration	Clustered formation: The satellites will operate in a loose cluster formation, with variable inter-satellite distances, maintaining relative positioning for coordinated observations.
Functional Configuration	Distributed collaborative: The satellites execute partially redundant tasks (e.g., imaging, environmental monitoring), sharing roles dynamically depending on operational conditions and subsystem availability.

Source: Author.

The organizational configuration determines the command-and-control structure between the satellites. In this mission each spacecraft is designed with sufficient onboard autonomy to perform essential tasks independently, including attitude determination, imaging, and navigation. However, coordination is periodically performed with the ground segment and between satellites to ensure synchronization and mission alignment. This results in a decentralized hybrid structure.

The physical configuration outlines the spatial arrangement of the satellite cluster in orbit. The constellation will operate in a loose clustered formation, where satellites maintain a relative spatial distribution within a predefined tolerance band. This setup allows them to perform coordinated observations without requiring tight proximity control.

The functional configuration defines how mission objectives and operational tasks are distributed across the satellite fleet. In this case, the satellites operate under a distributed collaborative model and are capable of performing partially redundant functions such as Earth observation and data acquisition. Tasks are dynamically reassigned based on satellite availability, health status, and orbital position.

Identify DSM and FFS Design Drivers

To ensure the mission architecture effectively addresses its objectives, it is necessary to identify the main design drivers that influence the configuration and performance of both the DSM and its FFS. These drivers represent key physical, operational, and environmental parameters that impose constraints or establish performance baselines, and for this mission are shown in Table 5.8.

Table 5.8 - DSM Design Drivers.

Driver	What Limits Driver	What Driver Limits
Size	CubeSat platform constraints (e.g., 6U–12U)	Payload integration, propulsion, and communication antenna size
Power	Solar panel size and attitude-dependent power generation	Sensor operation time, communication windows, and on-orbit autonomy
Communications	Availability of ground stations and inter-satellite links	Data relay delays, latency in cooperative control, command update frequency
Pointing	Budget constraints and limitations	Imaging accuracy, orbital correction effectiveness, stability of formation
Coverage	Orbital geometry and number of satellites	Revisit rate, observation frequency, event detection reliability
On-board autonomy	Processor capability and OBDH software design	Decision-making speed, real-time adaptation, mission resilience

Source: Author.

For the DSM design drivers, the satellite size is constrained by the CubeSat standard (6U–12U), which affects the available volume for payloads, propulsion modules, and communication systems. The power budget represents a critical driver, as energy generation and storage are limited by solar panel area and onboard battery capacity. These factors directly influence sensor operation time, autonomy levels, and communication availability.

Communication capabilities are determined by the coverage and availability of ground stations, as well as the performance of inter-satellite links. Any limitation in this area impacts data latency, system responsiveness, and fault recovery.

Pointing accuracy affects imaging quality and the ability to maintain formation. Coverage depends on the orbital parameters and the number of deployed spacecrafts, influencing the revisit rate and observation cadence. Finally, onboard autonomy is limited by processing capacity and software efficiency but directly enhances the mission's fault tolerance and responsiveness.

For the FFS-specific design drivers (Table 5.9), spatial control emerges as a primary concern. It refers to the system capability to maintain the geometric configuration of the spacecraft within acceptable deviation limits. This is achieved through a combination of attitude control and basic propulsion systems. The level of autonomy is determined by the system's ability to make real-time decisions onboard, leveraging AI-assisted algorithms for anomaly detection and adaptive mission planning.

Table 5.9 - FFS-Specific Design Drivers.

Driver	Description
Spatial Control	Based on performance and precision, FACSAT-3 will maintain loose formation flying with bounded tolerances.
Autonomy Level	Mid-level autonomy: real-time decision making supported by AI-based onboard processing for fault detection and event response.
Communication Architecture	Inter-satellite communication limited to short bursts; primary command via ground control.
OBDH & Task Allocation	Distributed task scheduling, event-driven data acquisition and onboard compression routines.

Source: Author.

For the FFS-specific design drivers, spatial control is a primary concern. It refers to the system's ability to maintain the geometric arrangement of the spacecraft within the allowed deviation range. This is accomplished through attitude control and basic propulsion. The autonomy level is defined by the system's capability to make onboard decisions in real time, using AI-assisted algorithms to handle anomaly detection and adaptive mission planning.

The communication architecture reflects a hybrid approach, where most control and planning are centralized on the ground, but critical updates and coordination among satellites occur through short inter-satellite bursts. Finally, On-Board Data Handling (OBDH) and task allocation mechanisms allow for distributed task scheduling and localized data processing, reducing reliance on ground control and enabling responsive payload operation.

Describe DSM Operational Environment

The operational environment (Table 5.10) defines the context in which the mission will be conducted. It includes both the physical and functional conditions that influence spacecraft behavior throughout the mission lifecycle. This environment directly impacts subsystem design, risk assessment, and key systems engineering decisions.

Table 5.10 - Operational Environment.

Parameter	FACSAT-3 Operational Profile
Precision of Operational Ranges	formation maintenance; attitude control within for imaging
Multiple Spacecraft Operation	Up to 3 - 5 satellites operating simultaneously in distributed roles
Spacecraft	Each unit equipped with 3-axis reaction wheels and magnetorquers; basic propulsion for drift correction
Hierarchical Layout	No fixed hierarchy: any satellite can act as lead for tasking based on position and health
Real-Time Decision-Making	Mid-level autonomy; AI-assisted anomaly detection and pre-programmed event response
On-orbit Decision-Making Autonomy	Semi-autonomous; fallback to ground in case of unknown scenarios
Simultaneous Deployment	Multi-satellite ejection from a single launch vehicle or rideshare opportunity
Cooperative Maneuvering	Basic inter-satellite spacing control and formation reconfiguration

Source: Author.

Hazard and Risk Analysis

Given the operational constraints and design drivers of the mission constellation, a risk analysis is essential to ensure mission robustness and subsystem resilience. This analysis identifies potential failure scenarios and system vulnerabilities that could compromise mission objectives, particularly in the context of formation flying and distributed tasking, as shown in Table 5.11.

Table 5.11 - Mission Risk Identification and Classification.

Risk Category	Description	Classification	Mitigation Strategy
Faulty performance	Sensor drift or actuator failure may destabilize formation flying	Medium–High	Fault injection testing, Kalman filter correction, redundancy in sensor suite
Loss of inter-satellite comms	Could lead to unsynchronized tasking and loss of redundancy	High	Autonomous fallback protocols, delayed sync via ground station relay
Power system failure	Impacts payload operation, comms, and orbit keeping	High	Power budget margins, multiple solar panel orientations, onboard power prioritization
Onboard software errors	Real-time decision logic may fail due to bugs or memory overflow	Medium	Use of flight-proven software components, watchdog timers, fault-tolerant OBDH design
Launch deployment failure	Failure of satellite release mechanism	Low–Medium	Mechanical deployment testing, CubeSat deployer redundancy
Ground station unavailability	Data latency and command delays	Medium	Multi-site ground segment design (national and international), onboard data buffering

Source: Author.

Step 5. Define FFS functional requirements

Orbital Conditions

Formation flying missions require precise control of the orbital behavior of each satellite, both individually and collectively. This category encompasses the

functional requirements related to spatial configuration, task execution per orbit, and the physical interaction between formation elements. Compliance with these requirements is essential to ensure harmonious, efficient, and safe operation in dynamic environments such as LEO. Table 5.12 presents these requirements, along with descriptions, involved systems, and the performance parameters to be met.

Table 5.12 - Functional requirements – Orbit conditions.

ID	Functional Requirement	Detailed Description	Involved System	Performance Parameter
FFS-01	Maintain specific relative positions between satellites	Ensure each satellite maintains a defined relative distance within the formation, compensating for disturbances.	GNC	Relative distance between satellites.
FFS-02	Allow dynamic task distribution among satellites	Enable each satellite to autonomously assume specific functions to optimize collective performance.	OBC / Mission	Tasks dynamically assigned by position/orientation; role flexibility by node.
FFS-03	Execute specific tasks per orbit	Perform activities such as image acquisition, calibrations, or maintenance during each orbital pass.	OBC / Payload	observation/calibration task per orbit, execution in min.
FFS-04	Manage shadow (eclipse) effects between satellites	Minimize the impact of shadow zones caused by other satellites on power generation or thermal conditions.	EPS / Thermal	Avoid prolonged eclipses; planning with orbital forecast.

Source: Author.

Communication and Control

The system's ability to coordinate actions, exchange data, and operate autonomously depends on its communication and control subsystems. This category includes functional requirements that allow synchronization, navigation precision, decision-making without ground intervention, and interoperability between satellites. These functions are critical to maintaining formation coherence and responding to changing conditions in real-time, as outlined in Table 5.13.

Table 5.13 - Functional requirements – Communication and control.

ID	Functional Requirement	Detailed Description	Involved System	Performance Parameter
FFS-05	Establish protocols and data transfer windows with Earth	Define communication formats and optimal times for data transmission and command reception.	TT&C / OBC	Transmission windows synchronized by station pass (LEO).
FFS-06	Maintain high precision in position and attitude control	Ensure precise control of satellite position and orientation within the mission-defined margins.	GNC	Position precision in meters, attitude precision degrees
FFS-07	Operate autonomously without ground intervention	Perform tasks autonomously with planning, control, and response capabilities.	OBC / FDIR	Percentage of nominal operations without intervention for at least 1 orbit.
FFS-08	Control both position and attitude simultaneously	Coordinate orientation and translation maneuvers based on formation and mission requirements.	GNC	Combined orientation and translation error in percentage of orbital tolerance.
FFS-09	Synchronize maneuvers between satellites	Coordinate maneuvers between satellites via inter-satellite links to maintain formation coherence.	ICS / OBC	Latency between satellites in seconds, real-time maneuver synchronization.
FFS-10	Allow flexible adjustments of relative and absolute positions	Modify the position of a satellite without affecting the overall system geometry, enabling controlled individual maneuvers.	Propulsion	Adjustment range and maneuver resolution in meters.

Source: Author.

Risk and Safety

Given the hostile and congested environment of space, it is crucial to consider risk factors that could jeopardize the mission. This category includes functional requirements aimed at mitigating environmental disturbances, such as atmospheric drag or solar radiation, and preventing collisions through detection and maneuvering capabilities. Its implementation enhances operational sustainability and protects the integrity of the involved space assets, as shown in Table 5.14.

Table 5.14 - Functional requirements – Risk and Hazard.

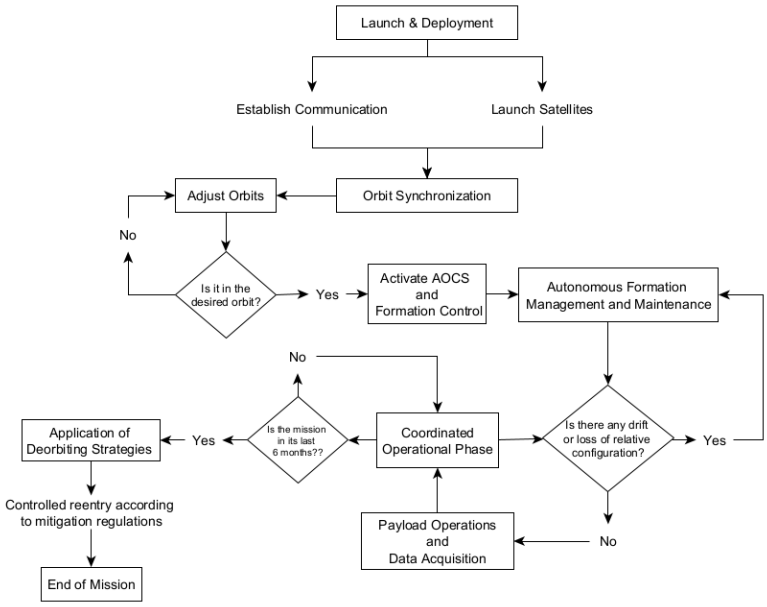
ID	Functional Requirement	Detailed Description	Involved System	Performance Parameter
FFS-11	Mitigate environmental disturbances	Compensate for atmospheric drag, solar radiation, and gravitational disturbances with adaptive control.	Sensors	Predictive models for drag and solar radiation; adaptive control.
FFS-12	Implement collision risk management	Detect potential collisions and execute safe evasion maneuvers based on predictions.	OBC / TT&C	Automated evasion capability; trajectory prediction software.

Source: Author.

Step 6. Propose life cycle development plan

The next figure illustrates the conceptual life cycle flow for the FACSAT-3 autonomous formation flying mission, outlining the high-level phases from launch to deorbiting. It highlights the key operational transitions, beginning with deployment, orbit synchronisation, with formation control. The diagram captures the iterative nature of formation maintenance, showcasing autonomous adjustments in response to deviations in relative configuration. It also reflects the progression into the coordinated operational phase, during which mission-specific payload tasks are executed. Finally, the diagram accounts for mission closure, incorporating deorbiting strategies in compliance with space debris mitigation standards. This visual representation serves as a structured reference for the system's life cycle architecture, prior to subsystem-level decomposition.

Figure 5.3 - Life cycle development plan.



Source: Author.

Step 7. Propose DSM logical decomposition

The logical decomposition table (Table 5.15) presents a structured representation of the hierarchical architecture supporting the Colombian FACSAT-3 FFS, aligned with DSM principles. It organises the system into five distinct hierarchical levels: Mission, System, and the Space, Ground, User, and Communication Segments.

Each level captures key architectural functions and associated components, ensuring full traceability from national-level strategic objectives to subsystem implementation. Special attention is given to the ISL, which serves as a fundamental integration point for maintaining synchronization across the distributed architecture. The table reflects how subsystems such propulsion, power and thermal control, payload, and communication systems are integrated across spaceborne and terrestrial segments to enable autonomous formation control and collaborative operations. This decomposition supports role allocation, interface definition, and system-level coherence throughout the mission lifecycle.

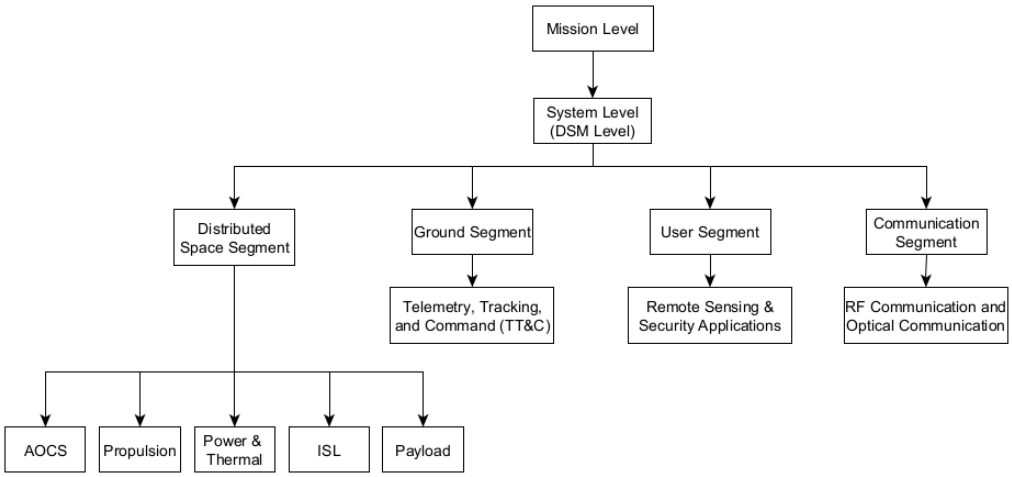
Table 5.15 - Logical decomposition table.

Hierarchy Level	Description	Associated Components
Mission Level	Defines strategic objectives, stakeholder needs, and overall goals of the FACSAT-3 formation flying mission.	National security, Earth observation, collaborative satellite operations.
System Level (DSM)	Manages coordination logic, autonomy strategy, and distributed architecture among satellites in formation.	FFS, ISL.
Space Segment	Physical layer comprising satellites and their onboard subsystems responsible for formation maintenance and payload operation.	Propulsion, Power & Thermal, ISL, Payload.
Ground Segment	Enables telemetry, command, and control from mission control centres; ensures mission safety and performance monitoring.	TT&C
User Segment	Processes and interprets mission data for end-user applications, especially in the national security and remote sensing domains.	Remote sensing terminals, data analytics units, security analysis systems.
Communication Segment	Provides high-bandwidth and resilient communication infrastructure for inter-satellite and satellite-to-ground links.	RF Communication, Optical Communication.

Source: Author.

The DSM logical decomposition diagram visually, shown in the Figure 5.4, represents the architecture of the FACSAT-3 FFS, illustrating how mission components are structured and interrelated within a distributed operational environment. At the top, the Mission Level defines strategic drivers, which cascade into the System Level that implements the DSM logic.

Figure 5.4 - DSM logical decomposition diagram.



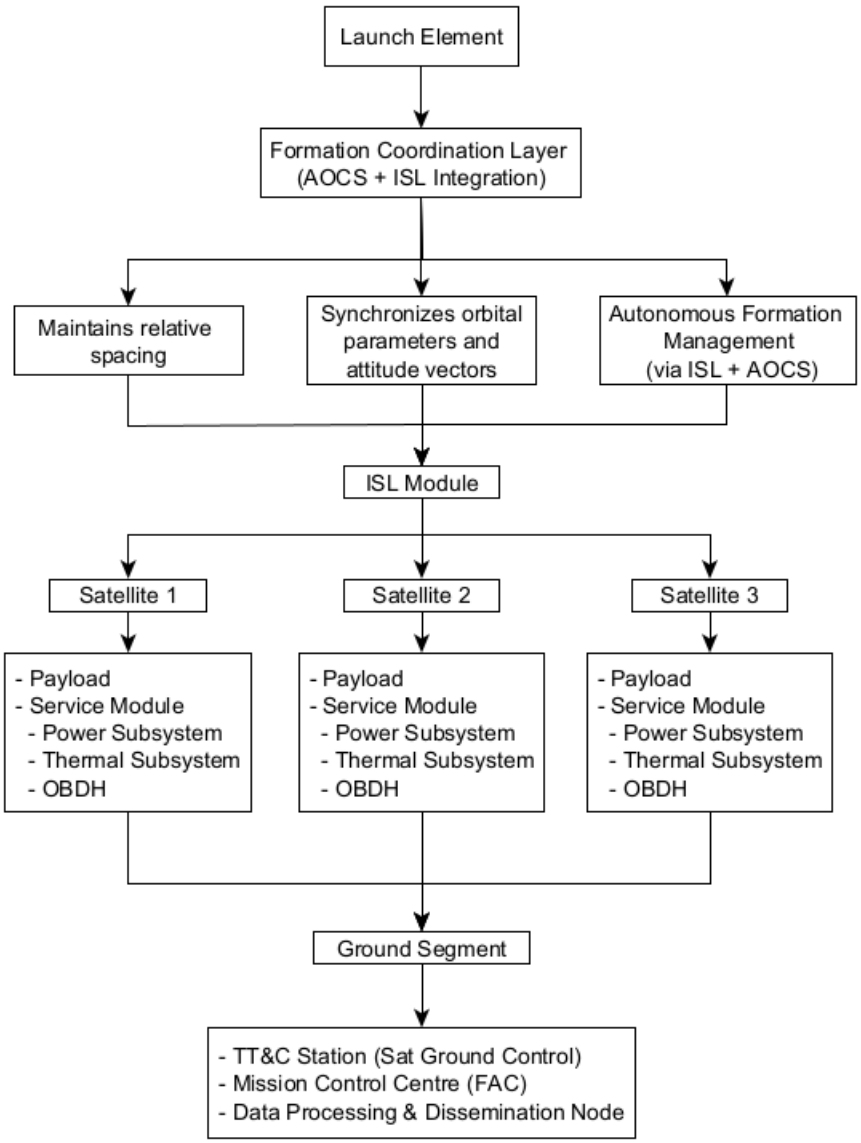
Source: Author.

The diagram then branches into four core system segments: Space, Ground, User, and Communication. Within the Space Segment, the decomposition reveals essential highlighting their roles in formation maintenance and distributed autonomy. The Communication Segment includes RF and optical links, enabling both satellite-to-ground and satellite-to-satellite communication. Ground control and user interaction are defined via TT&C and remote sensing applications. This diagram serves to clarify subsystem integration points and reinforce the coordinated functionality required in FFS architectures.

Propose individual architectures per project

The mission architecture diagram illustrated in the Figure 5.5, the hierarchical structure of the FACSAT-3 Formation Flying System, integrating launch, space, and ground segments to support autonomous, coordinated satellite operations. Following launch, the formation coordination layer manages orbit synchronisation, attitude alignment, and relative positioning among the satellites. Each satellite includes standard subsystems (payload, service, power, thermal, OBDH) and interacts through the ISL module to maintain formation geometry and enable autonomous control. The ground segment, featuring the TT&C station, the Colombian Air Force Mission Control Centre, and a data processing node, ensures command, monitoring, and information dissemination.

Figure 5.5 - Hierarchical structure of the FACSAT-3.

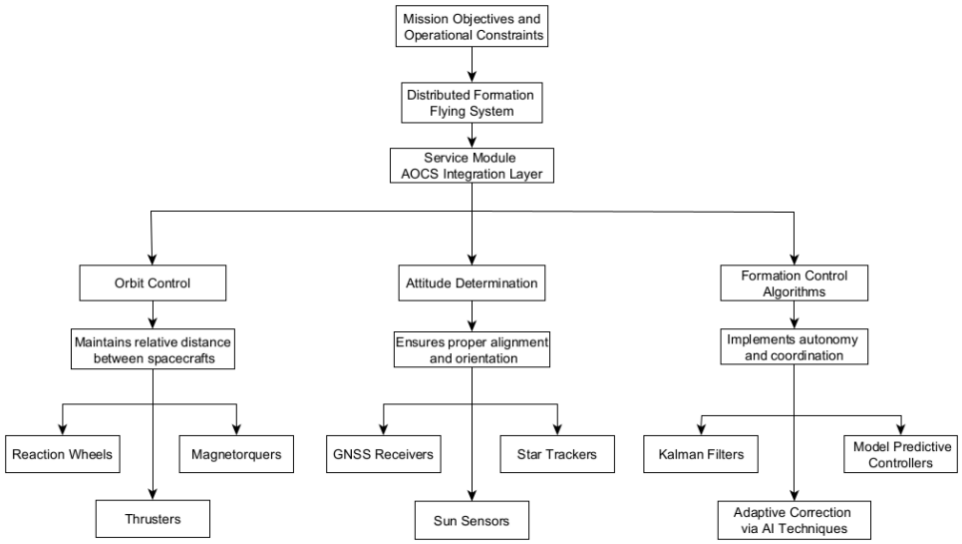


Source: Author.

Propose distributed architecture

The Figure 5.6 illustrates the distributed control architecture embedded within the integration layer of the FACSAT-3 FFS. This architecture decomposes the core functions required to maintain relative positioning, synchronise orbital elements, and execute autonomous coordination across multiple satellites. The Service Module's is structured around three primary domains: Orbit Control, Attitude Determination, and Formation Control Algorithms.

Figure 5.6 - Distributed architecture of the FACSAT-3 mission.



Source: Author.

These domains rely on specialised hardware such as reaction wheels, GNSS receivers, and sun sensors, as well as advanced algorithms like Kalman filters and model predictive controllers. At the heart of this distributed scheme is a harmonised design strategy that enables each satellite to operate independently while conforming to shared operational rules defined by the ISC and ISL requirements. The result is a resilient and adaptable architecture capable of sustaining coordinated autonomy in low Earth orbit missions.

Propose the model integration points

The integration points defined in the distributed architecture of the FACSAT-3 FFS serve as critical junctions that ensure consistency, synchronisation, and interoperability across individual satellite platforms and the mission as a whole. These points enable each subsystem to operate in concert with others, maintaining tight formation control, real-time data exchange, and autonomy-aware coordination.

Furthermore, integration points align system models with mission requirements, ensuring interoperability and enhancing system robustness in demanding operational environments. The key integration points of DSM architecture are detailed in Table 5.16.

Table 5.16 - Logical decomposition table.

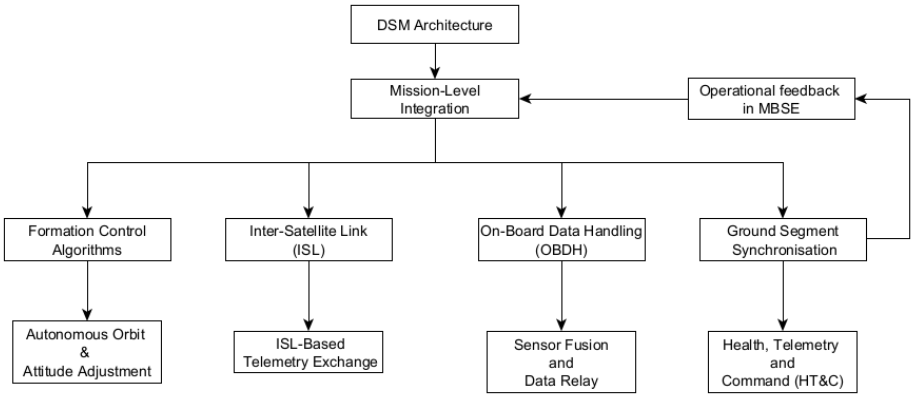
Integration Point	Functionality
Inter-Satellite Link (ISL)	Enables real-time communication for synchronising orbital positions, attitude data, and distributed control across FACSAT-3 satellites.
AOCS (Attitude and Orbit Control System)	Ensures tight formation-keeping for the constellation, aligning spacecraft attitudes for coordinated observations and manoeuvres.
Formation Control Algorithms	Manages relative positioning and trajectory planning using onboard autonomy, optimising propellant use and maintaining mission geometry.
On-Board Data Handling (OBDH)	Consolidates sensor and payload data onboard each satellite, preparing packets for ISL relay or downlink to the ground control node.
Ground Segment Synchronisation	Aggregates distributed mission data, monitors health/status, and uplinks command updates based on constellation-wide performance metrics.

Source: Author.

The following figure illustrates the architectural framework that supports mission-level integration across the FACSAT-3 constellation. At the core of this structure is the integration layer that harmonises subsystem functionalities from each satellite with the overarching mission objectives.

Key integration points include formation control algorithms, ISL, OBDH, and ground segment synchronization each enabling autonomous coordination, telemetry exchange, data fusion, and operational monitoring. Notably, the architecture incorporates an operational feedback loop into the process, ensuring iterative refinement based on system performance and evolving needs. Complementing this, the accompanying table outlines the specific functionality of each integration point. Together, they provide a comprehensive systems engineering perspective on how satellite coordination, on-board management, and ground operations are seamlessly orchestrated to reinforce mission robustness and precision.

Figure 5.7 - Distributed architecture of the FACSAT-3 mission.

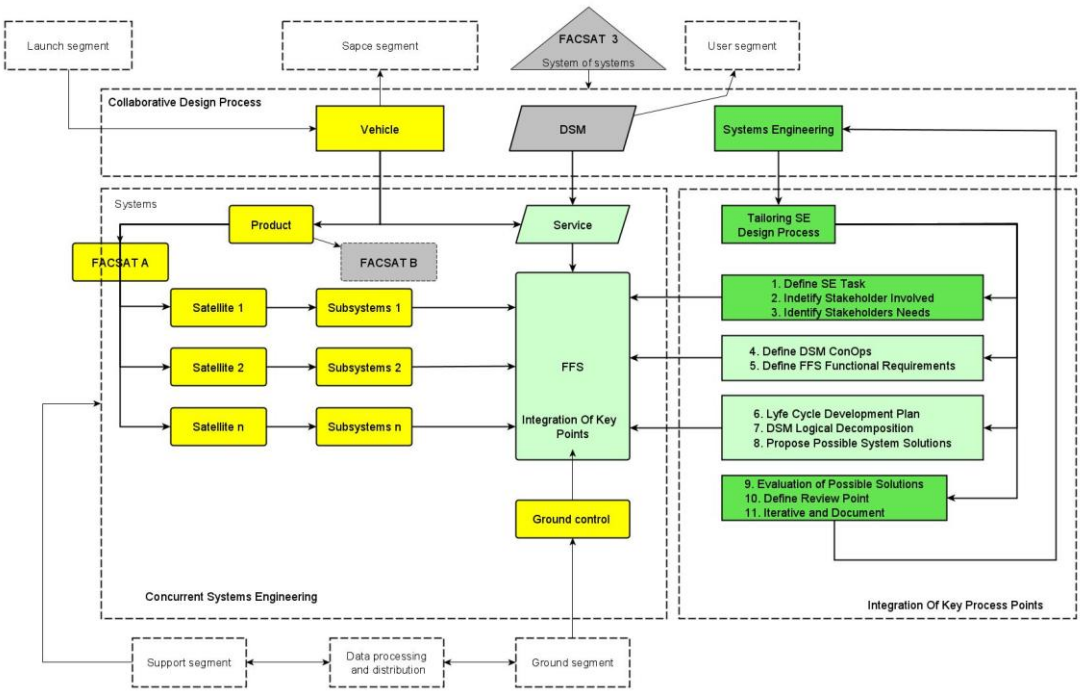


Source: Author.

Step 8. Propose possible system solutions and ConOps

The Figure 5.8 illustrates the proposed inter-satellite communication and coordination framework for the FACSAT-3 mission. This operational concept (ConOps) supports the distributed architecture of the constellation by defining clear roles, data flows, and coordination mechanisms among the satellites. It serves as a system-level solution that integrates orbital guidance, synchronised payload operation, and autonomous control.

Figure 5.8 - Model Integration.



Source: Author.

The constellation is organised hierarchically under a distributed Formation Flying System (FFS) paradigm:

- Leader Satellite: Functions as the coordination hub, interfacing with the ground segment via X-band (for TT&C) and Ka-band (for payload data), calculating the reference orbital parameters, and broadcasting synchronisation commands to the follower satellites;
- Follower Satellites: Operate semi-autonomously by receiving trajectory and attitude data via the ISC system;
- ISL: Enables low-latency communication (under 1 second), ensuring precise synchronisation for orbital alignment, attitude control, and coordinated data acquisition. The ISL also supports distributed decision-making and redundancy in control logic.

The data delivery process is underpinned by an OBDH architecture capable of fusing and relaying information from multiple sensors, synchronising payload tasks, and optimising downlink scheduling based on mission priorities. Software

modules across the satellites implement a service-oriented architecture that allows for distributed control, diagnostics, and payload coordination.

The proposed ConOps establishes a clear contrast between the current baseline ("as-is")—where each satellite functions independently with manual coordination—and the envisioned FACSAT-3 system ("as-it-would-be"), which features enhanced autonomy, dynamic synchronisation, and integrated ground interaction. This evolution enables more efficient use of resources, improved resilience in formation management, and higher precision in coordinated Earth observation tasks.

Identify satellite relationship

In the FACSAT-3 FFS, the relationship between satellites is governed by mission-specific drivers that emphasise autonomy, collaboration, and synchronisation within a DSM framework. The constellation, comprising a leader satellite (FACSAT-3) and two follower satellites, is designed to fulfil shared mission objectives while maintaining operational independence and precise formation geometry.

Each satellite is required to:

- Operate autonomously, with the capability to support its subsystems without constant intervention from the ground segment;
- Collaborate with other members of the formation via ISL, enabling real-time exchange of navigation and synchronisation data;
- Maintain and adapt their relative positioning within the constellation, meeting the FFS requirement of positional accuracy (e.g., ±10 m) through feedback loops;
- Reconfigure dynamically, adjusting spacing or orientation in response to mission phase transitions, anomalies, or task-specific demands (e.g., distributed payload operations or imaging campaigns);
- Contribute to the collective autonomy of the constellation by sharing state estimations and control updates, enabling decentralised decision-making in line with formation control algorithms;

- Maintain an independent free-flight capability, ensuring each unit can execute contingency manoeuvres or isolate from the formation if necessary;
- Adhere to a standardised size and interface definition, enabling compatibility with launch and integration infrastructure, and harmonised subsystem interaction.

A designated leader satellite is tasked with acting as the primary communication node with the ground station, using dual-band transmission (Ka for payload data and X for TT&C). This spacecraft also plays a central role in maintaining uplink coordination and serving as the gateway for downlinking synchronised mission data collected by the constellation.

Define Satellite Hierarchy

The FACSAT-3 FFS adopts a single-leader hierarchical architecture, in which FACSAT-3 functions as the primary coordination node for the constellation. This structure enables an efficient balance between centralised oversight and distributed autonomy, aligning with the mission's operational demands for precision, synchronisation, and responsiveness.

Within this hierarchy:

- FACSAT-3 (Leader Satellite) is responsible for global constellation coordination. It establishes the baseline orbital reference frame, distributes synchronisation updates, and interfaces directly with the Ground Segment via Ka-band (payload) and X-band (TT&C) channels. The leader also processes uplinked mission commands and disseminates them to the follower satellites through the Inter-Satellite Link (ISL);
- Follower Satellites (Satellites 2 and 3) operate semi-autonomously, adjusting their position and orientation based on the reference and commands from the leader. These satellites contribute to distributed sensing and data collection, while relying on the ISL for state sharing, synchronisation, and formation adjustments.

This centralised coordination with distributed execution supports:

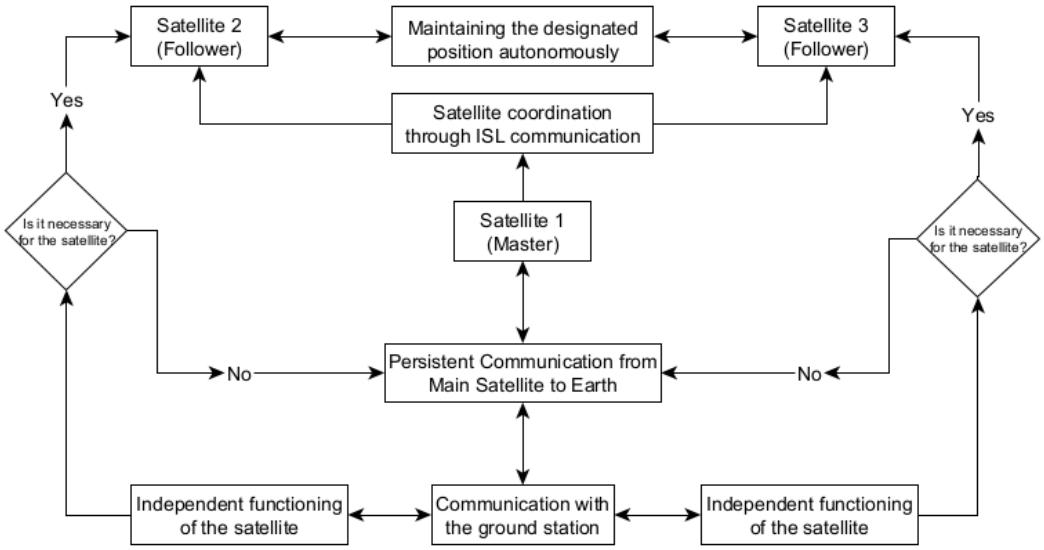
- High responsiveness to dynamic mission demands (e.g., formation reconfiguration, anomaly handling);
- Robustness, since follower satellites can retain autonomy if temporary disconnection from the leader occurs;
- Scalability, as new elements could be integrated with minimal architecture modification under the same hierarchy pattern.

The chosen hierarchy model ensures clear decision-making flow, minimises communication overhead, and supports efficient resource allocation. At the same time, autonomous onboard capabilities embedded in the formation control algorithms ensure that all satellites maintain operational integrity even during degraded communication scenarios.

This configuration aligns with the DSM paradigm, where mission-level objectives are achieved through the coordinated effort of independently operable units. The hierarchical structure of FACSAT-3 maximises mission assurance while accommodating future upgrades, such as adaptive re-hierarchisation in response to environmental or technical changes, as foreseen in more advanced MBSE-driven architectures.

Figure 5.9 illustrates the mission hierarchy in operation. It shows how the main satellite (Satellite 1) is responsible for maintaining constant communication with the ground station and coordinating the secondary satellites. However, the secondary satellites also have their own ground link, which can be activated if individual operation is required.

Figure 5.9 - Mission Communication Hierarchy.



Source: Author.

The diagram also reflects the decision path wherein each follower satellite determines, based on operational context or mission demand, whether coordination through ISL is necessary at a given moment. If not, it defaults to independent functioning. This logic supports dynamic reconfiguration, robustness, and energy-efficient behaviour in line with DSM principles.

Thus, this communication hierarchy ensures:

- Persistent central coordination without creating a single point of failure.
- Scalable autonomy, adaptable to various mission scenarios;
- Efficient communication, with differentiated channels (e.g., X-band for TT&C, Ka-band for payload data);
- Seamless ISL-based synchronisation, key to maintaining formation integrity.

Define ISC system

The Inter-Satellite Communication (ISC) system for the FACSAT-3 formation flying mission is essential to ensure coordination, synchronisation, and data flow across the constellation. The ISC supports autonomy, formation stability, and

communication with the ground station through the designated master node. Its definition integrates the following components:

Network Topology

- Hierarchical (Leader-Follower): One satellite serves as the master node, managing coordination with the follower satellites;
- Redundant Links: Although hierarchical, redundant links between followers are enabled for emergency coordination and resilience;
- Scalable Design: Topology allows for future satellite addition or replacement without reconfiguring the entire network.

Transmission Capabilities

- Minimum Data Rate: 1 Mbps for telemetry, synchronisation, and control;
- Latency Requirement: <1 second to maintain accurate relative positioning and synchronised operations;
- Operating Bands: S-band for general telemetry and control; X-band and Ka-band for payload data downlink to ground.

Hardware Components

- Miniaturised Transceivers: Optimised for CubeSat-class platforms with low SWaP (Size, Weight, and Power) constraints;
- Patch and Directional Antennas: Enable line-of-sight tracking between satellites in formation;
- Low-Noise Amplifiers (LNA): Ensure strong signal reception in noisy orbital environments.

ISC Communication Models

- Master-Slave Communication Model
    - The master satellite manages timing, formation logic, and relays ground commands;
    - Benefits: Centralised coordination, simplified routing;
    - Challenge: Single point of failure; mitigated by backup communication logic in follower satellites.

- Point-to-Point (P2P) Model (Backup)
    - Used for redundancy and local data exchange between followers if needed.

Communication Protocols

- Data Link Layer
    - CCSDS Protocol: Enables standardised data packaging and reliable delivery;
    - TDMA (Time Division Multiple Access): Allocates time slots to avoid signal collision and optimise channel use.
- Network and Transport Layers
    - DTN (Delay-Tolerant Networking): Handles intermittent connectivity and dynamic routing;
    - UDP/TCP: Used selectively based on reliability and time sensitivity of the data.

ISC Implementation and Security

- Authentication: Secure access control using symmetric key-based cryptographic authentication;
- Encryption: AES-256 encryption for all inter-satellite and satellite-to-ground communications;
- Fault Tolerance: Autonomous re-routing capabilities and cross-link redundancy to ensure continuous communication in the event of node failure.

Define data delivery process

At the heart of this process is the OBDH system of each satellite, which integrates telemetry collection, command execution, sensor fusion, and communication management. The OBC unit within the OBDH is responsible for real-time operations such as:

- Monitoring thermal and power conditions;
- Executing control commands from the ground station;

- Processing synchronisation signals and navigation data from other spacecraft.

In this formation, Satellite 1 (Leader) assumes centralised uplink coordination responsibilities, receiving mission-level commands from the ground and relaying task assignments and synchronisation cues to the follower satellites via ISL. The follower satellites (FACSAT-3B and 3C) respond by adjusting their position and collecting synchronised observations.

Key components of the data delivery process include:

Functional Segmentation of OBDH Subsystems

- Housekeeping Computer (HKC): Monitors system health and status;
- Payload On-Board Computer (POBC): Handles data from imaging or sensing instruments;
- Internal Data Storage (IDS): Temporarily buffers mission data until downlink windows;
- Attitude Determination and Control Computer (ADCC): Executes tasks using data received from the ISL and onboard sensors;
- Time-Tagged Command (TTC) Executor: Manages pre-programmed operations for autonomous control between communication windows.

Software Architecture

- Common Software Core: All spacecraft operate on a synchronised software baseline to ensure compatibility in inter-satellite communication and processing;
- Flight Software Updates: Capable of accepting updates from the ground or generating onboard reconfiguration via predefined logic;
- Fault Management: Includes embedded routines for error detection, correction, and task reassignment among satellites if anomalies occur;
- On-Orbit AI Integration: Machine learning models support adaptive behaviour, such as optimised data routing and anomaly prediction.

Data Flow Mechanism

- Upstream (Ground to Satellites): High-level mission commands are up linked via X-band to Satellite 1, then distributed via ISL;
- Lateral (Inter-Satellite): Synchronisation signals, navigation parameters, and collaborative task updates are exchanged between satellites;
- Downstream (Satellites to Ground): Payload data from all satellites is relayed to the leader for packaging and transmission via Ka-band to the ground station.

Synchronisation and Control

- The formation relies on time-stamped messages, synchronised clocks, and deterministic task windows to ensure coherent operations;
- The ADCC on each satellite cross verifies inputs from other spacecraft to maintain coordinated attitude and orbit control.

Step 9. Propose the evaluation of possible system solutions and ConOps

To ensure the selection of the most suitable configuration for the FACSAT-3 FFS, a structured decision-making process will be implemented based on a multi-criteria decision analysis (MCDA) framework. This methodology allows for an objective comparison of alternative system architectures and ConOps, integrating both quantitative performance indicators and qualitative expert assessments.

Definition of Mission Alternatives

A range of feasible architectural and operational configurations for the FFS will be identified:

- Satellite Formation Patterns: Linear configuration, equilateral triangular array, adaptive spacing;
- Architectures: Fully decentralised, centralised leader-follower, hybrid supervisory control;
- ISL Models: Point-to-point, full mesh, hierarchical.

Establishment of Evaluation Criteria

Each alternative will be assessed using mission-driven evaluation metrics, including:

- Formation-Keeping Accuracy (e.g., maintaining < ±10 m of baseline separation);
- Level of Autonomy (degree of onboard decision-making and fault handling);
- Communication Performance (minimum 1 Mbps bandwidth, <1 s latency);
- Energy Efficiency (daily consumption per satellite ≤ 20 Wh/day);
- System Complexity and Scalability;
- Ground Segment Dependence;
- Implementation Feasibility (technical readiness, manufacturing constraints);
- Compliance with Space Standards (e.g., ISO/IEC 15288, ITU-R regulations);

Weight Assignment Using AHP

An Analytic Hierarchy Process (AHP) will be applied to derive the relative importance of each criterion:

- Stakeholders and mission planners will conduct pairwise comparisons of criteria;
- Consistency ratio (CR) checks will be used to validate judgment coherence;
- Tools such as MATLAB AHP scripts or Expert Choice will support computation;

Development of an Evaluation Matrix

A Pugh matrix will be developed, scoring each architectural alternative against all criteria:

- Alternatives will be scored on a standardised scale (e.g., 1–5), multiplied by their assigned weights;

- The weighted scores will be summed to generate a final fitness value for each option;
- This allows a clear, traceable comparison of architectural configurations.

1.1.1. Simulation-Based Performance Validation

The top-ranked alternatives will undergo simulation using software environments such as MATLAB/Simulink, Systems Tool Kit (STK), or GMAT, to validate:

- Relative orbit control performance and long-term stability;
- Attitude pointing accuracy under perturbations;
- Inter-satellite communication latency and throughput;
- Power system efficiency across operational modes;

Cost-Benefit and Risk Analysis

Each candidate solution will be subjected to:

- Cost Analysis: Comparing implementation, launch, and operational costs vs. mission value;
- Robustness Assessment: Employing Monte Carlo simulations and FMEA to evaluate tolerance to failure and mission continuity under degraded modes;
- Risk Mitigation Strategies: Proposing contingency architectures and redundancies where necessary.

1.1.2. Decision and Justification

The configuration with the highest total score and acceptable simulation outcomes will be selected as the baseline system solution. The selection process will conclude with a formal decision report, including:

- Justification of the selected option based on mission criteria;
- Traceable decision logic and evaluation artefacts;
- Defined fallback options and reconfiguration strategies in case of unforeseen challenges.

Define compliance measures

To ensure alignment with international standards and mission-specific constraints of the FACSAT-3 FFS, a tailored compliance framework has been established. This framework is grounded in the ECSS tailoring matrix for Space Product Types and reflects the operational conditions, scale, and collaborative nature of small satellites in LEO. It focuses on three key regulatory domains:

Space Systems Engineering Standards

- ECSS-E-ST-10C: Adopted to guide the engineering process across the mission lifecycle;
- ISO/IEC 15288: Used to ensure traceability from stakeholder needs to system implementation;
- NASA SE Handbook (2016): Consulted for best practices in systems integration, testing, and validation.

Space Debris Mitigation

- UNOOSA Guidelines: Followed for orbital disposal and long-term debris mitigation strategies;
- NASA Orbital Debris Mitigation Standard Practices (ODMSP) and ESA Guidelines: Used to develop end-of-life and deorbit plans for each spacecraft in the formation.

Satellite Communications and Security

- ITU-R and CCSDS Standards: Ensure compliance with spectrum allocation, data transmission protocols, and ISL interoperability;
- Security Protocols: Data encryption, authentication mechanisms, and fault tolerance mechanisms are applied to support mission continuity and protect sensitive data.

The following compliance matrix presents a tailored selection of ECSS standards applicable to the FACSAT-3 FFS.

Each requirement has been evaluated for its relevance to the small satellite context, ensuring efficient alignment with the mission's operational environment in LEO. Tailoring decisions are justified based on mission constraints, and validation methods are defined to ensure traceability, accountability, and regulatory compliance throughout the system lifecycle.

Table 5.17 - ECSS Tailoring Compliance Matrix.

ECSS Ref	Requirement Summary	Applicability	Tailoring Notes	Validation Method	Compliance Status
ECSS-E-ST-10-02	Functional decomposition of system architecture	Applicable	Aligned with DSM/FFS structure	SysML modelling	Planned
ECSS-Q-ST-40	Safety risk analysis	Tailored	Adjusted for LEO small satellite mission	FMEA, expert review	In Progress
ECSS-E-ST-10-06	System verification planning	Applicable	Full verification and validation lifecycle	V&V matrix, simulation	Planned
ECSS-U-ST-20	Communication interoperability	Applicable	ISL & ISC validated with CCSDS protocol	Protocol testing	Pending
ECSS-E-ST-35-11	Deorbit strategy and space debris mitigation	Applicable	5-year post-mission disposal compliance	STK simulation	Verified

Source: Author.

The Table 5.18 is validation matrix that outlines the critical performance requirements for the FACSAT-3 mission and the methods by which they will be verified. Each requirement is linked to its corresponding system functionality such as formation maintenance, autonomy, or communication and is assessed through simulation, testing, or subsystem analysis.

The matrix supports the mission’s assurance strategy by identifying responsible teams, tracking progress, and ensuring that all system behaviours are consistent with mission objectives.

Table 5.18 - Mission Requirements Validation Matrix.

Requirement ID	Requirement Description	Validation Method	Verification Status	Responsible Team
REQ-01	Maintain satellite formation with deviation in meters	STK simulation, telemetry analysis	Planned	GNC Team
REQ-02	Achieve attitude control precision in degrees	Hardware-in-loop test, MATLAB/Simulink	In Progress	Control Team
REQ-03	Power consumption in Wh/day per satellite	Power budget analysis, testbed validation	Planned	Power Subsystem
REQ-04	Inter-satellite link in 1 Mbps, latency in seconds	Communication subsystem test bench	Planned	Comm Subsystem
REQ-05	Revisit frequency in hours	Orbital simulation (STK)	Pending	Mission Analysis
REQ-06	performance within deviation from design models	Simulation vs. model comparison	Planned	Verification
REQ-07	Autonomous formation flight for in months	Fault injection testing, autonomy test campaign	Planned	Autonomy Team
REQ-08	Satellite deorbits in years after end of mission	Deorbit trajectory analysis	Verified	Systems Engineering

Source: Author.

Step 10. Define the Review Points for the Validation of the System Solution and ConOps

To ensure traceable, systematic progress throughout the FACSAT-3 FFS development, a structured validation framework based on formal review points is established. These review milestones serve as critical checkpoints for evaluating compliance, assessing system performance, and verifying alignment with the mission objectives and ConOps.

The decision-making and validation process integrating decision analysis principles to support informed trade-offs, risk management, and design evolution.

Four key technical reviews are adopted in the context of FACSAT-3:

- MCR: Confirm the mission objectives, initial concept of operations, and strategic need for a formation flying system;
- SRR: Validate system-level requirements derived from stakeholder needs, including formation-keeping precision, communication latency, autonomy level, and power constraints;

- MDR: Refine the mission architecture and operational concept, integrating subsystem interactions, ISL/ISC specifications, and hierarchy models;
- SDR: Assess the completeness of system-level design, including ICDs, software architecture, and validation plans.

At each review, a descriptive report will be generated, including evaluation criteria, identified non-conformities or gaps, recommendations and corrective actions, and the rationale behind any design or requirement adjustments. This documentation ensures traceability and supports iterative refinement, enhancing both system integrity and project governance.

To formalize this approach, Table 5.19 presents the review points to be implemented throughout different stages of the project.

Table 5.19 - Review Points Across Different Project Phases.

Review Point	Purpose	Key Assessment Criteria	Deliverables
System Concept Review (SCR)	Validate the feasibility of the FACSAT-3 mission concept.	Mission objectives, operational feasibility, initial risk profile	Concept Definition Document, Feasibility Study
System Requirements Review (SRR)	Ensure system requirements align with stakeholder needs and mission goals.	Completeness, traceability to mission objectives, feasibility	Requirements Specification, Traceability Matrix
Preliminary Design Review (PDR)	Validate initial distributed architecture and ConOps.	Subsystem interaction, ISL/ISC architecture	Preliminary Design Document, ConOps Analysis
Critical Design Review (CDR)	Confirm system maturity before implementation.	Compliance with technical specifications, risk mitigation	Final Design Report, Updated ConOps
Test Readiness Review (TRR)	Verify system readiness for integration and validation.	Test procedures, fault management, subsystem validation	Test Campaign Plans, Validation Reports
Operational Readiness Review (ORR)	Confirm readiness for launch and operational deployment.	Deployment readiness, operational contingency planning	Mission Operations Handbook, Final ConOps
End-of-Life Review (ELR)	Ensure compliance with deorbit and sustainability requirements.	Space debris mitigation strategy, post-mission disposal plan	Deorbit Plan, ECSS/NASA Compliance Documentation

Source: Author.

Each phase includes tailored assessment methods and expected deliverables to ensure the system solution and ConOps meet operational and performance expectations.

To reinforce consistency and objectivity during validation, Table 5.20 summarizes the evaluation framework applied to each phase. These categories allow for

structured assessments of performance, alignment, and compliance using both qualitative and quantitative methods.

Table 5.20 - Evaluation Framework for System and ConOps Validation.

Category	Assessment Factors	Evaluation Method
Mission Alignment	Does the architecture meet the FACSAT-3 mission objectives?	Requirements traceability analysis
Technical Feasibility	Are subsystems meeting expected performance and reliability?	Simulation tests, hardware-in-the-loop validation
Risk Mitigation	Are failure modes and fault tolerance adequately addressed?	Monte Carlo simulations, FMEA
Operational Efficiency	Is the proposed ConOps optimised for autonomy and resource usage?	Power simulations, performance assessment
Regulatory Compliance	Does the system meet ECSS, ISO, and debris mitigation guidelines?	Expert audits, validation matrix reviews

Source: Author.

Step 11. Iterate and document

For the FACSAT-3 FFS, an iterative approach is essential to ensure continuous improvement in autonomy, synchronisation, and orbital stability across the satellite constellation. This method allows all system elements ranging to inter-satellite communication to be refined based on simulation outcomes, performance benchmarks, and stakeholder feedback.

The iteration process is designed to validate system functionality, integrate identified improvements, and document each refinement stage. It enables traceability of changes, facilitates alignment with ECSS, and guarantees compliance with international space regulations. Through progressive cycles of testing, analysis, and adjustment, the mission's final configuration is optimized to meet both technical requirements and operational expectations.

Below is a breakdown of the structured iteration workflow proposed for the FACSAT-3 mission:

Define Iteration Objectives

- Identify the target subsystem or process under assessment (e.g., ISL, OBDH);
- Establish measurable performance thresholds (e.g., ±10 m relative positioning, <1° attitude error, <1 s latency).

Execute Simulations and Tests

- Use platforms such as MATLAB/Simulink and STK to simulate control behaviour, data flow, and orbital dynamics;
- Validate the ISC system under nominal and degraded conditions;
- Evaluate system response under failure modes (e.g., node dropout, communication loss).

Analyse the Results

- Compare output against mission requirements and theoretical benchmarks;
- Identify performance gaps:
    - Control deviations → return to design step;
    - Communication faults → adjust ISC configuration;
    - Energy inefficiency → revise power subsystem algorithms;
- Update success metrics and document iteration impact.

Adjust Design and Models

- Implement control logic corrections, optimize software architecture, or reconfigure constellation geometry;
- Introduce redundancy where necessary to improve system robustness;
- Enhance autonomy levels using AI-assisted adjustments, if applicable.

Document the Iteration

- Record all modifications to system components (e.g., software, command structure, hardware settings);
- Update requirement traceability matrices and compliance reports;

- Generate a dedicated iteration report that includes:
    - Objectives and success criteria;
    - Test results and deviations;
    - Corrective actions;
    - Compliance status;
    - Stakeholder recommendations.

To ensure consistency, transparency, and continuous improvement throughout the project lifecycle, the following documentation strategy is proposed:

Table 5.21 - Documentation Control and Version Management.

Category	Tool Name	Purpose
Document Control	Confluence, SharePoint	Centralized document management and collaborative editing
Version Control	Git, Bitbucket	Tracking design changes and system iterations with version tags
Compliance Monitoring	DOORS, Jama Connect	Requirement traceability and standards validation
Risk Management	FMEA, Fault Tree	Identify potential failure modes and implement mitigation strategies
Simulation & Testing	MATLAB, Simulink, STK	System performance validation and behavior modelling

Source: Author.

Expected Outcomes of Each Iteration

The iterative process implemented for the FACSAT-3 FFS ensures continuous refinement and validation of system elements across all mission phases. Each iteration cycle is structured to yield specific deliverables and establish clear stopping conditions that confirm progress and maturity. This guarantees that the development evolves systematically, maintaining alignment with mission requirements and technical feasibility. The expected outcomes for each phase of the iteration are as follows:

Requirements Validation

This phase ensures that all mission, functional, and technical requirements are fully aligned with stakeholder expectations, environmental constraints, and regulatory guidelines applicable to small satellite formations in LEO.

- Deliverables:
    - Updated System Requirements Document;
    - Traceability matrix linking requirements to mission objectives and ECSS/ISO standards;
    - Preliminary compliance evaluation against tailored space regulations and standards.
- Stop Condition:
    - All requirements are validated, unambiguous, traceable, and consistent with the mission scope and operational environment.

Design Refinement

This phase focuses on updating and optimising the system architecture and ConOps, ensuring subsystem compatibility, efficient resource allocation, and synchronisation within the constellation.

- Deliverables:
    - Revised system architecture models (e.g., functional, physical, logical);
    - Trade-off analysis reports addressing subsystem alternatives (e.g., communication topology, autonomy levels);
    - Updated ICDs and design specifications.

- Stop Condition:
    - The design is stable, with all major trade-offs resolved and no critical redesigns pending.

System Integration

This stage validates the functional and physical integration of all onboard subsystems (OBDH, communication, energy, payload) and confirms their interoperability within the satellite and across the formation.

- Deliverables:
    - System Integration Report, detailing integration results and detected anomalies;

- Verification of the ISL and synchronisation protocols;
- Evaluation of distributed autonomy and coordination performance.

- Stop Condition:
  - All subsystems interact as expected within the integrated environment, without critical communication, command, or timing failures.

Final Validation and Review

This phase certifies that the integrated system meets all mission requirements, satisfies regulatory obligations, and is fully ready for operational deployment.

- Deliverables:
  - Final System Verification Report with validation results, model comparisons, and test outcomes;
  - Launch Readiness Assessment, including environmental, thermal, and electromagnetic compliance;
  - Updated compliance matrix with final status on all tailored ECSS and ISO standards.
- Stop Condition:
  - All mission objectives, constraints, and performance metrics have been met or exceeded, and the system is formally cleared for launch and operations.

5.2 TOM/TIM mission

Mission

The mission aims to design, develop, and operate a formation of cooperative pico/nanosatellites for three-dimensional Earth observation using photogrammetric techniques. Its primary purpose is to monitor atmospheric and environmental phenomena with high precision and cost-efficiency, while demonstrating advanced capabilities in formation flying and autonomous in-orbit cooperation.

Goals

To address scientific, technological, and operational challenges, the TOM/TIM mission establishes the following primary goals:

- Demonstrate the capability of small satellites to perform synchronized stereoscopic observations from multiple viewing angles;
- Validate in-orbit technologies related to attitude control, relative navigation, and inter-satellite communication in a cooperative formation;
- Contribute to the Telematics International Mission (TIM) as the Bavarian component, generating transferable expertise for future cooperative satellite constellations.

Objectives

Derived primarily from Schilling et al. (2018) and Zakšek et al. (2018), the mission sets the following scientific, technical, and operational objectives:

Scientific / Application Objectives

- Measure the height and temporal evolution of volcanic cloud formations with greater precision than existing LIDAR-based sensors (~30–140 m);
- Observe and characterize the following phenomena:
    - The three-dimensional distribution of volcanic ash clouds;
    - Atmospheric clouds and their vertical dynamics;
    - Events such as wildfires, lightning, floods, and soil moisture variations.

Technical Objectives

- Implement a formation of three nanosatellites (3U CubeSats) equipped with commercial optical cameras capable of:
    - Simultaneously capturing imagery from different viewing angles;
    - Achieving ground resolution of up to 30 m;
    - Obtaining angular disparities close to 10° between observation vectors.
- Synchronize observations to minimize motion-induced errors due to cloud movement;

- Ensure autonomous formation control through inter-satellite links and relative navigation sensors;
- Validate the following subsystems and algorithms:
    - High-speed reaction wheels;
    - Visual servo-control algorithms and autonomous target tracking (e.g., volcanic ash clouds).

Operational Objectives

- Secure at least one daytime observation window per week over each target area using the basic TOM formation;
- Demonstrate the feasibility of scaling to a future constellation based on similar formations to increase revisit frequency;
- Leverage international ground station networks to enable frequent communications (with contributions from partners such as Bavaria, Shandong, São Paulo, Quebec, etc.).

Step 1. Define the Systems Engineering (SE) Task

The Table 5.22. outlines the Systems Engineering (SE) tasks for the TOM mission within the Telematics International Mission (TIM) framework. These tasks are specifically tailored to address the unique technical and operational challenges of formation flying using 3U CubeSats for 3D Earth observation.

Table 5.22 - SE Task Roles for the TOM/TIM Formation Flying Mission.

Role	Responsibilities
Systems Engineering Team	Coordinates overall CubeSat system design, formation architecture, requirements derivation (e.g., resolution, baseline, Δv), traceability, and compliance with observation objectives.
Mission Architecture Team	Defines 3D Earth observation goals (e.g., volcano ash clouds), selects formation geometry (e.g., triple pendulum), and aligns mission design with international partner contributions.
AOCS Engineering Team	Designs distributed attitude and orbit control using custom high-speed reaction wheels and propulsion systems; ensures <1° pointing accuracy and coordinated formation alignment.
Orbital Analysis Team	Evaluates out-of-plane manoeuvres, baseline separation (~100 km), deployment strategies, and Δv budgeting for polar orbits (500–700 km), including passive-active topologies.
Communication Team	Develops UHF inter-satellite links for synchronisation, S-band downlink for data, and integrates optical communication (e.g., OSIRIS) for high-speed experimental data relay.
Power System Team	Implements dual-board EPS with MPPT, battery cycling, and efficient power distribution to support high-consumption payloads and compute units under orbit-based energy constraints.
Software Team	Develops algorithms for visual servoing, autonomous cloud tracking, and synchronised image acquisition; distributes control tasks across UNISEC-based processing nodes.
Integration & Testing Team	Assembles 3U CubeSat platforms, verifies inter-satellite interfaces, validates synchronisation protocols, and conducts hardware-in-the-loop testing of attitude and data systems.

Source: Author.

The workflow ensures alignment with mission objectives by supporting coordinated development of formation control, payload synchronization, and ground segment integration. The activities reflect the multi-partner context of the TIM project and are informed by the design decisions and mission requirements.

Define SE team responsibilities

To ensure effective coordination among interdisciplinary engineering teams involved in the TOM mission, a FF Earth observation initiative within the TIM, a structured responsibility matrix has been developed based on the RACI model. This matrix provides clear role definitions for each team across key SE activities, including formation architecture design, payload synchronization, integration, and overall system verification.

The RACI framework is particularly well-suited to distributed missions such as TOM, which rely on international collaboration involving distinct contributions to satellite subsystems and ground infrastructure. Table 5.23 presents the adapted RACI matrix tailored to the TOM formation.

Table 5.23 - RACI Matrix – Systems Engineering Team Responsibilities.

Activity	Systems Engineering	Mission Architecture	AOCS Eng.	Orbital Analysis	Comms	Power	Software	Integration & Testing
Requirements Elicitation & Definition	A/R	R	C	C	C	C	C	I
Architecture Definition	R	A/R	C	C	C	C	C	I
Subsystem Interface Control	A/R	C	R	C	C	C	C	C
Risk Identification & Mitigation	R	C	C	R	C	C	C	I
Configuration Management	A/R	I	I	I	I	I	I	C
Test & Validation Planning	R	I	C	C	C	C	C	A/R
Integration Coordination	C	I	C	C	C	C	C	A/R
Stakeholder Communication	R	C	I	I	I	I	I	I

Source: Author.

By explicitly assigning responsibilities, the matrix improves traceability of design decisions, promotes communication among geographically dispersed contributors, and minimizes ambiguity in task ownership.

Defining the responsibilities within the SE framework for the TOM mission entails identifying key participants and categorising them based on their relative influence and engagement in the international FF programme.

This structured classification enhances stakeholder coordination across partner regions such as Bavaria, Shandong, São Paulo, and Quebec and ensures that communication, coordination, and decision making processes remain efficient throughout the system life cycle.

Given the distributed and modular nature of the TOM mission, which integrates satellite components, ground stations, and testing facilities from multiple international partners, a Power-Interest Grid has been developed. This tool enables SE leadership to align mission roles and expectations with stakeholder

involvement and authority, fostering strategic collaboration across technical and institutional domains.

The Power-Interest Grid supports the differentiation of actors involved in the mission based on their decision-making authority and technical engagement.

By positioning stakeholders within this matrix, the TOM SE team can ensure appropriate levels of engagement, consultation, and information sharing particularly critical in FF missions where inter-satellite synchronisation, interface standardisation, and coordinated testing depend on seamless collaboration across geographically distributed teams.

This matrix can be observed in the Table 5.24.

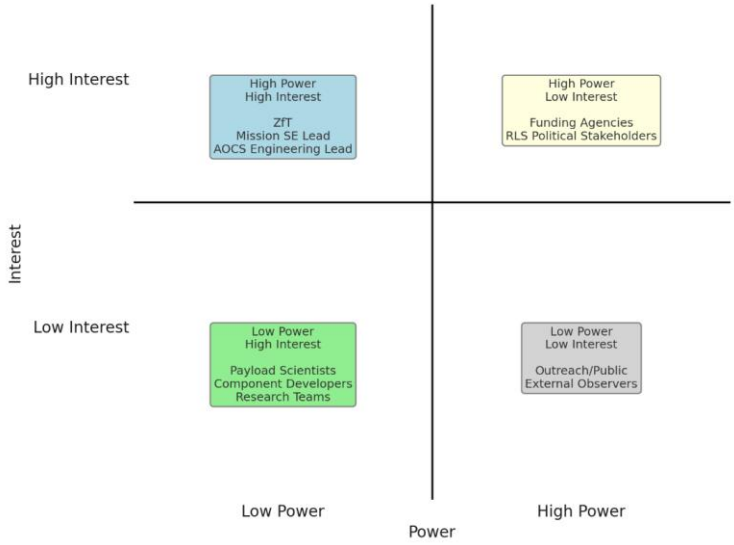
Table 5.24 - Power–Interest Grid – Stakeholders in the TOM/TIM FF Mission.

Category	Description	Examples (from TIM/TOM context)
High Power – High Interest	Key decision-makers and highly involved technical leaders. Must be closely managed and actively engaged.	- Zentrum für Telematik (ZfT) (mission coordination, satellite development) - AOCS Engineering Lead - Mission Systems Engineers
High Power – Low Interest	Influential actors with limited day-to-day involvement. Must be kept satisfied and informed.	- Funding agencies (e.g., regional RLS funders) - Policy stakeholders in Bavaria, Shandong
Low Power – High Interest	Contributors with deep technical interest but less authority. Should be kept informed and consulted.	- Payload scientists (e.g. volcano ash observation experts) - CubeSat component developers - University research teams
Low Power – Low Interest	Peripheral stakeholders. Minimal engagement, but informed of major milestones.	- General public / outreach groups - External observers or academic liaisons

Source: Author.

The information from the previous table is graphically represented in Figure 5.10.

Figure 5.10 - Power–Interest Grid for TOM/TIM Stakeholders.



Source: Author.

SE Scheduling and Control for TOM/TIM Mission

To ensure the successful execution of the TOM mission, which entails the coordinated deployment and operation of a formation of small satellites for three-dimensional Earth observation, it is crucial to implement structured control mechanisms across all engineering domains. Owing to the mission's international scope, involving contributions from Bavaria, Shandong, São Paulo, and other RLS regions, a robust scheduling and monitoring framework is essential for managing the complex integration of satellite subsystems, ground infrastructure, and overarching mission objectives.

The mission development is divided into six primary phases, with an expected duration of approximately 40 months, reflecting the staged progression from requirement definition to launch and operational deployment. These phases are aligned with formation flying design milestones, including validation of control strategies, synchronized imaging, and the integration of inter-satellite communication and payload systems. As can be observed in Table 5.25.

Table 5.25 - Timeline for the identified phases.

Phase	Title	Duration	Key Objective
1	Requirements Definition	6 months	Define mission goals (e.g., cloud height detection), derive system and performance constraints.
2	System Design and Analysis	6 months	Define 3U CubeSat formation geometry, select subsystems (AOCS, comms, EPS), and model system performance.
3	Prototyping and Partial Validation	8 months	Develop subsystem prototypes, validate formation control algorithms, and test synchronised operations.
4	Final Prototype Development	6 months	Assemble full engineering models integrating propulsion, control, and visual tracking systems.
5	Testing and Full Validation	7 months	Execute environmental, functional, and formation-level testing prior to launch readiness.
6	Launch and Operations	7 months	Perform integration, final verifications, and deploy the formation into orbit for mission operations.

Source: Author.

Each phase will be monitored and controlled using a set of project management and SE tools adapted to the complexity of a FF CubeSat constellation.

Mission Control Instruments:

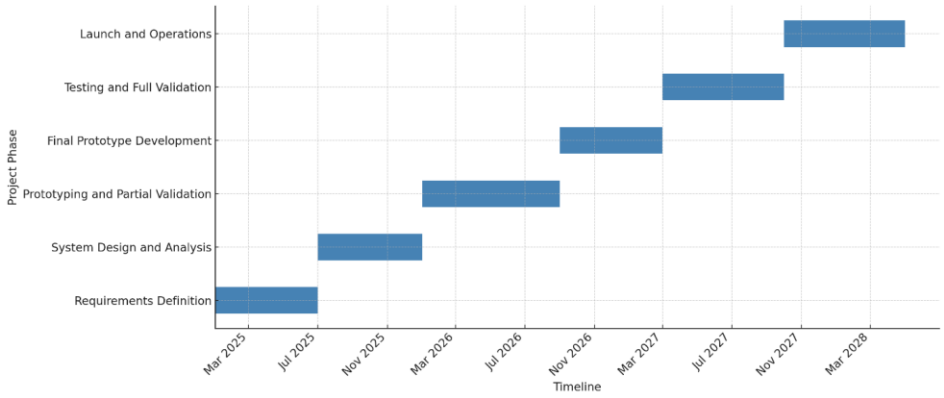
- PERT/CPM Diagrams: To identify time-critical activities and interdependencies;
- Kanban Boards: To facilitate agile coordination among international subsystem teams;
- RACI Matrix: To define clear responsibility assignments across technical roles;
- Milestone Charts: To track achievements such as interface validation or formation synchronization;

- Progress Heatmaps: To monitor test coverage and identify bottlenecks in prototyping or integration;
- Time Management Matrices: To optimise resource allocation and align development pacing with launch timelines.

Effective time and resource management in the TOM FF mission, developed as part of the TIM, necessitates a structured SE approach to coordinate the planning, scheduling, and control of all technical activities. This strategy is essential for managing the distributed nature of the project, which involves international partners contributing satellite subsystems, software modules, and ground infrastructure from multiple regions.

To support oversight across all mission phases, a Gantt-style timeline is proposed to visualize the sequential development of the mission, from requirements elicitation through launch and operation. This timeline helps estimate the full mission schedule, identify overlapping technical tasks, and improve control over deliverables, milestones, and cross-team coordination. Figure 5.11 presents the proposed Gantt chart aligned with the 40-month development plan.

Figure 5.11 - SE Schedule.



Source: Author.

In order to adopt a preventive and structured approach to potential technical and organizational challenges across the TOM mission lifecycle, a comprehensive risk assessment was carried out for each development phase, as can be observed in the Table 5.26.

Table 5.26 - Risk Matrix – Systems Engineering Phases for TOM/TIM.

Phase	Risk Description	Probability	Impact	Mitigation Strategy
Requirements Definition	Incomplete or misaligned scientific and technical requirements across partners	Medium	High	Organise international coordination workshops; validate use cases early in the process
System Design and Analysis	Inconsistent formation design or incompatible subsystem interfaces	High	High	Use MBSE tools and enforce Interface Control Documents (ICDs) for all partner modules
Prototyping and Partial Validation	Instability of formation control algorithms or sensor mismatch	High	Medium	Perform staged simulations and hardware-in-the-loop testing across different sites
Final Prototype Development	Subsystem integration failures due to hardware/software divergence	Medium	High	Conduct integration readiness reviews and harmonise testing procedures between teams
Testing and Full Validation	Failure during coordinated functional or environmental testing	Medium	High	Implement cross-site verification campaigns and system-level fault injection tests
Launch and Operations	Deployment failure or communication issues post-launch	Low	High	Prepare contingency deployment scenarios and pre-launch communication rehearsals

Source: Author.

It summarizes the key risks identified for each phase, including their estimated likelihood, potential impact, and recommended mitigation strategies, drawing upon established best practices in small satellite FF.

Step 2. Identify all stakeholders involved

Within the TOM mission, an international formation-flying initiative developed under the TIM program, a structured stakeholder identification strategy is essential to ensure alignment with the mission's strategic, scientific, and technical objectives. Operating within a SoS architecture and involving contributions from multiple RLS regions such as Bavaria, Quebec, São Paulo, and Shandong, stakeholder mapping enables effective coordination of geographically distributed infrastructure and capabilities.

To classify the roles and interests of key mission stakeholders, a high-level SIPOC model is applied. This method offers a structured overview of stakeholder engagement across the mission's value chain, as detailed below:

Table 5.27 - Stakeholder Interests in the TOM/TIM Project.

Category	Stakeholders / Elements
Suppliers	Zentrum für Telematik (ZfT, Germany), Shandong Academy of Sciences (China), INPE (Brazil), Satellite component manufacturers, Academic technology contributors
Inputs	Regional funding from RLS partners, Shared ground station infrastructure, International CubeSat standards, Open-source control algorithms, Institutional expertise
Process	Joint development of 3U CubeSats, Formation control algorithm design, Subsystem integration across countries, Validation and testing campaigns, Launch coordination
Outputs	Fully integrated satellite formation, 3D atmospheric observation data (e.g., cloud height, volcanic plumes), Demonstration of cross-national cooperation in space systems
Customers	Regional space agencies, Environmental monitoring institutions, Scientific research groups (e.g., atmospheric physics), Civil protection authorities, Educational institutions

Source: Author.

BPMN-Based Internal Stakeholder Coordination

In the context of the TOM mission, effective coordination among stakeholders is essential to ensure the successful implementation of formation-flying behaviours, and synchronized Earth observation. Given the SoS nature of the mission, where satellite units are developed and operated by partners across multiple RLS regions, a BPMN framework provides a structured means to visualize technical and organizational interactions. The BPMN coordination model highlights the roles and interactions of the following internal stakeholders: Satellite engineering teams, responsible for control algorithm development and sensor calibration.

- Satellite engineering teams (e.g., ZfT, Shandong Academy): responsible for developing formation-control algorithms, sensor fusion, and calibration logic for visual and GNSS-based navigation;

- Mission operations centers: interpret state estimation data, assess orbital conditions, and issue reconfiguration or commands to maintain formation geometry;
- Ground segment operators: execute TT&C routines and provide cross-platform synchronization support between satellites;
- Data processing units: handle onboard and ground-based processing of payload imagery, generate stereoscopic products, and ensure scientific data integrity;
- Regulatory and coordination bodies: ensure compliance with international CubeSat standards, frequency allocations, and cross-border operational protocols.

This coordination framework is particularly critical as TOM evolves towards a more autonomous and scalable FF constellation, where synchronization, decentralized control, and responsiveness to environmental dynamics become defining performance criteria.

Step 3. Identify Stakeholders Needs

The TOM mission addresses a broad spectrum of needs expressed by international, institutional, and technical stakeholders involved in the TIM. As a DSM constellation collaboratively developed by partners in Bavaria, Shandong, São Paulo, and other RLS regions, the mission enhances regional capabilities in FF, autonomous system design, and environmental monitoring. The constellation architecture is designed to enable high-resolution, synchronized three-dimensional Earth observation, also to foster academic collaboration, ensure compliance with regulatory frameworks, and support dual-use applications across both civilian and scientific domains. Table 5.28 outlines the principal stakeholder driven requirements, along with the corresponding systems intended to meet them.

Table 5.28 - Requirements of Stakeholders.

Stakeholder Need	Description	Corresponding System
Regional autonomy and cooperation	Enhancing participating regions' capacity for independent Earth observation while fostering cross-border collaboration.	Distributed formation of CubeSats with shared control algorithms, modular ground segments, and data-sharing protocols.
Environmental monitoring	Observation of cloud height, ash plumes, forest dynamics, and meteorological patterns to support climate studies.	Stereoscopic imaging via synchronized payloads; coordinated orbital paths for enhanced temporal and spatial coverage.
Disaster preparedness and resilience	Timely detection of natural hazards through multispectral and 3D imaging.	Coordinated overpasses, rapid tasking of satellites, and inter-satellite communication for data fusion and alerting.
Scientific and technological advancement	Building capacity in formation flying, visual navigation, ISL, and onboard autonomy.	CubeSat platforms, onboard processing, and visual/GNSS navigation tested across international labs.
Educational and institutional growth	Strengthening ties between universities, research centers, and space institutions through joint development and training.	Open-access hardware/software standards, student-led subsystem development, and shared mission datasets.
Economic development and innovation	Encouraging growth of local aerospace sectors and future commercialisation of remote sensing services.	Scalable, standardised satellite designs with modular payload bays and public–private co-development platforms.

Source: Author.

Define baseline DSM ConOps and Identify Risks

Identify DSM Taxonomy

The DSM taxonomy is a critical tool for characterizing how the TOM constellation functions in a SoS framework. It provides a structured classification of the mission across three main dimensions: organizational, physical, and functional. These dimensions help define how spacecraft within the TOM formation interact, distribute tasks, and maintain synchronisation to achieve high-precision Earth observation goals. The classification for the TOM mission is presented in Table 5.29.

Table 5.29 - Identified DSM Taxonomy for the Mission.

Taxonomy Element	TOM/TIM Classification
Organizational Configuration	**Decentralized collaborative:** Each satellite features onboard autonomy for formation control and synchronized imaging, with periodic coordination through shared ground segments and peer-to-peer exchange.
Physical Configuration	**Loose cluster formation:** The satellites maintain relative positioning within a variable tolerance, enabling coordinated stereo observations of cloud heights and atmospheric phenomena.
Functional Configuration	**Distributed collaborative tasks:** Satellites carry partially redundant payloads and share observation tasks dynamically based on visibility, system health, and orbital geometry.

Source: Author.

Organizational Configuration

The TOM mission employs a decentralized collaborative control structure. Each 3U CubeSat is equipped with autonomous navigation and vision-based control systems. Local autonomy allows satellites to make onboard decisions, such as initiating image capture or performing minor trajectory adjustments. However, overall coordination is maintained through periodic synchronization using shared planning routines and standardized communication protocols. This distributed control approach reduces dependence on a single central node, thereby enhancing system resilience and scalability.

Physical Configuration

The constellation follows a loose cluster geometry, maintaining predefined separation distances between satellites. This configuration supports stereoscopic imaging from multiple vantage points and offers flexibility to adapt the spatial arrangement to specific observational objectives, such as cloud height triangulation.

Functional Configuration

Functionally, the TOM formation is both collaborative and distributed. All satellites are equipped with comparable sensing and control capabilities, yet their roles may vary dynamically depending on orbital conditions and mission requirements.

This architecture supports fault tolerance and enables dynamic reallocation of tasks, contributing to the robustness and adaptability of the mission.

Identify DSM and FFS Design Drivers

To ensure that the architecture of the TOM mission fulfils its scientific and technical objectives, it is essential to identify the primary design drivers that shape the configuration and performance of both the DSM and its associated FFS. These design drivers encompass critical physical, operational, and environmental parameters, which define the mission envelope, impose architectural constraints, and influence the behavior of the satellite cluster throughout its operational lifecycle.

In the context of TOM/TIM, where the goal is to achieve synchronised three-dimensional Earth observation, the architecture must support precise temporal and spatial coordination between CubeSats while ensuring robustness and autonomy in distributed environments.

The key design drivers derived from the technical literature and mission briefings include:

- Relative navigation accuracy: The formation-flying architecture requires precise estimation and control of relative positions between satellites, leveraging visual and GNSS-based techniques as explored in the TOM prototypes developed by ZfT and its partners;
- Observation geometry: The constellation must maintain dynamic baselines that enable triangulation for stereo imaging. This directly influences orbital separation, attitude coordination, and camera pointing strategies;
- Autonomy in attitude and orbit control: As identified in Schilling et al. (2018), onboard autonomy for attitude determination, formation maintenance, and coordination logic is essential to reduce ground intervention and enable real-time responsiveness;
- Latency and synchronization: Inter-satellite coordination and observation synchrony depend on low-latency communication protocols or shared

timing strategies, particularly during cloud-tracking experiments or ash-plume observation campaigns;

- Environmental dynamics: The formation must be robust to orbital perturbations, thermal fluctuations, and atmospheric drag (for low Earth orbit conditions), which are particularly relevant for 3U CubeSats operating in loosely coupled constellations;
- Payload co-registration and calibration: Accurate scientific output depends on precise alignment of the optical sensors and time-tagged imaging, requiring calibration strategies both pre-launch and in-orbit.

These drivers collectively define the boundaries within which the TOM architecture is designed, ensuring that the mission is capable of achieving its distributed Earth observation objectives while maintaining resilience, autonomy, and international interoperability.

To shape the mission concept and ensure that the formation-flying architecture meets its scientific and operational goals, several system-level design drivers have been identified. These drivers emerge from mission objectives, environmental constraints, and the need for coordination across distributed platforms. The Table 5.30 presents the most relevant drivers influencing the high-level architecture of the TOM/TIM mission.

Table 5.30 - System-Level Design Drivers for TOM/TIM.

Driver	Implications for Mission Design
Relative Navigation Accuracy	Requires visual/GNSS sensor fusion and continuous estimation of inter-satellite positions for formation stability.
Observation Geometry	Drives baseline planning, camera alignment, and orbit selection to enable accurate stereoscopic measurements.
Autonomy	Minimises dependence on ground control; requires onboard fault tolerance and decentralised coordination logic.
Latency and Synchronisation	Affects coordination precision in cloud/ash observation; mandates efficient timing protocols or low-latency ISLs.
Environmental Dynamics	Requires design robustness to atmospheric drag, thermal cycles, and orbital perturbations in LEO.
Payload Co-Registration	Demands precise alignment of imaging payloads and time-synchronised data capture across the constellation.

Source: Author.

Beyond the conceptual architecture, the practical implementation of the TOM mission is governed by constraints typical of CubeSat-class platforms. These technical design drivers define the boundaries within which subsystems must be engineered to ensure feasibility, reliability, and performance. The Table 5.31 outlines the key physical and engineering parameters that directly impact system integration and functionality.

Table 5.31 - Implementation-Level Design Drivers for TOM/TIM.

Driver	What Limits the Driver	What the Driver Limits
Size	3U CubeSat constraints, modular bus limitations	Payload volume, antenna aperture, propulsion availability
Power	Surface area for solar panels, orbital dynamics, panel orientation	Duty cycle of payload, comms link duration, autonomy runtime
Communications	Ground station access, low-power radios, ISL availability	Latency in synchronised imaging, control uplinks, downlink throughput
Pointing	Cost-effective components, calibration precision	Image quality, formation maintenance, attitude synchronisation
Coverage	Number and spacing of satellites, orbital inclination and phasing	Event detection window, revisit frequency, stereoscopic observation effectiveness
Onboard Autonomy	Processor limits, software reliability, sensor fusion integration	Real-time formation reactivity, fault recovery, independence from ground operations

Source: Author.

The effectiveness of the TOM FF architecture depends on several key design drivers specific to the FFS. These drivers define how the spacecraft maintain coordination, distribute tasks, and respond autonomously in a distributed configuration. Spatial control is central to ensuring relative positioning within defined tolerances, while onboard autonomy enables adaptive behaviour and fault management without continuous ground intervention. Additional drivers such as communication architecture and OBDH influence how tasks are synchronised and data is managed across the constellation.

These elements are summarised in Table 5.32.

Table 5.32 - FFS-Specific Design Drivers.

Driver	Description
Spatial Control	Based on performance and limited propulsion, TOM maintains a loose formation with bounded tolerances for synchronised observation.
Autonomy Level	Mid-level autonomy with real-time decision-making supported by AI-based onboard processing for anomaly detection and mission adaptation.
Communication Architecture	Hybrid model with short inter-satellite communication bursts; primary coordination remains ground-based.
OBDH & Task Allocation	Distributed task scheduling, event-driven acquisition, and onboard data processing reduce latency and ground dependency.

Source: Author.

In the TOM mission, spatial control is a critical formation-flying design driver, as the constellation must maintain a loose geometric configuration to enable coordinated stereoscopic observations. This is achieved through a combination of visual-based navigation, GNSS data fusion, and attitude control using low-power actuators. Although tight formation is not required, maintaining relative positioning within predefined bounds is essential for achieving reliable cloud height and atmospheric structure measurements.

The system's autonomy level supports real-time decision-making onboard, reducing dependency on ground control. Each satellite employs local sensing and embedded processing to identify events, detect anomalies, and adapt observation schedules capabilities supported by AI-based routines and visual recognition algorithms, as demonstrated in the TOM demonstrator platforms.

The communication architecture follows a hybrid model. While command and control are primarily managed from ground stations, critical coordination for synchronised imaging or reconfiguration can be exchanged through short inter-satellite communication bursts.

Lastly, the OBDH system plays a key role in distributed task allocation. Payload operations are scheduled in an event-driven manner, and onboard data compression and filtering reduce the volume of information sent to Earth.

Describe DSM Operational Environment

The operational environment of the TOM mission defines the physical and functional conditions under which the CubeSats operate during FF campaigns. This context directly affects the design of subsystems, communications, and onboard processing, and informs key systems engineering decisions regarding autonomy, coordination, and risk management.

Given the mission's focus on stereoscopic cloud observation and distributed sensing, the environment requires flexible coordination, moderate attitude precision, and resilience to orbital perturbations. Table 5.33 summarizes the key

Table 5.33 - Operational Environment.

Parameter	TOM Operational Profile
Precision of Operation	Designed for loose formation flying; relative positioning sufficient for stereoscopic tasks.
Multiple Spacecraft Use	Multi-satellite collaboration among international partners, with several units in orbit.
Control Capabilities	Basic attitude control via miniaturized systems.
Control Hierarchy	Dynamic and decentralized; any satellite can assume coordination depending on context.
Real-Time Decision-Making	Moderate onboard autonomy with event detection and reaction capabilities.
On-Orbit Autonomy	Semi-autonomous behavior with fallback to ground for complex scenarios.
Deployment Strategy	Coordinated deployment through shared or individual launch opportunities.
Cooperative Operations	Designed for collaborative Earth observation and shared data acquisition.

Source: Author.

Hazard and Risk Analysis

In light of the collaborative nature of the TOM mission and the inherent constraints of CubeSat-based formation flying, a structured risk identification process is essential to preserve mission integrity and ensure operational continuity. Due to the system's distributed architecture, dependence on lightweight components, and limited inter-satellite communication capabilities, specific vulnerabilities arise that must be addressed through proactive design measures and robust operational planning. Table 5.34. provides a summary of the main risks identified in the literature, along with the corresponding mitigation strategies.

Table 5.34 - Mission Risk Identification and Classification.

Risk Category	Description	Classification	Mitigation Strategy
Performance Limitations	Inaccurate attitude control or degraded navigation can affect observation alignment and formation geometry.	Medium–High	Use of visual-based navigation, onboard calibration, and experimental validation of pointing strategies.
Loss of Inter-Satellite Comms	Temporary loss of synchronization between satellites during joint observations.	High	Reliance on pre-scheduled tasks, short data bursts, and fallback coordination via ground stations.
Power Budget Constraints	Limited generation and storage may affect payload use and onboard processing.	Medium–High	Power-aware duty cycling and prioritization of payload vs. communication functions.
Software or Autonomy Errors	Onboard decision-making logic may fail under unanticipated events or corrupted data.	Medium	Progressive testing with real data, use of AI under supervision, and ground-assisted fallback mechanisms.
Deployment Issues	Incomplete or delayed satellite separation may affect mission configuration.	Low–Medium	Mechanical qualification testing and heritage deployment systems via international launch providers.
Ground Segment Limitations	Limited access or delays in receiving data and updates due to scheduling conflicts.	Medium	Multi-institutional ground station network (ZfT, partners), buffering strategies onboard.

Source: Author.

Step 5. Define FFS functional requirements

Orbital Conditions

Formation flying missions, like TOM, require coordinated control of the orbital dynamics of multiple CubeSats operating simultaneously. This includes maintaining relative positioning, scheduling coordinated observations, and mitigating physical interactions such as shadowing. These conditions are critical to mission success, particularly for applications involving stereoscopic cloud imaging and distributed sensing. Table 5.35 presents the core functional requirements related to orbital conditions, the systems involved, and relevant qualitative performance considerations, in line with the TOM architecture.

Table 5.35 - Functional requirements – Orbit conditions.

ID	Functional Requirement	Detailed Description	Involved System	Performance Consideration
FFS-01	Maintain relative positioning	Each satellite must sustain formation geometry suitable for coordinated observations despite perturbations.	GNC	Loosely coordinated cluster; visual/GNSS-based relative navigation.
FFS-02	Enable dynamic task distribution	Satellites must adapt roles based on geometry and health to maximize observation efficiency.	OBC / Mission Management	Decentralized tasking logic; autonomy in role assignment.
FFS-03	Execute orbital-pass-specific functions	Specific operations such as imaging or calibration must be completed within designated orbital segments.	OBC / Payload System	Observation windows managed per pass; synchronization via onboard logic.
FFS-04	Mitigate inter-satellite interference (e.g. eclipse)	Avoid configurations that cause prolonged eclipse or signal shadowing among satellites.	EPS / Thermal Control	Pre-planned trajectories; reactive power and thermal load management.

Source: Author.

Communication and Control

The TOM mission's ability to perform distributed Earth observation depends on precise coordination and semi-autonomous control among its CubeSats. Communication and control subsystems are fundamental to this capability, enabling synchronization, onboard autonomy, and inter-satellite cooperation. These systems allow for real-time responses to environmental changes, efficient execution of tasks, and formation maintenance with minimal ground intervention. Table 5.36 outlines the primary functional requirements for communication and control within the TOM FF architecture.

Table 5.36 - Functional requirements – Communication and control.

ID	Functional Requirement	Detailed Description	Involved System	Performance Consideration
FFS-05	Schedule data transfer with ground	Define suitable transmission formats and windows based on ground station visibility.	TT&C / OBC	Coordinated downlink windows using multi-station ground segment (e.g., ZfT).
FFS-06	Ensure precise position and attitude knowledge	Maintain awareness of satellite state vectors to support coordinated imaging and formation keeping.	GNC	GNSS and visual tracking fused for relative navigation.
FFS-07	Enable semi-autonomous operation	Execute routine tasks with limited human supervision and fallback to ground in edge cases.	OBC / FDIR	Real-time onboard planning with reactive logic based on visual cues.
FFS-08	Coordinate position and orientation simultaneously	Adjust spacecraft attitude and trajectory in a harmonised manner for cooperative sensing.	GNC	Coupled control strategies developed for stereoscopic cloud tracking.
FFS-09	Synchronize multi-satellite maneuvers	Ensure temporal coordination of maneuvers for formation coherence during mission phases.	ICS / OBC	Maneuver preplanning and visual confirmation; limited inter-satellite bursts.

Source: Author.

Risk and Safety

Operating in LEO presents unique risks due to environmental disturbances, such as atmospheric drag, solar radiation pressure, and the increasing density of space objects. For the TOM mission, addressing these hazards is critical to preserving formation integrity and ensuring mission longevity.

The architecture must support basic evasion capabilities and implement resilience against orbital perturbations. Table 5.37 outlines the functional requirements associated with risk and hazard management for formation flying CubeSats.

Table 5.37 - Functional requirements – Risk and Hazard.

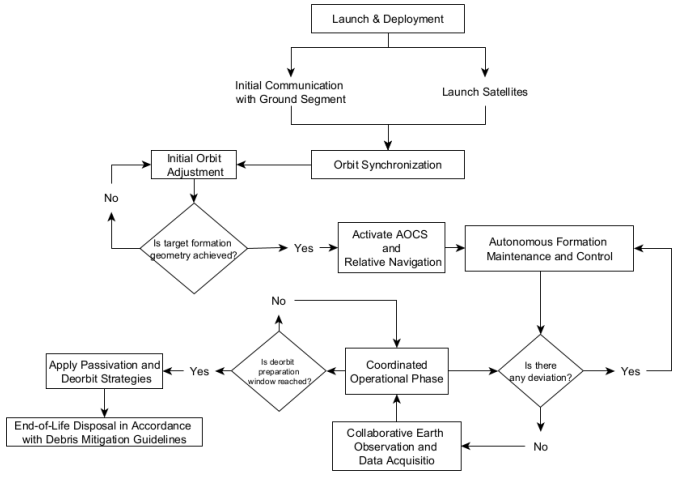
ID	Functional Requirement	Detailed Description	Involved System	Performance Consideration
FFS-11	Mitigate environmental disturbances	Account for orbital perturbations such as drag and solar radiation using onboard sensing and adaptive control.	Environmental Sensors	Use of simplified force models and onboard sensors to maintain orientation and stability.
FFS-12	Implement collision risk management	Monitor orbital conjunctions and support safe reconfiguration of satellite positioning if needed.	OBC / TT&C	Coordination via ground segment; responsive maneuver planning using ground-track updates.

Source: Author.

Step 6. Propose life cycle development plan

The Figure 5.12 presents the conceptual life cycle for the TOM FF mission, depicting the major operational phases from launch to end-of-life. The diagram outlines the progression from initial satellite deployment and orbit injection to synchronization, followed by the establishment of relative positioning for formation flying.

Figure 5.12 - Life cycle development plan.



Source: Author.

This conceptual flow emphasizes the iterative nature of formation maintenance, where each satellite autonomously adjusts its position based on visual navigation and GNSS inputs to preserve the desired geometry. As the system transitions

into its nominal operational phase, the satellites begin coordinated observations, including cloud-top stereo imaging and volcanic plume monitoring, depending on their payload configuration. The life cycle concludes with the mission closure activities.

Step 7. Propose DSM logical decomposition

The logical decomposition presented in the Table 5.38 outlines the hierarchical structure supporting the TOM FFS, consistent with the principles of DSM. It divides the system into five main levels: Mission, System, Space Segment, Ground Segment, and User Segment, with an additional emphasis on the Communication Layer, which enables coordination between spacecraft and with ground infrastructure.

Table 5.38 - Logical decomposition table.

Hierarchy Level	Description	Associated Components
Mission Level	Defines scientific and operational goals of the formation flying demonstration mission.	Earth observation, cooperative satellite operations, distributed stereo imaging.
System Level (DSM)	Governs coordination logic, autonomy levels, and distributed operations between formation elements.	Formation Flying System (FFS), onboard autonomy modules, visual-based relative navigation, inter-satellite coordination.
Space Segment	Contains the CubeSat platforms and their onboard subsystems, responsible for flight dynamics and sensing.	power & thermal control, payload instruments, ISL (optical or RF).
Ground Segment	Provides command uplink, telemetry downlink, and mission planning functions.	Ground stations, mission control centers, planning tools.
User Segment	Receives and processes acquired data for scientific or application-specific usage.	Image processing facilities, visualization platforms, research institutions.
Communication Layer	Enables synchronized operations and data relay within the constellation and toward ground stations.	Inter-Satellite Links (ISL), UHF/S-band RF communication, optical downlink (where applicable).

Source: Author.

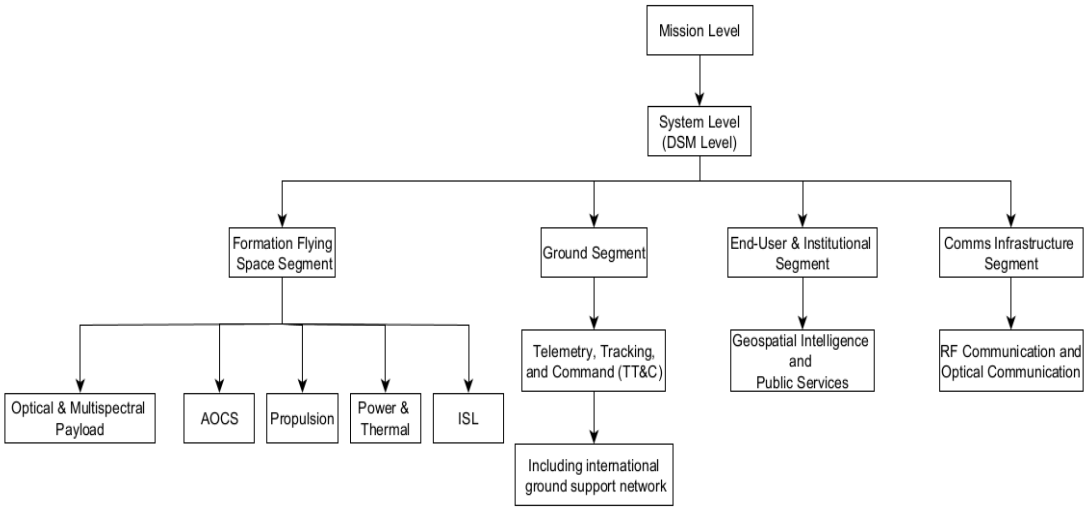
Each level addresses a specific architectural function, ensuring traceability from high-level Earth observation objectives to subsystem implementation. A core architectural element is the ISL, which supports coordination and autonomy

within the formation, particularly during distributed cloud tracking or volcanic ash monitoring campaigns.

This hierarchical model facilitates subsystem integration, interface definition, and coherent development throughout the mission lifecycle.

The Figure 5.13 illustrates the logical decomposition of the FF architecture implemented in the TOM mission, representing how the mission's components are structured and interrelated within a distributed spacecraft environment.

Figure 5.13 - DSM logical decomposition diagram.



Source: Author.

At the top, the Mission Level defines high-level scientific and technological objectives, which cascade down to the System Level, where distributed coordination, autonomy, and task allocation strategies are established according to DSM principles.

The architecture then branches into four main segments:

- The Distributed Space Segment groups the CubeSats and their onboard subsystems responsible for maintaining formation and acquiring observation data. It includes critical subsystems, propulsion units, power and thermal management, Inter-Satellite Links (ISL), and payload instrumentation;

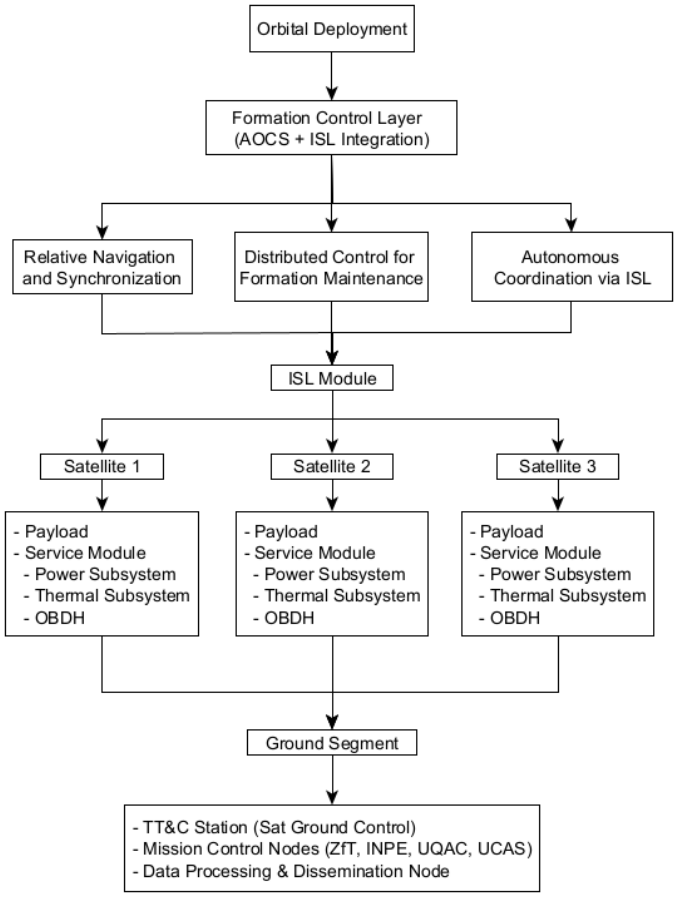
- The Ground Segment supports command, telemetry, and operational control through dedicated stations and mission control centres;
- The User Segment receives processed data for applications such as remote sensing, atmospheric studies, or disaster monitoring;
- The Communication Segment ensures reliable links within the constellation and toward the ground segment, incorporating both RF and optical communication methods, as explored in TOM's experimental configurations.

This decomposition clarifies how the key mission elements interact across segments and supports the coordinated functionality essential for formation-flying systems with distributed autonomy.

Propose individual architectures per project.

The Figure 5.14 presents the hierarchical architecture of the distributed satellite formation system developed as part of the Telematics International Mission (TIM) project. This architecture integrates the launch, space, and ground segments to enable coordinated and autonomous operations among multiple picosatellites. Following orbital insertion, the formation coordination layer manages orbit synchronisation, attitude alignment, and relative positioning across the constellation.

Figure 5.14 - Hierarchical structure of the TOM/TIM mission.



Source: Author.

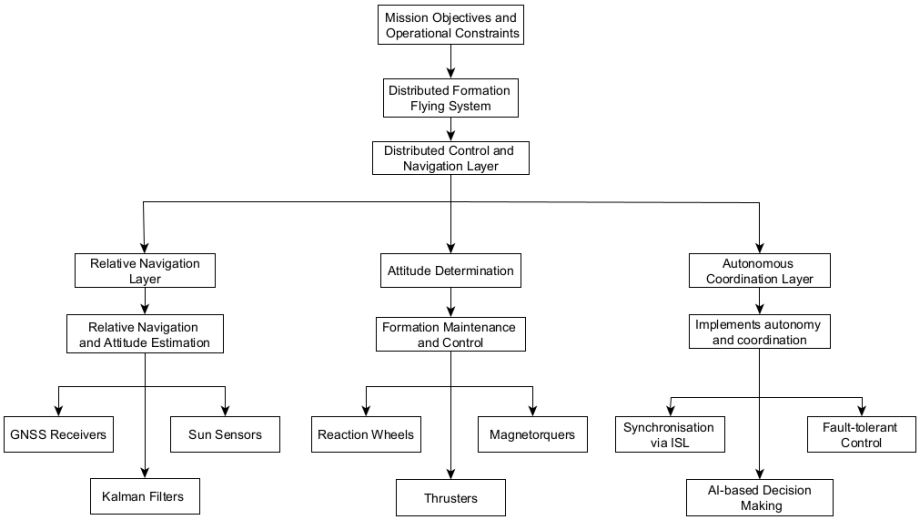
Each satellite is equipped with essential subsystems, including the payload, thermal regulation, and OBDH. ISL facilitate communication between units, ensuring maintenance of the formation geometry and supporting distributed control logic.

The ground segment comprises TT&C stations and mission control centres distributed across participating regions such as Bavaria, Quebec, São Paulo, and Shandong. It also includes data processing centres that oversee mission performance and ensure the timely delivery of Earth observation products to end users. This architecture enhances international interoperability and supports collaborative, responsive, and autonomous Earth observation capabilities.

Propose distributed architecture

The figure 5.15 is the distributed architecture embedded in the control layer of the formation-flying system developed under the TOM and TIM initiatives. This structure reflects the need for coordination between multiple pico-satellites engaging in joint Earth observation tasks, such as cloud tracking, ash plume analysis, and photogrammetry.

Figure 5.15 - Distributed architecture of the TOM/TIM mission.



Source: Author.

The onboard control systems integrate several functions, including attitude determination, formation geometry maintenance, and orbital synchronization. These are supported by hardware elements such as sun sensors, GNSS receivers, and reaction wheels, alongside algorithmic solutions like Kalman filtering and fault-tolerant logic. While each satellite is capable of performing essential control tasks autonomously, coordination is enabled through periodic inter-satellite communication and synchronization with ground stations across partner regions.

This distributed control approach, as demonstrated in the TOM constellation, ensures operational flexibility and resilience. It allows satellites from different partner regions to cooperate in data acquisition and event monitoring without

centralized real-time control, thus meeting the autonomy and adaptability requirements highlighted in the TIM framework.

Propose the model integration points

The integration points in the TOM FF architecture represent critical interfaces that support synchronized operations, autonomy, and robustness across the distributed satellite system. These integration elements ensure that attitude and orbit control, data handling, inter-satellite communication, and formation control operate cohesively.

A harmonized control approach, supported by onboard autonomy and the use of inter-satellite links, enables each CubeSat to maintain coordinated formation geometry and execute imaging tasks in real time. This integrated design is essential for ensuring accurate 3D Earth observation through simultaneous stereoscopic imaging. The primary integration components are summarized in Table 5.39.

Table 5.39 - Logical decomposition table.

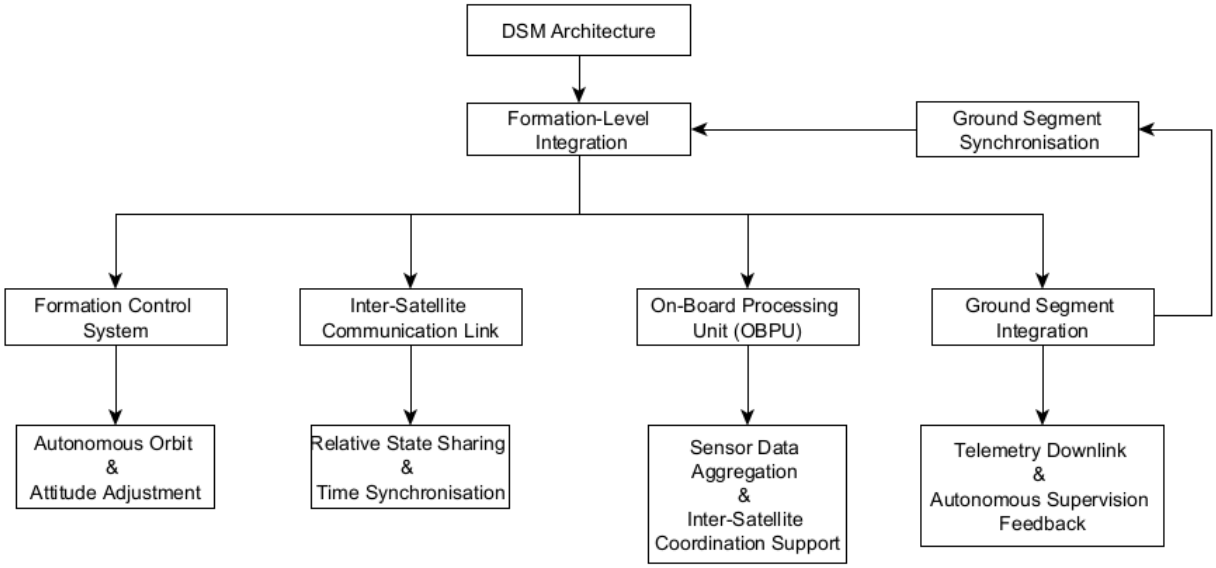
Integration Point	Functionality
Inter-Satellite Link (ISL)	Supports synchronised stereo imaging by enabling real-time exchange of attitude and orbital data.
AOCS (Attitude & Orbit Control System)	Maintains formation geometry and target pointing using high-speed reaction wheels and GNSS.
Formation Control Algorithms	Manages relative positioning, baseline separation (~100 km), and trajectory adjustments.
Onboard Data Handling (OBDH)	Processes and packages stereo images; supports distributed computing using multi-processor nodes.
Communication Subsystems	UHF for telemetry and ISL; S-band and optical links (e.g., OSIRIS) for high-speed payload downlink.

Source: Author.

The Figure 5.16 illustrates the systems architecture supporting mission-level integration within the TOM distributed FFS. This integration framework ensures alignment between the mission's high-level objectives and the coordinated operation of multiple CubeSats. It consolidates several critical subsystems such as formation control algorithms, inter-satellite communication, onboard data

handling, and ground segment operations into a unified architecture that facilitates autonomy, synchronized telemetry exchange, sensor fusion, and ground-based health monitoring.

Figure 5.16 - Distributed architecture of the mission.



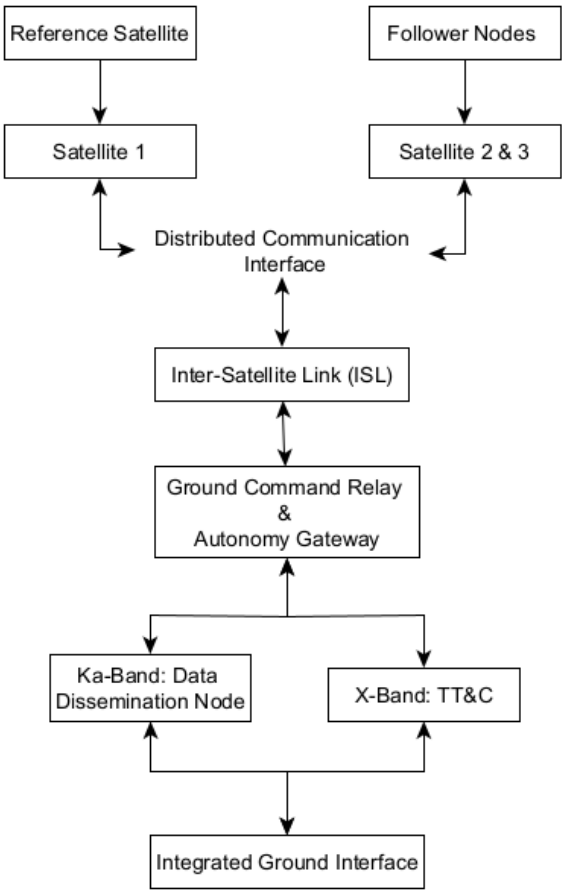
Source: Author.

The architecture reflects a robust, distributed control approach that integrates autonomous orbit and attitude control, cross-satellite data sharing via ISL, and real-time ground segment synchronization to maintain operational coherence and mission reliability.

Step 8. Propose possible system solutions and ConOps

Figure 5.17 illustrates a proposed communication and coordination concept for a distributed FF mission, as derived from the TOM demonstrator architecture. The scheme reflects a hybrid leadership model within the constellation, leveraging ISC to support synchronization, data exchange, and autonomous coordination across the networked spacecraft.

Figure 5.17 - Model Integration.



Source: Author.

The architecture is composed of the following functional elements:

- Leader Satellite: Acts as the reference node within the formation. It maintains primary coordination duties, including orbit propagation, task scheduling, and synchronization signal dissemination. It is responsible for interfacing with the ground segment via distinct communication channels—Ka-band for payload data downlink and X-band for Telemetry, Tracking, and Command (TT&C);
- Follower Satellites: Operate in a semi-autonomous manner, receiving reference trajectories and timing cues through the inter-satellite communication network. Each satellite autonomously adjusts its position and orientation, which are guided by shared formation objectives and distributed control logic;

- Inter-Satellite Link (ISL): Enables continuous low-latency communication among the satellites. It facilitates orbital synchronization, attitude alignment, and distributed task coordination. In the TOM mission, the ISL also supports inter-node fault tolerance and redundancy in decision-making;
- Mission Control Uplink Coordination: Centralized ground-based commands are relayed to the constellation and adapted through on-board autonomy. The service architecture across spacecraft supports decentralized operations through modular software components for data management, diagnostics, and coordinated sensing.

This concept replaces traditional "monolithic" spacecraft command structures with a collaborative and adaptive formation, enhancing operational flexibility, system robustness, and mission performance. It supports iterative refinement of the distributed system based on in-orbit telemetry and performance feedback.

Identify satellite relationship

In distributed formation flying missions, the relationship among satellites is defined by decentralized coordination, collaborative autonomy, and synchronization through ISL. This architecture typically adopts a leader follower model, where one satellite takes a central role in coordination while others operate semi-autonomously in a responsive configuration.

Within this framework:

- Autonomy: Each satellite integrates its own control logic and sensor suite, enabling independent navigation, attitude estimation, and fault-tolerant operations without requiring continuous intervention from the ground segment;
- Inter-Satellite Coordination: Real-time communication via ISL supports the exchange of navigation data, state estimations, and synchronization signals, enabling coordinated maneuvers and formation maintenance;
- Relative Navigation: Satellites estimate and adjust their relative positions and velocities through a combination of GNSS data, inter-satellite range

measurements, and attitude determination systems (e.g., sun sensors, star trackers);

- Formation Reconfigurability: The constellation is capable of adapting its geometry in response to operational phases or specific mission tasks, such as collaborative observation or distributed data collection;
- Decentralized Control Algorithms: Each unit contributes to formation maintenance through the execution of distributed algorithms, allowing the system to function collectively while retaining node-level autonomy;
- Fallback and Isolation: Satellites are designed to maintain free-flight capability, ensuring mission continuity even if one unit must isolate due to faults or anomaly resolution;
- Standardization and Compatibility: A harmonized interface definition ensures mechanical and operational compatibility across the formation, facilitating launch integration, data fusion, and subsystem interoperability.

Define Satellite Hierarchy

FF missions operating under a DSM architecture frequently implement a single-leader hierarchical coordination model. In such configurations, one satellite assumes the role of coordination leader, responsible for managing system level synchronization, uplinked command dissemination, and reference frame definition, while the remaining units function as semi-autonomous followers within the formation.

Under this architecture:

- The leader satellite defines the common orbital reference for the formation and coordinates synchronization across the constellation. It establishes communication with the ground segment, typically via dual-band links X-band for TT&C and Ka-band for high-rate payload downlink ensuring efficient data transfer and command relay;
- The follower satellites adjust their relative positions and attitude based on information received via the ISL. These units are capable of executing formation-keeping, synchronized observation, and cooperative data acquisition, based on distributed control inputs and local estimations.

This hierarchical structure supports the balance between centralized coordination and distributed autonomy, offering the following system-level benefits:

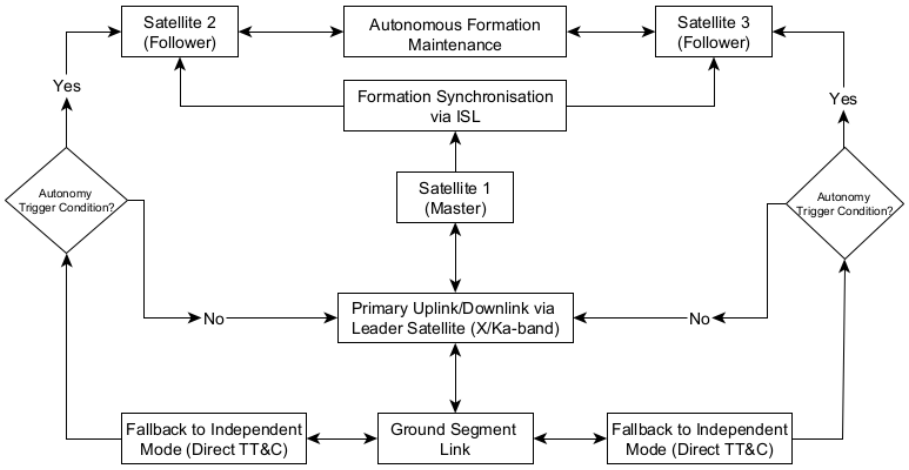
- Dynamic responsiveness: Rapid adaptation to changes in mission requirements, environmental conditions, or system state through real-time updates from the leader;
- Resilience: In case of temporary loss of connection to the leader, follower satellites maintain basic functionality via onboard autonomy and predictive control algorithms;
- Scalability: Additional spacecraft can be integrated into the formation with minimal changes to the coordination architecture, as long as interface standards and synchronization protocols are maintained.

The leader follower model also improves decision-making efficiency by reducing communication overhead while maintaining coordinated operations. At the same time, the autonomous capabilities embedded within each satellite, including onboard logic, relative navigation, and formation control algorithms, allow the system to degrade gracefully in the event of partial communication loss.

This architecture is consistent with DSM principles, wherein mission-level functionality emerges from coordinated interaction among individually operable units.

Figure 5.18 illustrates the coordination logic of the TOM mission, based on a hierarchical leader–follower model. The master satellite maintains ground communication and formation control via ISL, while follower satellites use onboard logic to hold position and can switch to autonomous mode if needed. This conditional autonomy ensures continued operation during connectivity loss or leader failure, aligning with DSM principles of flexibility, fault tolerance, and reconfigurable control.

Figure 5.18 - Mission Communication Hierarchy.



Source: Author.

The decision logic embedded within the formation control architecture allows each follower satellite to dynamically evaluate its communication and coordination requirements. Depending on mission phase, task priority, or energy constraints, a satellite may opt to operate independently or maintain active synchronization via the ISL.

This flexibility is critical for supporting fault tolerance, resource optimization, and decentralized autonomy core features of distributed spacecraft missions.

The hierarchical coordination scheme described shows:

- Continuous synchronization across the formation without reliance on rigid central control, enhancing robustness against subsystem failures;
- Adaptive autonomy, where satellites can scale their engagement level depending on real-time mission demands;
- Optimized use of communication resources, including the employment of differentiated frequency bands for task separation (e.g., X-band for TT&C functions, Ka-band for high-volume payload data);
- Formation integrity through ISL coordination, enabling relative navigation, attitude alignment, and distributed control even in scenarios with limited ground contact.

Define ISC system

The ISC system is a foundational enabler of coordination and autonomy in distributed formation flying missions.

The ISC ensures synchronization, distributed control, and efficient data exchange among spacecraft units within the constellation. It supports a robust and scalable architecture capable of sustaining formation integrity and decentralised operations even in the presence of link degradation or node failure.

Network Topology

- Leader-Follower Hierarchy: A central coordination satellite (typically designated as the leader) manages the formation logic and external communication;
- Redundant Inter-Satellite Links: While the topology is hierarchical, peer-to-peer backup links between satellites enhance resilience and allow local coordination in the event of degraded leader communication;
- Scalability: The architecture supports the addition or replacement of satellites without full system reconfiguration, a key feature in modular DSM frameworks.

Transmission Characteristics

- Throughput: Nominal data rates in the range of 1 Mbps are suitable for telemetry, synchronisation, and formation control exchanges;
- Latency: Low-latency communication (<1 second) is critical to ensure timely relative positioning and attitude correction, particularly in low-Earth orbit;
- Frequency Bands: The use of S-band for inter-satellite telemetry, X-band for TT&C, and Ka-band for high-volume payload downlink aligns with architectures outlined in the literature.

Hardware Components

- Miniaturised RF Modules: Compact transceivers are designed to meet SWaP constraints typical of CubeSat-class platforms, as outlined in Klemen (2019);
- Antennas: Patch and directional antennas enable efficient line-of-sight communication within tight formations;
- Low-Noise Amplifiers (LNAs): Integrated to maintain signal integrity under orbital noise and relative motion.

Communication Models

- Centralised Model: The leader satellite handles coordination, timing dissemination, and relays uplinked commands from the ground segment to the followers;
- Advantages: Simplified routing and control;
- Limitations: Potential single point of failure, mitigated by autonomous reversion to fallback logic in follower satellites;
- Point-to-Point (P2P): Backup direct links between followers enable lateral communication in the event of leader unavailability or task-specific collaboration.

Protocol Stack

- Data Link Layer:
    - CCSDS Protocols support reliable and standardized packet delivery across spacecraft systems;
    - TDMA (Time Division Multiple Access) allocates discrete time slots to each node, preventing collisions and ensuring deterministic scheduling.
- Network and Transport Layers:
    - Delay-Tolerant Networking (DTN) handles intermittent connections and supports data persistence during eclipses or occlusions;
    - UDP/TCP: Implemented based on trade-offs between real-time delivery and reliability.

Security and Fault Tolerance

- Authentication: Symmetric key-based access control is essential for secure coordination and command dissemination;
- Encryption: End-to-end AES-256 encryption is implemented for both ISL and satellite-to-ground transmissions;
- Resilience: Autonomous routing and cross-link redundancy improve survivability in dynamic mission contexts, ensuring robustness against node loss or signal degradation;

Define data delivery process

At the heart of the TIM/TOM mission's coordinated operations is the OBDH system implemented on each satellite. This system is central to managing telemetry, executing commands, fusing sensor inputs, and facilitating inter-satellite communication. Each satellite's OBC, as part of the OBDH system, supports real-time operations critical to maintaining synchronized behaviour across the constellation.

Key responsibilities of the OBC include:

- Monitoring thermal and electrical subsystem states;
- Executing received control instructions;
- Processing synchronization inputs and orbital data from other satellites within the formation.

Within the TOM formation, comprising three pico-satellites developed as Bavaria's contribution to the wider TIM constellation, one unit typically serves as the reference node. It receives high-level mission inputs, such as synchronization signals and task priorities, and relays them to the others via low-latency inter-satellite links. The follower satellites autonomously adjust their positions and sensing schedules based on this distributed coordination logic.

Functional Segmentation of OBDH Subsystems:

- Health Monitoring Module: Oversees housekeeping data to track system health;

- Sensor Payload Processor: Manages Earth observation instruments, such as cameras or radiometric sensors;
- Data Storage Unit: Temporarily buffers image and telemetry data prior to downlink;
- Attitude Control Processor: Executes orbit and attitude control tasks, integrating sensor feedback and ISL-based updates;
- Autonomous Operation Module: Executes preloaded, time-stamped commands between communication windows for autonomous operations.

Software Architecture:

- Harmonized Software Stack: Ensures all satellites operate on a synchronised platform, simplifying inter-node communication;
- Update Capability: Enables remote software updates and reconfigurations as the mission evolves;
- Fault Management Logic: Detects anomalies and redistributes control tasks or sensor operations as needed;
- Machine Learning Algorithms: Support functions such as adaptive routing of data or dynamic sensor tasking based on real-time conditions.

Data Flow Mechanism:

- Upstream: Mission-level commands are transmitted from partner ground stations (e.g., in Bavaria or São Paulo) to the constellation's coordinating node;
- Inter-Satellite Exchange: Navigation updates, task coordination, and synchronization signals are shared laterally between satellites to maintain formation coherence;
- Downstream: Earth observation data is collected by each satellite, potentially routed through the coordinating node, and transmitted to the nearest available ground station for processing.

Synchronisation and Coordination:

- The TOM formation relies on shared timing references and distributed control logic to maintain coordinated flight. Synchronisation messages and control algorithms ensure that Earth observation tasks such as photogrammetric imaging, lightning detection, or environmental monitoring are executed with temporal and spatial precision across the constellation;
- This distributed architecture enables TIM/TOM to function as a cohesive sensor network in orbit while maintaining flexibility, robustness, and scalability in line with DSM principles.

Step 9. Propose the evaluation of possible system solutions and ConOps

To determine the most appropriate configuration for the TIM/TOM FF mission, a structured multi-criteria decision-making approach was implemented. This process supported the selection of optimal architecture and operational strategies by combining quantitative performance analysis with qualitative assessments rooted in mission experience and engineering constraints.

Definition of Mission Alternatives

- Several viable configurations were explored during the early design and integration phases;
- Formation Geometries: Options included a string-of-pearls configuration and close-range distributed arrays enabling coordinated Earth observation;
- Control Strategies: Distributed autonomous control, a semi-centralised leader-follower model (as used in TOM), and ground-supervised cooperative modes were evaluated;
- Communication Architectures: Considerations included serial ISL, broadcast mode, and leader-based coordination with redundancy via direct links.

Establishment of Evaluation Criteria

- Mission design teams defined a set of evaluation metrics based on technical performance and implementation feasibility:
- Formation Accuracy: Required to support coordinated Earth imaging (within decimetre-level precision);
- Autonomy Level: Degree of satellite self-management, particularly relevant in LEO where contact opportunities are limited;
- Communication Reliability: Bandwidth and latency thresholds necessary for synchronous data exchange and coordination;
- Energy Consumption: Efficiency of the control and communication subsystems within strict CubeSat power budgets;
- System Complexity: Ease of manufacturing, integration, and deployment;
- Dependence on Ground Infrastructure: Level of onboard autonomy to reduce reliance on frequent ground intervention;
- Technical Readiness: Maturity of candidate components, particularly those related to ISL;
- Compliance: Conformance with international protocols and frequency regulations (e.g., ITU-R coordination, CCSDS standards).

Weight Assignment Using AHP

- The Analytic Hierarchy Process (AHP) was used to prioritize the above criteria:
- Team members conducted pairwise comparisons to determine relative importance;
- Judgment consistency was verified through standard consistency ratio thresholds;
- MATLAB scripts and decision support tools were used to compute final weights.

Development of Evaluation Matrix

- A weighted scoring matrix (similar to a Pugh matrix) was created:
- Each alternative was scored across the selected criteria;

- Scores were multiplied by the derived weights to obtain a composite score;
- This matrix facilitated traceable and transparent decision-making.

Simulation-Based Performance Validation

- Leading alternatives were validated using numerical simulations and software-in-the-loop environments:
- Orbit propagation and formation dynamics;
- Control performance was evaluated under representative disturbance models;
- Communication system behavior, including latency and robustness, was tested through real-time emulation setups;
- Power consumption under typical operational cycles was modelled and compared against satellite energy budgets;

Cost-Benefit and Risk Analysis

- Each configuration was analyzed for operational viability:
- Cost Factors: Included component availability, production scalability, and deployment logistics;
- Robustness Metrics: Monte Carlo simulations assessed system tolerance to single-point failures;
- Redundancy Options: Alternative control logics and cross-link strategies were defined for fallback operations.

Decision and Justification

- The final architecture—based on a semi-autonomous formation with a synchronisation-capable leader and cooperative followers was selected due to its balance of autonomy, robustness, and feasibility. The decision was supported by:
- Documented scoring results and simulation validations;
- Alignment with mission objectives, especially coordinated Earth imaging and formation maintenance;

- Built-in flexibility for reconfiguration and future upgrades, consistent with the DSM philosophy applied in the TIM/TOM mission.

Define compliance measures

To ensure compliance with international standards and mission-specific requirements for the TIM/TOM formation flying mission, a tailored regulatory framework has been developed. This framework draws on established space engineering and operational guidelines while taking into account the constraints inherent to nanosatellite constellations operating in Low Earth Orbit (LEO). It focuses on three main regulatory domains that reflect the distributed and collaborative nature of the mission:

Space Systems Engineering Standards

- ECSS-E-ST-10C: Adopted as the baseline for systems engineering processes throughout the mission lifecycle, providing structure to requirements derivation, design validation, and subsystem integration;
- NASA SE Handbook (2016): Used as a reference for best practices in test planning, interface management, and risk-informed design, especially in the context of inter-satellite coordination and autonomous operations.

Space Debris Mitigation

- UNOOSA Space Debris Mitigation Guidelines: Followed to define end-of-life operations, including deorbit strategies designed to minimise long-term debris generation;
- NASA ODMSP and ESA Guidelines: Applied in the development of passive disposal strategies, including drag-enhancing devices and orbit lowering techniques to ensure re-entry within regulatory timeframes.

Satellite Communications and Security

- ITU-R and CCSDS Standards: Ensure compliance with frequency coordination, protocol standardization, and interoperability for both ISL and satellite-to-ground communications. The mission makes extensive

use of CCSDS-compliant telemetry, command, and data transfer protocols;

- Security Measures: Incorporate AES-based encryption and authentication schemes for secure telecommanding and inter-satellite coordination, with fault tolerance mechanisms included to preserve mission continuity under degraded conditions.

The following compliance matrix outlines the tailored application of ECSS standards within the TIM/TOM context. Each standard has been evaluated in terms of its applicability, taking into account the mission's scale, autonomy, and collaborative nature. Tailoring decisions are documented alongside validation mechanisms to ensure consistent regulatory alignment throughout system development and operations.

Table 5.40 - ECSS Tailoring Compliance Matrix.

ECSS Ref	Requirement Summary	Applicability	Tailoring Notes	Validation Method	Compliance Status
ECSS-E-ST-10-02	Functional decomposition of system architecture	Applicable	Aligned with DSM formation logic and modular design	SysML modelling	Planned
ECSS-Q-ST-40	Safety risk analysis	Tailored	Adapted to nanosatellite risk profile in short LEO ops	FMEA, redundancy analysis	In Progress
ECSS-E-ST-10-06	System verification planning	Applicable	Covers MBSE-driven V&V across hardware and software	Simulation and V&V matrix	Planned
ECSS-U-ST-20	Communication interoperability	Applicable	Complies with CCSDS ISL protocols	Integration testing	Pending
ECSS-E-ST-35-11	Space debris mitigation and disposal planning	Applicable	Passive deorbit within <5 years as per ODMSP	STK-based analysis	Verified

Source: Author.

Table 5.41 presents a validation matrix that outlines the critical performance requirements of the TIM/TOM formation flying mission, along with the verification methods to be applied throughout both development and operational phases. Each requirement is directly associated with key system functionalities, including coordinated formation control, ISC, autonomous operations, and adherence to

resource constraints. Validation is conducted through a combination of simulations, subsystem-level testing, and analytical methods. The matrix contributes to mission assurance by maintaining clear traceability between requirements and system performance, assigning validation responsibilities, and monitoring implementation progress across participating teams.

Table 5.41 - Mission Requirements Validation Matrix.

Requirement ID	Requirement Description	Validation Method	Verification Status	Responsible Team
REQ-01	Maintain relative formation with ±10 m baseline deviation	Relative orbit propagation in STK; GNSS logs	Planned	Guidance & Control
REQ-02	Achieve < 0.1° attitude control precision	Hardware-in-the-loop with sensor-in-the-loop	In Progress	AOCS Engineering
REQ-03	Average daily power consumption ≤ 20 Wh per nanosatellite	Power profiling using ground testbeds	Planned	Power Subsystem
REQ-04	Inter-satellite communication rate ≥ 1 Mbps, latency < 1 s	ISL protocol testing and RF link characterisation	Planned	Comms & Networking
REQ-05	Constellation revisit period < 12 hours for target region	Orbital scenario simulation (GMAT/STK)	Pending	Mission Planning
REQ-06	performance deviation ≤ 5% from reference model	MATLAB/Simulink validation vs. flight data	Planned	AOCS Verification
REQ-07	Sustained autonomous coordination for > 90 days	Autonomy campaign with fault injection scenarios	Planned	Onboard Autonomy
REQ-08	Passive deorbit within 5 years post-mission	Deorbit analysis using drag augmentation models	Verified	Systems Engineering

Source: Author.

Step 10. Define the Review Points for the Validation of the System Solution and ConOps

To ensure traceable and systematic progress throughout the development of the TIM/TOM FF mission, a structured validation framework has been established,

anchored in formal review milestones. These review points serve as checkpoints to evaluate compliance, assess system maturity, and verify alignment with mission goals and the distributed operations concept.

The validation approach integrates formal decision-making principles to support informed trade-offs, risk identification, and design iteration. The following key technical reviews are planned throughout the project lifecycle:

- Mission Concept Review (MCR): Establishes the scientific and technological justification for distributed satellite operation, confirming the overall feasibility and relevance of a formation flying configuration for remote sensing and synchronized measurements;
- System Requirements Review (SRR): Validates the translation of mission objectives into system-level requirements, including formation geometry accuracy, inter-satellite communication latency, autonomy, and resource constraints (e.g., power and data bandwidth);
- Mission Definition Review (MDR): Refines the distributed architecture and operational scenario, integrating subsystem responsibilities, data handling flows, and the coordination model among satellites;
- System Definition Review (SDR): Evaluates the detailed system architecture, including onboard software structure, synchronization strategies, and interface definitions required for distributed operation and ground interaction.

At each of these review stages, detailed documentation will be produced, identifying validation criteria, technical risks, unresolved issues, and justifications for any system refinements. This process ensures traceability across all phases and reinforces mission assurance through iterative review cycles.

Table 5.42 summarizes the main review points adopted throughout the TIM/TOM project, specifying the purpose, evaluation focus, and expected deliverables for each stage:

Table 5.42 - Review Points Across Different Project Phases.

Review Point	Purpose	Key Assessment Criteria	Deliverables
System Concept Review (SCR)	Validate the feasibility of the formation flying mission concept	Scientific objectives, mission feasibility, preliminary risk profile	Concept Definition Document, Feasibility Report
System Requirements Review (SRR)	Confirm alignment of system requirements with mission needs	Requirement completeness, traceability, technical feasibility	System Requirements Specification, Traceability Matrix
Preliminary Design Review (PDR)	Assess initial system architecture and formation strategy	Subsystem interaction, viability, communication model	Preliminary Design Document, Operational Concept Draft
Critical Design Review (CDR)	Verify maturity of the integrated system design	Interface completeness, risk mitigation, implementation readiness	Final Design Documentation, ICDs
Test Readiness Review (TRR)	Confirm readiness for validation and testing campaign	Test plan robustness, hardware/software integration, failure scenarios	Test Plans, Validation Protocols
Operational Readiness Review (ORR)	Assess mission preparedness for launch and commissioning	Readiness of operational procedures, contingency planning	Mission Operations Manual, Final ConOps
End-of-Life Review (ELR)	Ensure post-mission compliance and sustainability measures are in place	Space debris mitigation, deorbit compliance with guidelines	Deorbit Plan, ESA/NASA Compliance Confirmation

Source: Author.

To reinforce consistency and objectivity throughout the validation process of the TIM/TOM formation flying mission, a structured evaluation framework has been established. This framework ensures that both the system architecture and the ConOps are assessed against mission objectives, technical performance criteria, and regulatory standards.

Each validation phase employs defined categories that guide the evaluation using both qualitative and quantitative methods as can be observed in Table 5.43.

Table 5.43 - Evaluation Framework for System and ConOps Validation.

Category	Assessment Factors	Evaluation Method
Mission Alignment	Does the distributed architecture fulfil the scientific and technological goals of the mission?	Requirements traceability and mission function mapping
Technical Feasibility	Are onboard systems, such as OBDH, and communication links, meeting required performance levels?	Subsystem simulation, hardware-in-the-loop tests
Risk Mitigation	Are potential failure modes adequately anticipated, and are fallback mechanisms in place?	Monte Carlo simulations, Fault Tree Analysis (FTA), FMEA
Operational Efficiency	Is the coordination scheme optimized for autonomy, synchronization, and energy use?	Formation control analysis, power budget simulations
Regulatory Compliance	Does the system comply with applicable space engineering and communication protocols?	Standards-based validation using ECSS tailoring and protocol audits

Source: Author.

Step 11. Iterate and document

For the TIM/TOM FFS, an iterative development and validation approach is essential to enhance the mission's capacity for autonomous coordination, precise synchronisation, and long-term orbital stability.

The iterative process is closely aligned with systems engineering standards and structured to ensure that each design loop reinforces traceability, mission robustness, and operational compliance with spaceflight regulations. Each iteration consolidates lessons learned, implements targeted improvements, and produces updated documentation for system verification and integration phases. Below is the proposed iterative workflow for the TIM/TOM mission:

Define Iteration Objectives

- Select the subsystem under analysis (e.g., formation control, inter-satellite communication, onboard coordination);
- Establish quantitative performance metrics (e.g., ±10 m inter-satellite positioning, <1° attitude error, <1 s communication latency).

Execute Simulations and Tests

- Use numerical environments such as MATLAB/Simulink and Systems Tool Kit (STK) to validate control performance, communication reliability, and orbital dynamics;
- Assess formation stability under both nominal and degraded operating scenarios, including single-node failure, communication delays, or environmental perturbations.

Analyse the Results

- Evaluate simulation outputs relative to design baselines and expected performance margins;
- Identify discrepancies or degradation:
    - Deviations in attitude or position control → refine models;
    - Communication failures → review and reconfigure ISC/ISL structure;
    - Power anomalies → adjust task scheduling and subsystem activation logic.
- Update key performance indicators (KPIs) and document resolution strategies.

Adjust Design and Models

- Apply corrections to the control algorithms, revise inter-satellite data exchange schedules, or adapt constellation geometry to improve resilience and responsiveness;
- Where necessary, introduce redundancy and failover logic to preserve functionality during anomalies;
- Incorporate autonomy enhancements where applicable, including event-driven operations and adaptive synchronization routines.

Document the Iteration

- Record all changes applied to the system configuration, software models, and mission parameters;

- Update requirement traceability matrices and validation records to reflect improved performance or altered design constraints.
    - Prepare a formal iteration report including:
    - Goals and assessment thresholds;
    - Simulation/test results;
    - Non-conformities and adjustments;
    - Updated compliance status;
    - Recommendations for subsequent iterations or design freeze.

To ensure consistency, traceability, and structured development throughout the lifecycle of the TIM/TOM FF mission, a comprehensive documentation and configuration management strategy has been established. The strategy is tailored to support the mission's distributed and iterative nature by incorporating tools for collaborative editing, version control, requirements validation, risk management, and performance evaluation. These elements are summarized in Table 5.44.

Table 5.44 - Documentation Control and Version Management.

Category	Toolset / Method	Purpose
Document Control	Internal Wikis, Shared Repositories (e.g., GitLab Wiki)	Manage centralised documentation, engineering logs, and design artefacts collaboratively.
Version Control	Git, GitLab CI/CD	Track modifications in software, configuration files, and control models over design cycles.
Requirements Traceability	SysML Models, Structured Tables	Link stakeholder needs with technical specifications and monitor compliance during system evolution.
Risk Management	Functional Failure Analysis, Simulation-Based Stress Scenarios	Identify and mitigate critical failure points through scenario testing and fault injection.
Simulation & Testing	MATLAB/Simulink, STK, in-house mission tools	Validate system dynamics, formation control, and synchronization performance under varying mission conditions.

Source: Author.

Expected Outcomes of Each Iteration

The iterative development framework implemented for the TIM/TOM FF mission ensures progressive refinement and validation of system components throughout all mission phases. Each cycle is structured around clearly defined deliverables

and stopping conditions to verify the readiness, consistency, and technical feasibility of the distributed satellite architecture. This structured evolution supports the alignment of the system with mission-specific goals, inter-satellite synchronization needs, and distributed autonomy constraints.

Requirements Validation

In this initial stage, mission objectives and system constraints are translated into concrete, traceable technical requirements. These include navigation accuracy, synchronization fidelity, and coordination robustness within the multi-satellite environment.

- Deliverables:
    - Updated System Requirements Definition based on formation flight needs;
    - Traceability artefacts linking mission goals to functional and technical parameters;
    - Preliminary compliance check aligned with small satellite mission constraints in LEO
- Stop Condition:
    - All system and formation-level requirements are validated for consistency, feasibility, and traceability within the distributed mission context.

2. Design Refinement

This phase focuses on optimising subsystem interactions and refining formation control models. It also addresses trade-offs between autonomy levels, communication topology, and energy consumption.

- Deliverables:
    - Updated architecture diagrams (logical and functional) reflecting inter-satellite coordination mechanisms;
    - Trade-off reports comparing centralized vs distributed control strategies;

    - Draft interface definitions for timing, navigation, and payload coordination.
- Stop Condition:
    - All critical design decisions are justified, interfaces defined, and no further major reconfigurations required.

System Integration

Subsystem-level functionalities (e.g., onboard data handling, inter-satellite communication, formation control) are tested collectively to confirm interoperability and coordinated execution.

- Deliverables:
    - System Integration Summary documenting performance of key interfaces and communication links;
    - Validation results of time-synchronized observation and inter-satellite communication tests;
    - Analysis of coordination logic performance under nominal and degraded conditions.
- Stop Condition:
    - Full subsystem interoperability is demonstrated within a distributed simulation or hardware-in-loop environment, and synchronization logic is verified.

Final Validation and Review

This final iteration confirms system readiness for operational deployment, including hardware-software integration, thermal and power readiness, and formation management capability.

- Deliverables:
    - Final system verification documentation, including simulation benchmarks and hardware test results;
    - Operational readiness checklist confirming compliance with mission timing and control performance;

    - Updated validation framework confirming alignment with project and system-level goals.
- Stop Condition:
    - All technical performance metrics and mission constraints have been satisfied, and the system is ready for launch and coordinated in-orbit operation.

6 DISCUSSION

Throughout the development of this research, the proposed systems architecting approach for autonomous formation flying was continuously refined through iterative analysis and expert feedback. Notably, collaborators from the Zentrum für Telematik (ZfT) and the National Institute for Space Research (INPE) provided valuable insights that guided substantial methodological improvements. Their observations underscored the importance of explicitly defining the expected outputs at each stage of the process, establishing clear stopping criteria for iteration cycles, and indicating where mission level requirements should be derived and decomposed.

In response, structural refinements were introduced, particularly in step 5 of the proposed architecting process. These modifications distinguish between mission-level constraints and the functional requirements of individual system elements, ensuring that architectural decisions are traceable and appropriately scoped. Diagrams illustrating the FFS architecture (Figures 4.4 to 4.6) were revised to enhance clarity regarding the distributed configuration and to support the visual representation of subsystem integration within the SoS. Emphasis was also placed on step 7, which details a logical decomposition strategy for distributed architectures. This step identifies points of harmonisation across spacecraft and supports consistent requirement allocation to inter-satellite interfaces, ground systems, and user segments.

Following the recommendations of the thesis reviewers, the focus of this research was centred on the systems engineering of a SoS architecture, rather than on subsystem-level development. Instead, the methodology concentrated on the allocation of requirements at the architectural level, covering interfaces between satellites, ground stations, data centres, and user segments.

Despite the methodological advancements, the study acknowledges persistent challenges associated with distributed system integration. These include managing constraints on mass, power, and volume while integrating critical subsystems. Additionally, maintaining reliable ISC links is essential for preserving relative positioning and enabling autonomous operations.

The case study examples used to illustrate the proposed methodology were based on publicly available information from representative formation flying missions. These served as conceptual baselines to demonstrate the applicability of the proposed systems engineering approach in realistic mission contexts.

Future research directions include the development of adaptive control algorithms that respond dynamically to orbital and environmental conditions, and the extension of the proposed architecting process to larger satellite constellations. Such extensions would introduce new challenges related to synchronisation, data fusion, and autonomy coordination. Crucially, validating the process through real world implementation and in-orbit testing remains a key objective to confirm its applicability and robustness.

This research advances a process centric methodology tailored to the architectural design of autonomous FF missions with small satellites. While the approach provides a structured foundation, transitioning from conceptual architecture to operational systems will require continued iteration, validation, and collaboration with both academic and industry stakeholders.

6.1 Validation of the proposed tailoring through the TIM and TOM projects at ZfT

A significant contribution to the validation of the proposed systems architecting approach stems from the collaboration with the Zentrum für Telematik (ZfT), which has led the implementation of the TIM and the TOM. Both initiatives, framed within international scientific cooperation, address architectural and coordination challenges closely aligned with those examined in this research specifically, the development of distributed systems and formation flying configurations with small satellites.

The TOM mission, developed as the Bavarian contribution to TIM, involves a formation of three CubeSats (3U+) designed to perform synchronised photogrammetric imaging of atmospheric phenomena. By capturing images from multiple angles and performing ground-based data fusion, TOM aims to generate high-resolution three-dimensional models for scientific analysis. The mission architecture incorporates modular components, decentralised control, and a

reusable platform previously validated in the NetSat mission. These characteristics reflect many of the architectural principles outlined in the proposed tailoring process.

From a systems engineering perspective, TOM serves as a concrete example of how a distributed system of systems can be realised in practice. The feedback provided by the engineering team at ZfT (documented in Annex C) was instrumental in refining several aspects of the proposed methodology particularly regarding logical decomposition (step 7), interface identification, and synchronisation across multiple systems. Notably, their input reinforced the need to focus on requirement allocation across the entire SoS, including inter satellite interfaces, ground segments, and data infrastructure, rather than at the level of individual subsystems.

Furthermore, the broader context of the TIM mission, which brings together institutions from five continents under a unified mission architecture, validates the relevance of tailoring strategies that support modularity, iterative refinement, and cross institutional compatibility. This level of distributed engineering coordination underpins the tailoring principles proposed in this research.

Taken together, the alignment between the engineering practices observed in the TIM and TOM missions and the methodology proposed in this research demonstrates the practical feasibility and conceptual soundness of the tailoring approach. It also highlights the critical role of adaptability and modular decomposition in enabling successful FF missions. Future research should aim to build upon this foundation, extending validation through in orbit demonstrations and expanding the framework to accommodate larger and more complex constellations.

6.2 Comparison of the Tailored SE design process with theoretical backgrounds

The tailored SE design process proposed in this research aligns with the principles of lifecycle oriented frameworks such as those defined by NASA and the ECSS. These standards provide a structured approach for the design and development of space systems, focusing on stages from need identification to

requirement allocation and architectural synthesis. However, the methodology presented here diverges from these classical models by introducing domain specific adaptations to address the complexity of FF missions composed of multiple small satellites.

One of the distinguishing features of the proposed tailoring lies in its emphasis on system of systems abstraction rather than subsystem level engineering. This abstraction shift was introduced in response to expert review and reflects the need to address requirements allocation across distributed components including satellites, ground segments, inter satellite interfaces, and data centres.

Additionally, the tailoring methodology formalises the design process using traceable steps and harmonisation checkpoints that allow the integration of mission drivers, interface requirements, and stakeholder expectations across multiple elements. The proposed structure facilitates consistent architectural evolution from concept definition to requirement decomposition and interface coordination. This ensures alignment between functional and physical architectures, even when multiple institutional contributors are involved.

Overall, the proposed tailoring expands traditional SE frameworks by incorporating specific adaptations for distributed space missions. It provides a conceptual and procedural baseline that could be further extended for larger constellations and more complex formations, ultimately supporting the future development of interoperable and autonomous multi satellite architectures.

6.3 Comparison of the Tailored SE design process with literature review

The tailored SE process developed in this research builds upon and extends the approaches found in the current literature on DSM and FFS. While existing studies have made substantial contributions at the subsystem level especially within domains such as GNC and ISL, among others, they typically lack a cohesive architectural perspective that spans the full design lifecycle for distributed missions.

This work addresses that gap by proposing a structured systems architecting methodology that prioritises the SoS in high levels, enabling the definition of

interfaces, requirement allocations, and harmonisation checkpoints across cooperating mission elements. Unlike previous contributions that often isolate subsystem development or focus narrowly on specific lifecycle stages, this methodology provides a holistic design process aligned with mission level objectives and coordination requirements.

The tailoring also introduces a formal mechanism to link stakeholder expectations, design drivers, and mission constraints with early phase architectural choices an area often underrepresented in prior DSM and FFS research. Through the integration of concurrent and collaborative engineering principles, the proposed approach enhances traceability, supports iterative refinement, and offers a scalable pathway for future autonomous satellite constellations.

6.4 Lessons learned

During the development of this research, several key lessons emerged that informed the refinement and effectiveness of the proposed systems architecting process. First, early cross disciplinary collaboration proved essential to addressing the multifaceted nature of DSM and FFS. The involvement of experts across domains such as orbital mechanics, telecommunications, SE, and mission design enabled the early identification of trade offs, improved interface definitions, and minimised rework.

Second, the complexity of achieving lower levels of abstraction became increasingly evident throughout the process. While this research focused on the early phases of the system life cycle from need identification to architectural definition it also highlighted the difficulty of ensuring precision and traceability at the subsystem level in distributed architectures. This justified the decision to limit the scope of the thesis to higher abstraction levels, particularly within the system of systems domain.

Third, the identification and management of harmonisation points particularly those related to ISC and interface control emerged as a critical factor in ensuring consistency and interoperability between distributed elements. Recognising

these harmonisation points early in the process allowed for a more robust allocation of requirements and more predictable system behaviour.

Finally, maintaining rigorous traceability of decisions, assumptions, and requirements throughout the architecting process was found to be indispensable. This practice supports future iterations and adaptation of the architecture in response to evolving mission contexts, stakeholder needs, or technology upgrades.

6.5 Contributions of Tailored SE design process

This research proposes a systems architecting process tailored to the characteristics of distributed missions involving small satellites operating in autonomous formation. The process focuses on the initial phases of the system life cycle specifically, stakeholder need identification, logical decomposition, and architectural definition developed at a SoS level of abstraction. These aspects are detailed in Chapter 4, particularly in Sections 4.2.3 through 4.2.7.

Unlike approaches that emphasise subsystem level developments, the methodology presented in this thesis redirects attention toward the integration of multiple satellite elements, their interfaces, and the supporting ground segment. This reorientation is supported by structured guidance for requirement allocation and architectural decomposition, as described in Section 4.2.4, which helps maintain alignment between segment-specific developments and overarching mission objectives.

One of the key contributions identified is the formalisation of integration and harmonisation points across systems. These are addressed in Section 4.2.6, where interface control points and coordination mechanisms are defined. Such formalisation may reduce the risk of inconsistencies in later phases by encouraging early clarification of dependencies and shared resources.

The tailoring steps of the proposed process draw upon architectural models and SoS thinking, and align with recognised frameworks such as ECSS and NASA. However, the tailoring itself is contextualised to support distributed autonomy and

collaborative mission structures. This contextual adaptation is presented in detail in Section 4.2.5.

Although the scope of this research does not extend to the engineering of individual subsystems or their verification activities, the architectural foundation laid out may inform subsequent design stages. This is especially relevant in contexts where formation-level coordination imposes constraints or requirements that influence subsystem behaviour.

The methodology was conceptually validated using publicly available data from representative formation-flying missions, such as TIM and TOM, as described in Chapter 6.1. These case studies were not implemented directly but served as a basis for assessing the feasibility and applicability of the proposed process in a realistic setting.

6.6 Limitations

One of the primary limitations of this research is the absence of in-orbit validation. Although the tailored systems architecting approach has been informed by expert feedback and supported by illustrative case studies, it has not yet been implemented in a real-world space mission. As such, the methodology's effectiveness under operational constraints such as inter satellite synchronisation, environmental uncertainty, and unexpected system behaviour remains to be confirmed through actual deployment.

Another limitation concerns the scope of abstraction. While this thesis focuses deliberately on the system-of-systems level, it does not address the detailed engineering of subsystems or their specific verification strategies. Reaching lower abstraction levels such as those required for subsystem integration and AIT requires a higher degree of modelling precision, which lies beyond the scope of this work.

Additionally, the successful application of the proposed tailoring process depends on multidisciplinary expertise and the availability of collaborative tools. The implementation of distributed systems architectures demands knowledge across multiple domains such as telecommunications, mission design, software

architecture, and systems engineering which may pose a barrier in teams with limited capacity. Moreover, integrated toolchains that combine architecture modelling, interface management, and requirement traceability are still under development, potentially limiting industrial adoption.

7 CONCLUSIONS

This research focused on tailoring SE processes for distributed satellite missions, particularly those involving autonomous formation flying of small satellites. The effort concentrated on the early stages of the system life cycle from need identification to logical decomposition and architectural definition reflecting a shift in abstraction from subsystem-level engineering to the coordination of SoS architectures. This direction emerged in response to expert reviews and was aligned with the overarching objective of addressing high-level mission requirements, harmonisation challenges, and architectural coherence across distributed mission elements.

Chapter 4 defined the proposed tailoring methodology, integrating classical SE frameworks such as those from NASA and ECSS with the specific challenges of distributed architectures. Rather than focusing on the detailed design of subsystems, the research aimed to define a scalable framework that supports concurrent development and synchronisation of all elements within a distributed constellation. This approach acknowledges the interdependence of platforms, inter-satellite interfaces, and ground segment elements, requiring the alignment of functional, physical, and operational perspectives.

The architectural breakdown introduced in Section 4.2 enables the systematic allocation of functions, responsibilities, and interfaces across mission segments, including satellites, ground stations, data centres, and user segments. The methodology facilitates the identification of harmonisation points and interface coordination requirements particularly critical in missions with multiple institutional contributors. Emphasis was placed on traceability, modularity, and iterative development, ensuring that evolving mission constraints and stakeholder needs could be accommodated effectively.

The tailored SE process contributes a structured mechanism to support the design of distributed missions operating under coordination constraints, with multiple autonomous spacecraft contributing to a common objective. Although the research did not address detailed subsystem engineering, it laid a foundation for

future work at lower abstraction levels and provided actionable insights for mission architects and SE practitioners engaged in SoS projects.

By developing a system wide tailoring approach rooted in mission level requirements and validated against international case studies such as TIM and TOM, this work advances the application of SE in the context of distributed space systems. It highlights the necessity of architectural integration, early stakeholder involvement, and harmonisation of requirements across subsystems. Future research should focus on implementing and validating the proposed methodology in operational settings, expanding the framework to support complex constellations and incorporating model-based and digital engineering tools for real-time system coordination and verification.

7.1 Objectives achievement

The objectives established for this research were successfully achieved, including the general objective and each of the three specific objectives defined at the outset of the study.

The general objective to propose a systems architecting process tailored to autonomous formation flying missions using small satellites, spanning from stakeholder need identification to detailed design was accomplished through the development and formalisation of a structured methodology presented in Chapter 4. This methodology defines activities for architectural decomposition, requirement allocation, and interface coordination across system-of-systems configurations, addressing the specific challenges of distributed spacecraft missions.

Specific Objective 1 (Identify key architectural design drivers relevant to monolithic satellites, DSM, and FFS) was met through the analysis presented in Chapter 4, Section 4.2, where spatial constraints, autonomy requirements, and coordination needs were identified as primary drivers. These were used to inform the mission architecture and guide the decomposition process.

Specific Objective 2 (Define and structure the architecting process activities needed to address autonomy, coordination, and interface design within

formation-flying missions) was fulfilled through the proposed tailoring methodology, which establishes phased activities and deliverables to manage architectural complexity, define harmonisation points, and support concurrent development across distributed elements.

Specific Objective 3 (Apply the proposed tailored architecting process through selected case studies involving distributed satellite systems) was addressed through illustrative applications based on publicly available data from the TIM and TOM and FACSAT 3 missions. These case studies were used to demonstrate the feasibility and relevance of the proposed approach under realistic constraints and configurations.

Although the initial scope included lower-level subsystem design, including, reviewer feedback prompted a refined focus on higher abstraction levels. Consequently, the final methodology addresses early life cycle phases and system of systems integration rather than detailed subsystem implementation.

7.2 Generality, applicability, relevance, usefulness, originality

The systems architecting process proposed in this research demonstrates broad applicability and generality within the context of distributed satellite missions, particularly those involving autonomous formation flying in LEO. Although the methodology was illustrated using conceptual references to specific case studies, its abstraction level allows for adaptation to a wide range of mission scenarios, including satellite constellations for Earth observation, telecommunications relays, and scientific cooperation missions across multiple institutions.

Its generality stems from the fact that the process is not constrained to a specific formation geometry or subsystem configuration, but rather focuses on architectural principles such as modularity, synchronisation, harmonisation of interfaces, and allocation of mission functions across multiple system elements. The approach supports scalability in terms of the number of satellites, varying levels of autonomy, and the inclusion of ground infrastructure and user segments within the same architectural framework.

In terms of applicability, the methodology can be adopted during the early stages of space mission development to guide the definition of requirements, logical decomposition, and interface coordination. It is particularly suitable for missions that require concurrent development of distributed elements and for organisations seeking structured mechanisms to align institutional responsibilities, technical interoperability, and stakeholder expectations across international collaborations.

The relevance of this contribution is reinforced by the increasing trend toward distributed, autonomous, and service oriented architectures. The proposed process addresses a current gap in Systems Engineering literature, offering a solution that bridges monolithic satellite development processes with the emergent needs of multi-agent and cooperative space systems.

Its usefulness lies in its ability to support decision-making at early lifecycle phases, providing a formalised and traceable structure that aligns system design with mission objectives while maintaining flexibility for future iterations. By prioritising harmonisation points and requirement allocation across system segments, the methodology enhances coherence and reduces integration risks in later stages.

This systemic view has not been thoroughly addressed in prior literature and offers a novel contribution to the field, particularly by formalising an architecting process adapted to DSM.

7.3 Future research

Future research should prioritise the operational implementation and validation of the proposed systems architecting framework in real or simulated mission environments. While this study focused on the early life cycle phases from stakeholder needs to architectural decomposition subsequent work must address the transition from architectural definition to detailed design, integration, and testing.

A key direction lies in extending the tailoring process to support more complex and heterogeneous constellations, incorporating multiple types of spacecraft, dynamic task allocation, and varying levels of autonomy. Additionally, there is a

need to develop digital tools and collaborative environments that facilitate architecture traceability, interface management, and scenario-based validation of distributed missions.

The integration of autonomy aware design mechanisms and adaptive coordination strategies particularly in relation to inter-satellite interactions and interface protocols presents another promising research avenue. These aspects are essential for supporting higher mission resilience and reconfigurability.

Finally, applying the tailoring methodology in diverse operational contexts (e.g., Earth observation, inter-satellite relays, and science-driven formations) would further demonstrate its generality and contribute to the refinement of architectural practices for future system-of-systems missions in the space domain.

REFERENCES

ANDERSON, L. et al. Enterprise modeling for CubeSats. In: IEEE AEROSPACE CONFERENCE, 2014, Big Sky, Montana, USA. **Proceedings…** IEEE, 2014. Available from: https://doi.org/10.1109/AERO.2014.6836343.

ANYANHUN, A. I.; EDMONSON, W. W. An MBSE conceptual design phase model for inter-satellite communication. In: IEEE INTERNATIONAL SYSTEMS CONFERENCE, 12., 2018, Vancouver, BC, Canada. **Proceedings…** IEEE, 2018. Available from: https://doi.org/10.1109/SYSCON.2018.8369575.

ASUNDI, S.; FITZ-COY, N. CubeSat mission design based on a systems engineering approach. In: IEEE AEROSPACE CONFERENCE, 2013, Big Sky, Montana, USA. **Proceedings…** IEEE, 2013. Available from: https://doi.org/10.1109/AERO.2013.6496900.

BATALEBLU, A. A. et al. Model-based Systems Engineering for sustainable factory design. **Procedia CIRP**, v. 122, p. 748-753, 2024. Available from: https://doi.org/10.1016/j.procir.2024.01.104.

BURRONI, T. et al. Distributed satellite system autonomous orbital control with recursive filtering. **Aerospace Science and Technology**, v. 145, 108859, 2024. Available from: https://doi.org/10.1016/j.ast.2023.108859.

CÁRDENAS-GARCÍA, J. M. et al. Análisis de partes interesadas para la misión satelital FACSAT-3. **Revista UIS Ingenierías**, v. 23, n. 3, p. 71-84, 2024. Available from: https://doi.org/10.18273/revuin.v23n3-2024006.

CHANG, Y.-K.; HWANG, K.-L.; KANG, S.-J. SEDT (System Engineering Design Tool) development and its application to small satellite conceptual design. **Acta Astronautica**, v. 61, n. 7/8, p. 676-690, 2007. Available from: https://doi.org/10.1016/j.actaastro.2007.01.067.

D'AMICO, S. **Autonomous formation flying in low Earth orbit**. 2010. 230 p. Thesis (PhD in Aerospatial Engineering) – Delft University of Technology, Delft, 2010.

DAI, C.-Q.; QoE-aware intelligent satellite constellation design in satellite Internet of Things. **IEEE Internet of Things Journal**, v. 8, n. 6, p. 4855-4867, 2021. Available from: https://doi.org/10.1109/JIOT.2020.3030263.

DE FLORIO, S.; D'AMICO, S.; ARDAENS, J.-S. Autonomous navigation and control of formation flying spacecraft on the PRISMA mission. In: INTERNATIONAL ASTRONAUTICAL CONGRESS, 61., 2010, Prague, Czech Republic. **Proceedings…** IAF, 2010.

EUROPEAN COOPERATION FOR SPACE STANDARDIZATION (ECSS). **ECSS-E-ST-10C Rev.1: Space engineering: system engineering general requirements**. Noordwijk: ECSS, 2017.

EUROPEAN COOPERATION FOR SPACE STANDARDIZATION (ECSS). **ECSS-E-ST-60-30C: space engineering: satellite attitude and orbit control system (AOCS) requirements**. Noordwijk: ECSS, 2013.

DE FLORIO, S. **Precise autonomous orbit control in low earth orbit: from design to flight validation**. 2013. 225p. Thesis (PhD in Aerospatial Engineering) – University of Glasgow, Glasgow, 2013. Available from: http://theses.gla.ac.uk/4502/.

GU, Y.; WANG, H.; ZHANG, M. Implementation optimal control model of smart grid engineering cluster construction based on Markov decision process. **Alexandria Engineering Journal**, v. 125, p. 399-408, 2025. Available from: https://doi.org/10.1016/j.aej.2025.04.046.

HAN, D. et al. BIS-model: an explicit SysML-based modeling and analysis framework for smart building systems. **Journal of Building Engineering**, v. 104, 112411, 2025. Available from: https://doi.org/10.1016/j.jobe.2025.112411.

HERZIG, S. et al. Integrating analytical models with descriptive system models: implementation of the OMG SyML standard for the tool-specific case of MapleSim and MagicDraw. **Procedia Computer Science**, v. 16, p. 118-127, 2013. Available from: https://doi.org/10.1016/j.procs.2013.01.013.

HIEP, C. X. **A Model-Based Systems Engineering (MBSE): approach to development of attitude determination and control subsystem for first micro-satellite in Vietnam**. 2016. Available from: https://www.researchgate.net/publication/332900693_A_Model-Based_Systems_Engineering_MBSE_Approach_to_development_of_Attitude_Determination_and_Control_Subsystem_for_First_Micro-_Satellite_in_Vietnam.

KWADRAT, C. F.; HORNE, W. D.; EDWARDS, B. L. Inter-satellite communications considerations and requirements for distributed spacecraft and formation flying systems. In: IEEE AEROSPACE CONFERENCE, 2003, Big Sky, MT, USA. **Proceedings...** IEEE, 2003. Available from: https://ntrs.nasa.gov/citations/20030025224.

KASLOW, D. et al. Developing a CubeSat model-based system engineering (MBSE) reference model-interim status. In: IEEE AEROSPACE CONFERENCE, 2015, Big Sky, MT, USA. **Proceedings...** IEEE, 2015. 18 p. Available from: https://doi.org/10.1109/AERO.2015.7118965.

LARSON, W. J. et al. **Applied space systems engineering**. [S. l.]: McGraw-Hill Education, 2009. 920p.

LARSON, W. J.; WERTZ, J. R. **Space mission analysis and design**. 3. ed. Dordrecht: Kluwer Academic Publishers, 1999. 919p.

LE MOIGNE, J. Distributed Spacecraft Missions (DSM) technology development at NASA Goddard Space Flight Center. In: IEEE

INTERNATIONAL GEOSCIENCE AND REMOTE SENSING SYMPOSIUM (IGARSS), 2018, Valencia, Spain. **Proceedings…** IEEE, 2018. p. 293–296. Available from: https://doi.org/10.1109/IGARSS.2018.8519065.

LE MOIGNE, J.; ADAMS, J. C.; NAG, S. A new taxonomy for distributed spacecraft missions. **IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing**, v. 13, p. 872-883, 2020. Available from: https://doi.org/10.1109/JSTARS.2020.2964248.

LIMA, I. et al. Optimization of patient flow in a cohort study using Business Process Model and Notation (BPMN). **Procedia Computer Science**, v. 256, p. 1224-1231, 2025. Available from: https://doi.org/10.1016/j.procs.2025.02.232.

LOUREIRO, G.; PANADES, W. F.; SILVA, A. Lessons learned in 20 years of application of systems concurrent engineering to space products. **Acta Astronautica**, v. 151, p. 44-52, 2018. Available from: https://doi.org/10.1016/j.actaastro.2018.05.042.

MURALI, N. **A systems engineering approach to small satellite mission formalization**. 2006. 169 p. Thesis (Master in Electrical Engineering) - Mississippi State University, Mississippi, 2006.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA). **NASA systems engineering handbook**. Washington, DC: NASA, 2016. (NASA/SP-2016-6105 Rev2). Available from: https://www.nasa.gov/connect/ebooks/nasa-systems-engineering-handbook.

NOSHCHENKO, O.; HAGSPIEL, V.; DESHPANDE, P. C. Assessing the sustainability of offshore platform power supply alternatives using Multi-Criteria Decision Analysis (MCDA): a case study of Norway. **Science of The Total Environment**, v. 973, e179053, 2025. Available from: https://doi.org/10.1016/j.scitotenv.2025.179053.

RADHAKRISHNAN, R. et al. Survey of inter-satellite communication for small satellite systems: physical layer to network layer view. **IEEE Communications Surveys & Tutorials**, v. 18, n. 4, p. 2442-2473, 2016. Available from: https://doi.org/10.1109/COMST.2016.2564990.

RIDOLFI, G.; MOOIJ, E.; CORPINO, S. A system engineering tool for the design of satellite subsystems. In: AIAA MODELING AND SIMULATION TECHNOLOGIES CONFERENCE, 2009, Chicago, IL, USA. **Proceedings...** Reston, VA: AIAA, 2009. Available from: https://doi.org/10.2514/6.2009-6037.

SOUZA, A. et al. Systems concurrent engineering for the conception of an attitude and orbit control system. In: ROZENFELD, H. et al. (Ed.). **Advances in concurrent engineering**. London: Springer, 2011. p.41-50. Available from: https://doi.org/10.1007/978-0-85729-799-0_5.

STANCEK, M. et al. Collaborative software design and modeling in virtual reality. **Information and Software Technology**, v. 166, 107369, 2024. Available from: https://doi.org/10.1016/j.infsof.2023.107369.

SUBRAMANIAN, G. P. et al. Information-driven systems engineering study of a formation flying demonstration mission using six CubeSats. In: AIAA AEROSPACE SCIENCES MEETING, 53., 2015, Kissimmee, FL, USA. **Proceedings...** Reston, VA: AIAA, 2015. Available from: https://doi.org/10.2514/6.2015-2043.

THANGAVEL, K. et al. Multidisciplinary design and optimization of intelligent distributed satellite systems for Earth observation. **Acta Astronautica**, v. 216, p. 411–427, 2024. Available from: https://doi.org/10.1016/j.actaastro.2023.12.055.

UNITED NATIONS OFFICE FOR OUTER SPACE AFFAIRS. **Guidelines for the long-term sustainability of outer space activities of the Committee on the Peaceful Uses of Outer Space**. Vienna: United Nations, 2021. (ST/SPACE/79).

UTAMA, D. M.; ABIRFATIN, M. Sustainable Lean Six-sigma: a new framework for improve sustainable manufacturing performance. **Cleaner Engineering and Technology**, v. 17, e100700, 2023. Available from: https://doi.org/10.1016/j.clet.2023.100700.

VANZETTA, M. et al. Bibliometric study on multicriteria decision analysis (MCDA) applied to the selection of operational means in a military environment. **Procedia Computer Science**, v. 242, p. 821-828, 2024. Available from: https://doi.org/10.1016/j.procs.2024.08.205.

WATSON, M. D.; MESMER, B. L.; FARRINGTON, P. A. **Engineering elegant systems: the practice of systems engineering**. Huntsville: NASA, 2020. (NASA/TP–20205003646).

WERTZ, J. R.; EVERETT, D. F.; PUSCHELL, J. J. (Ed.). **Space mission engineering: the new SMAD**. Hawthorne, CA: Microcosm Press, 2011. (Space Technology Library, v. 28).

WINGATE, L. M. The future of systems engineering: achieving positive outcomes in a complex world. In: _____. **Systems engineering for projects: achieving positive outcomes in a complex world**. New York: Auerbach, 2018. p. 243–272.

WU, P. P. Y.; MENGERSEN, K. A review of models and model usage scenarios for an airport complex system. **Transportation Research Part A: Policy and Practice**, v. 47, p. 124-140, 1 jan. 2013. Available from: https://doi.org/10.1016/j.tra.2012.10.010.

YANG, T.; CHEN, C.-W. An incentive pay system for project management based on responsibility assignment matrix and fuzzy linguistic variables. **Expert Systems with Applications**, v. 36, n. 6, p. 12585-12591, 2009. Available from: https://doi.org/10.1016/j.eswa.2009.05.067.

APPENDIX A - AEROSPACE JOURNAL DATA

Table A.1 -Aerospace Journal area the JCR greater than or equal to 0.5.

Journal Title	Issn	SJR	SJR Quartile
Progress in Aerospace Sciences	3760421	2,328	Q1
Mechanical Systems and Signal Processing	08883270 – 10961216	2,275	Q1
Journal of Guidance, Control, and Dynamics	15333884 – 07315090	1,573	Q1
International Journal of Impact Engineering	0734743X	1,534	Q1
Astrodynamics	25220098	1,418	Q1
International Journal of Industrial Organization	1677187	1,391	Q1
IEEE Transactions on Vehicular Technology	00189545 – 19399359	1,365	Q1
International Journal of Robust and Nonlinear Control	10498923 – 10991239	1,361	Q1
Journal of Intelligent Transportation Systems	15472450	1,321	Q1
Experimental Thermal and Fluid Science	8941777	1,307	Q1
Aerospace Science and Technology	12709638	1,277	Q1
Environmental and Resource Economics	09246460 – 15731502	1,27	Q1
Nonlinear Dynamics	0924090X - 1573269X	1,252	Q1
IEEE Transactions on Aerospace and Electronic Systems	189251	1,137	Q1
Acta Astronautica	945765	1,134	Q1
Journal of Propulsion and Power	15333876 – 07484658	0,913	Q1
International Journal of Engine Research	14680874 – 20413149	0,89	Q1
International Journal of Computer Integrated Manufacturing	0951192X – 13623052	0,884	Q1
Probabilistic Engineering Mechanics	02668920 – 18784275	0,884	Q1

(continue)

A.1 – Conclusion.

Journal Title	Issn	SJR	SJR Quartile
Multibody System Dynamics	13845640 - 1573272X	0,852	Q1
Navigation, Journal of the Institute of Navigation	00281522 – 21614296	0,847	Q1
Engineering Failure Analysis	13506307	0,84	Q1
AIAA Journal	1533385X – 00011452	0,828	Q1
Experimental Mechanics	00144851 – 17412765	0,815	Q1
Journal of Spacecraft and Rockets	15336794 – 00224650	0,758	Q1
JVC/Journal of Vibration and Control	10775463 – 17412986	0,734	Q1
Chinese Journal of Aeronautics	10009361	0,719	Q1
Drones	2504446X	0,713	Q1
Journal of the Astronautical Sciences	00219142 – 21950571	0,698	Q1
Advances in Space Research	02731177 – 18791948	0,682	Q1
International Journal of Structural Stability and Dynamics	2194554	0,648	Q1
Journal of Aircraft	218669	0,64	Q2
International Journal of Computational Fluid Dynamics	1061856 – 10290257	0,588	Q2
Mechanics Based Design of Structures and Machines	15397742 – 15397734	0,588	Q2
Journal of Engineering for Gas Turbines and Power	15288919 – 07424795	0,567	Q2
Optimization and Engineering	13894420	0,552	Q2
Journal of Thermophysics and Heat Transfer	15336808 – 08878722	0,548	Q2
Propulsion and Power Research	2212540X	0,541	Q2
New Space	21680264 – 21680256	0,534	Q2
Journal of Aerospace Engineering	8931321	0,521	Q2

Source: Scimago Journal & Country Rank (2020).

APPENDIX B - EVOLUTION OF AOCS IN FFS MISSIONS

Table B.1 – Evolution Of AOCS Of FFS Missions And The SE Applied To Space Products.

Year and place	Paper identification	Paper summary
1998 United States	CORAZZINI, T., ROBERTSON, A., ADAMS, J.C., HASSIBI, A. and HOW, J.P. Stanford University, Stanford, California	**Experimental Demonstration of GPS as a Relative Sensor for Formation Flying Spacecraft** The paper describes the application of carrier-phase differential GPS (CDGPS) techniques to high-accuracy positioning and Attitude determination in a testbed of 3 vehicles in formation flying. It is approached considering two architectures, distributed and centralized control in static and dynamic cases. The behaviors were analyzed from simulations and experimentally, in order to estimate the position error. Experimentally results shows that techniques used has high-accuracy, approximately 2 cm error position. Additionally, were compared both architectures, the distributed architecture has the less computational cost.
1999 Brazil England	G. Loureiro, Mr. and P. G. Leaney, Dr. Brazilian Institute for Space Research (INPE) Loughborough University,	**A SYSTEMS ENGINEERING ENVIRONMENT FOR INTEGRATED SATELLITE DEVELOPMENT** There is approached the application of systems engineering in integrated satellite development. Considering functional and lifecycle process requirements was implemented a commercial system engineering environment (SEE) software package. The application of systems engineering in space product development, results in lower lifecycle cost and shorter development.
2002 United Kingdom	S. M. Veres, S. B. Gabriel., D. Q. Mayne and E. Rogers. University of Southampton, D. Q. Mayne Imperial College	**Analysis of Formation Flying Control of a Pair of Nanosatellites** In this note is proposed a solution to stabilization and maneuver control of two nanosatellites in formation flying throughout a “Diamon” method used to compute approximate controllability set.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2003 Brazil England	G. Loureiro, P.G. Leaney Brazilian Institute for Space Research – INPE Loughborough University,	**A systems and concurrent engineering framework for the integrated development of space products** In this document is proposed an approach a framework to space product development called “total view framework”, supported by “concurrent structured analysis method”, integrating the Systems Engineering (SE) and Concurrent Engineering (CE) that consists of the three analysis processes: requirements, functional and physical. There was proposed: - Generic model of integrated product - Development - The total view framework - SE and CE within the total view framework - The concurrent structured analysis method - An integrated satellite development example - The Impact Finally, this document shows the need to apply early the development of space product integrating the requirements and function throughout lifecycle process.
2006 UK	K.K.T. Thanapalan, S.M. Veres, E. Rogers and S.B. Gabriel University of Southampton	**Fault Tolerant Controller Design to Ensure Operational Safety in Satellite Formation Flying** Initially, is described some benefits about use of formation flying of several smaller satellites, between them, the failure of one satellite not necessarily result in failure of the whole mission, the interchange roles between satellites, smaller overall cots, fulfillment of missions together, among others. Then, states that control of these satellites is subject of much research effort in the control system community. In this way, is proposed a reconfigurable position control (RPC) based on model reference adaptive control (MRAS) method. It consists of changing the control structure of the satellites in case of finding a fault, it is possible to have a new leader satellite, by means of a new direct reconfigurable satellite method. The design of the control system that does not use fault detection and isolation (FDI) and redesign of the system is investigated. Additionally, model reference adaptive control and quaternion based adaptive feedback control were proposed.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2007 Korea	Young-Keun Chang, Ki-Lyong Hwang and Suk-Jin Kang School of Aerospace and Mechanical Engineering Aerospace University	**SEDT (System Engineering Design Tool) development and its application to small satellite conceptual design** Is presented the software tool "Systems Engineering Design Tool" (SEDT) in order to minimize the amount of labor involved in the conceptual design phase of small satellites. It can be applied in satellite conceptual design and early satellite development proposal phases. It is not directly relationship with formation flying systems, however, it is one more proposal about of Systems engineering applied to space product.
2007 UK	Sandor Veres, Nick Lincoln and Steve Gabriel University of Southampton	**Testbed for Satellite Formation Flying Under Ground Conditions** Is presented a formation flying testbed for ground-based testing of satellite formation control from two approaches Ground-based Satellite Frames Testing (GSFT) and Hardware in the Loop Testing (HILT), testing of the processors and communication Electronics and control algorithms, respectively. Despite not being a test to certify space products, it is part of the life cycle of the space product in the AIT.
2009 Norway	Raymond Kristiansen and Per Johan Nicklasson Narvik University College.	**Spacecraft formation flying: A review and new results on state feedback control.** The paper presents some works about spacecraft formation flying modeling approaches and controller design. However, in Formation flying systems. Shall be considered the strict and time-varying boundaries on spacecraft reference trajectories, and collisions between spacecraft should of course be avoided at all costs. Considering the spacecraft masses and orbital parameters as altitude, eccentricity and inclination, were proposed five controllers' model, throughout simulation were computed settling time, Power consumption and max error. The controller analyzed were: PD, Lyapunov, Velocity SS, Position SS and Backstepper

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2009 Norway	Raymond Kristiansen and Per Johan Nicklasson Narvik University College.	Results from simulation were presented, and compared considering the power consumption and tracking performance.
2010 China	Hu Min, Zeng Guoqiang and Song Junling The Academy of Equipment Command & Technology Institute of Aerospace and Material Engineering National University of Defense Technology	**Navigation and Coordination Control System for Formation Flying Satellites** This research presents the guidance, navigation and control (GNC) system design and architecture able to enable the control of formation flying satellites on near-circular orbits. Then, was proposed a distributed architecture of the simulation systems and the complete GNC system by combining the leader and chaser satellite. To determine the relative orbit, the chaser satellite receive the GPS information and apply an extended Kalman filter.
2012 Scotland, United Kingdom	Derek J. Bennet and Colin R. McInnes. University of Strathclyde	**Pattern transition in spacecraft formation flying using bifurcating potential fields** In this case is developed a new methodology for the control of multiple spacecraft. Based on the artificial potential function method using bifurcation theory as a means of controlling the transition between different formations. It consists in each satellite move to an equal distance from other to reconfigure positions between them. The simulations performed considered the gravitational effects in low-Earth-orbit.
2012 Germany Sweden	S. D'Amic, J.-S. Ardaens and R. Larsson DLR, German Aerospace Center OHB Sweden	**Spaceborne Autonomous Formation-Flying Experiment on the PRISMA Mission** This research approaches the Prototype Research Instruments and Space Mission Technology Advancement (PRISMA), it is the first European technology demonstration of formation-flying and on-orbit-servicing techniques. There is described the guidance, navigation, and control (GNC) functionalities and the Spaceborne Autonomous Formation-Flying Experiment (SAFE). The GNC architecture as a top-level functional view of the GPS-based GNC system is described based on self-contained GNC system for autonomous formation acquisition, keeping, and reconfiguration.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2013 Netherlands Belgium	E. Gill, P. Sundaramoorthy, J.Bouwmeester, B.Zandbergen And R. Reinhard Delft University of Technology von Karman Institute for Fluid Dynamics	**Formation flying within a constellation of nano-satellites: The QB50 mission** The QB50 mission is an international network of 50 nano-satellites for multi- point. The Delft University of Technology intends to contribute with two nanosatellites in Formation Flying (FF), this paper presents the opportunities and challenges about it. About FF the major opportunities are: - Enhanced science return. - Technology demonstration Finally, is described that FF is an innovative and Unique subject. Thus, a variety of new research areas have been identified in science, technology, engineering and operations.
2014	Anna Guerman, Erick Lansard and Alfred Ng Guest editors - Acta Astronautica	**Satellite constellations and formation flying** This document mentions the growth of the satellite constellations and the increase of interest in formation flying missions. Thus, is described the International Work-shop of Satellite Constellation and Formation Flying (IWSCFF), idea of IWSCFF was discussed and decided by the Astrodynamics Committee at the 48th IAC Beijing in 1996. Only in the 7th IWSCFF 120 papers from 25 countries were submitted, 68 papers accepted after a thorough review process, and 50 papers were presented at the workshop thematic sessions.
2014 Taiwan	Huan-Sheng Chen, Yusie Rizal, Ming-Tzu Ho National Cheng Kung University	**Cold Gas Attitude Control Systems** The paper discusses the development of a cold gas attitude control system for spacecraft, highlighting the system's configuration including sensors, gas tanks, and solenoid valves. The research focuses on the dynamics and control mechanisms, employing a bang-bang control approach and verifying it through simulations and experimental results.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2016 Germany.	Johannes Gross and Stephan Rudolph University of Stuttgart	**Modeling graph-based satellite design languages** In this paper is proposed the Graph-based design language using Unified Modeling Language (UML) to spacecraft designs. As an example, the FireSat mission given in the textbook "Space Mission Analysis and Design," from Wertz is used to demonstrate the analysis of designs in shorter time.
2018 Brazil	G. Loureiro, W.F. Panades and A. Silva Brazilian Institute for Space Research – INPE	**Lessons learned in 20 years of application of Systems Concurrent Engineering to space products** The paper presents the lessons learned in 20 years of application of Concurrent Systems Engineering (CSE) applied in the Brazilian Strategic Program for Space Systems (PESE) and the satellite formation "Telematics International Mission" (TIM). Mainly, is described since the beginning of the method in 1999 to the method proposed in 2017, considering the analysis of Stakeholders, requirements, functions and implementation, additionally, the integration of product and services, and finally the hierarchical structure of mission layer.
2020 South Africa	Dr. Rudolph Oosthuizen and Prof. Leon Pretorius University of Pretoria and CSIR	**A Bibliometric Method for Analysis of Systems Engineering Research** This research presents a method to determine the main research topics published in the Systems Engineering Journal (INCOSE) considering a bibliometric analysis, Natural language processing and a method based in research question. Thus, were identified 9 topics: Systems Engineering Process Systems Management Decision Support Requirements Engineering Product Development Complex Systems Engineering Systems Architecting Systems Modelling Systems Design Finally, the application of the method is proposed to incorporate the fringe systems engineering publications such as IEEE Systems, ASME JCISE, ASME, JMD, MDPI Systems

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2020 United States	Jacqueline Le Moigne, John Carl Adams, and Sreeja Nag NASA	**A New Taxonomy for Distributed Spacecraft Missions** In this paper is presents a taxonomy for Distributed Spacecraft Missions (DSM) based on 3 main characteristics and some categories within them: **Organization** Appearance Inter-Spacecraft Relationships **Physical configuration** Spatial Relationship Spatial Control Temporal Relationship Temporal Control **Functional configuration**. Functional Distribution Autonomy
2020 United States	Melanie L. Grande, Ashish S. Patel, Liam D. Durbin, and Daniel DeLaurentis School of Aeronautics and Astronautics, Purdue University	**Modeling Architectures and Parameterization for Spacecraft** In this paper is presents the Modeling Architectures and Parameterization for Spacecraft (MAPS) environment in order to realize a model-based systems engineering (MBSE) philosophy for spacecraft applications applying Systems Modeling Language (SysML) and orbital trajectory analysis for mission simulations. It is applied to a low-Earth orbit satellite constellation study, generating Notional diagram depicting the baseline constellation, assembly-level Block Definition Diagram (BDD), Attitude Determination and Control Subsystem BDD, Propulsion Subsystem BDD, Propulsion Subsystem Internal Definition Block Diagram (IBD), Orbital Trajectory Analysis, Architecture Design and Design Evaluation.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2021 Republic of Korea	Youngbum Song, Sang-Young Park, Sangwon Lee, Pureum Kim, Eunji Lee and Jaejin Lee Yonsei University Korea Astronomy and Space Science Institute	**Spacecraft formation flying system design and controls for four nanosats mission** This research aims to design a spacecraft formation flying composed by four nanosats, called the "Ionosphere Plasma Experiment (SNIPE) mission". It proposes changes the formation flying shapes and size in two phases, the Cross-track and Along-track phases. The design of formation flying system considers the coordinate system, Top-level requirements, orbital scenarios and constraints. Additionally, the control system is addressed, considering Orbit control methods (drift recovery, station keeping, initial configuration, and reconfiguration control, were derived.) and Attitude of the nanosat for orbit controls. Through simulations was validated the time interval between the orbital information and orbit control, the inability to control the attitude during orbit control, constraints on power stability, and characteristics of the thrust module.
2021 USA Madrid	Nathan Reiland, Aaron J. Rosengren, Renu Malhotra, Claudio Bombardelli Aerospace and Mechanical Engineering, University of Arizona, Mechanical and Aerospace Engineering, Lunar and Planetary Laboratory, University of Arizona, Space Dynamics Group, Technical University of Madrid,	**Assessing and minimizing collisions in satellite mega-constellations** This study presents a novel algorithm for conjunction prediction in satellite mega-constellations. The research includes baselines of endogenous conjunction events for OneWeb LEO and SpaceX Starlink mega-constellations. A probabilistic approach from Solar-System dynamics is applied to improve close-encounter prediction. The results provide valuable insights for satellite operators and researchers to evaluate and mitigate collision risks effectively in mega-constellations.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2021 Republic of Korea	Eunji Lee, Jihae Son, Sang-Young Park Department of Astronomy, Yonsei University	**Title: Relative navigation technique with constrained GNSS data for formation-flying CubeSat mission, CANYVAL-C** This study presents a relative navigation technique for a formation-flying CubeSat mission. The technique aims to achieve precise relative positioning between two CubeSats, by incorporating adaptive parameter tuning in the EKF. Hardware-in-the-Loop Simulations are conducted to validate the performance of the proposed technique, demonstrating a relative positioning error of 10 to 20 cm on each axis, meeting the mission requirement of 1 m. The results indicate the effectiveness of the navigation approach in constrained GNSS environments for CubeSat missions.
2021 China	Qingliang Meng, Meiyu Huang , Yao Xu, Naijin Liu, and Xueshuang Xiang Qian Xuesen Laboratory of Space Technology, China Academy of Space Technology	**Decentralized Distributed Deep Learning with Low-Bandwidth Consumption for Smart Constellations** Abstract: With the advancement of artificial intelligence and onboard computing capabilities, this paper presents RD-PSGD, a method for decentralized distributed training in low-bandwidth networks for smart constellations. The approach enables efficient utilization of real-time sensing data from multiple satellites, addressing the need for onboard learning to adapt to dynamic changes in observation scenes. The study explores the benefits of distributed deep learning in improving collaborative perception and cognitive capabilities of space-based remote sensing systems
2021 Italy	S. Huang ∗,1 , C. Colombo2 , F. Bernelli-Zazzera3 Politecnico di Milano	**Multi-criteria design of continuous global coverage Walker and Street-of-Coverage constellations through property assessment** This research paper presents a systematic method for the design of continuous global coverage Walker and Street-of-Coverage constellations by assessing critical constellation properties. The authors identify seven key properties (coverage, robustness, self-induced collision avoidance, launch, build-up, station-keeping, and end-of-life disposal) as design criteria. Through the analysis of characteristic parameters, the constellation configuration is determined, and a series of indexes are proposed to quantitatively assess the constellation properties. By formulating a multi-objective optimization problem, the study aims to find globally optimal constellations for specific missions, contributing to the advancement of constellation design methodologies in the field of aerospace engineering.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2021 Finland	Antti Anttonen ∗ , Markku Kiviranta, Marko Höyhtyä VTT Technical Research Centre of Finland	**Space debris detection over intersatellite communication signals** This innovative method aims to address the challenges of long-distance and ground-based detection without the need for a separate radar infrastructure. The study evaluates the performance of the Space-borne Radar and Communications (SBRC) concept in the context of high-density constellations and 5G satellites, uncovering new insights through advanced simulations.
2021 South Korea	Soung Sub Lee Department of Aerospace System Engineering, Sejong University	**Closed-form solution of repeat ground track orbit design and constellation deployment strategy** A novel approach is proposed for designing circular repeat ground track (RGT) orbits and optimizing satellite constellation deployment. The research presents a closed-form formula with low computational cost for designing RGT orbits and multiple satellites with identical constellation patterns. Additionally, a satellite deployment strategy is suggested to minimize revisit time by aligning the RGT orbit intersection point of the satellite group over a specific target. The study contributes to the field of RGT orbit dynamics by providing efficient design solutions and deployment strategies for satellite constellations.
2021 China	Quan Chen, Giovanni Giambene, Lei Yang, Chengguang Fan, and Xiaoqian Chen National University of Defense Technology Università degli Studi di Siena University of Technology Sydney	**Analysis of Inter-Satellite Link Paths for LEO Mega-Constellation Networks** The research sheds light on the intricate network paths within LEO mega-constellations. The analysis aims to provide insights into optimizing the performance of these networks, which is crucial for the future development and deployment of satellite communication systems.
2021 China	Sijing Ji, Di Zhou, Min Sheng, Jiandong Li Xidian University	**Mega Satellite Constellation System Optimization: Network Control for Future Space Wireless Communications Networks** The focus is on proposing an optimal network control structure that can significantly enhance the temporal effectiveness of network control operations. By addressing the challenges associated with managing massive network nodes in space, the study aims to improve the efficiency and reliability of operations and services within space wireless communications networks.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2021 USA	Chloe Gentgen, Sheila Baber, William E. Parker, Elwyn Sirieys, Shane J. Vigil, Benjamin Yu, Maria Regina Apodaca Moreno, Daniel Erkel, Madelyn A. Hoying, Seamus Lombardo, Aaron Makikalli, Codrin Oneci, Ufuoma Ovienmhada, Edward D. Crawley, Olivier L. de Weck Massachusetts Institute of Technology	**A Path to Flight for Reconfigurable Satellite Constellations: Mission Design and Systems Architecture** This paper introduces the concept of reconfigurable satellite constellations (ReCon) designed to offer timely and targeted data on demand. The operational modes of ReCon constellations include a Global Observation Mode (GOM) for global coverage and a Regional Observation Mode (ROM) for higher revisit frequencies over specific locations of interest. The paper outlines the design of a 12U CubeSat demonstrator mission named ROAMS (Reconfigurable on-Orbit Adaptive Maneuverable Spacecraft) and a propulsion payload de-risking effort on Aerospace's Slingshot-3 (SS-3) mission. The study emphasizes the necessity of hybrid chemical/electric propulsion systems to achieve the required revisit frequency, mission longevity, and time-to-target performance. The mission objective of ROAMS involves executing transfers between GOM and RGT ROM orbits to enhance disaster prevention capabilities and weather forecasting accuracy.
2022 USA	Athip Thirupathi Raj, Jekan Thangavelautham University of Arizona	**High-Speed Docking and Applications for Small Spacecraft** The study examines various docking adapters like inflatables and electromagnetic systems that can handle higher relative velocities, which are crucial for docking non-cooperative targets such as space debris.
2022 USA	Giovanni Lavezzi, Nathan J. Stang, Marco Ciarcià South Dakota State University	**Development of a Low-Cost Satellite Three-Axis Attitude Simulator Testbed** This study introduces the development and preliminary testing of a Suspended Satellite Three-Axis Rotation Testbed (START), a low-cost solution for simulating satellite attitude control. The testbed comprises a suspended 3D printed platform, a single-board processor, reaction wheels, and a battery, providing a three degrees-of-freedom rotation range. The setup allows for minimal resistive torque and precise equilibrium adjustments. A PC workstation and motion capture system facilitate the generation and streaming of desired angular rates for hardware-in-the-loop experimentation of attitude control strategies. START offers a cost-effective alternative to traditional simulators, enabling educational and research purposes in the field of spacecraft attitude determination and control.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2022 China	Yong Zhao, Qingguang Zhao, Fei Yang, Honghao Yue, Xiaoze Yang, Huaiyu Li Harbin Institute of Technology Shanghai Institute of Satellite Engineering	**Design and Analysis of a Compression and Separation Device for Multi-Satellite Deployment** This paper discusses the design and analysis of a novel compression and separation device for multi-satellite deployment, specifically focusing on improving the efficiency of launching and releasing multiple satellites simultaneously. The device employs a four-bar perimeter arrangement to compactly store and then reliably release satellites into orbit, aiming to enhance the deployment process and reduce the risk of collision between satellites during separation.
2022 Egypt UK Czech Republic	Mohamed Torky, Tarek Gaber, Essam Goda, Vaclav Snasel, Aboul Ella Hassanien Higher Institute of Computer Science and Information Systems University of Salford Arab Academy for Science, Technology and Maritime Transport VSB Technical University of Ostrava	**A Blockchain Protocol for Authenticating Space Communications between Satellites Constellations** This article presents a blockchain protocol designed to authenticate communications between satellite constellations, enhancing security and reliability in space operations. The protocol, called Proof of Space Transactions (PoST), utilizes blockchain technology to manage and secure satellite communications, focusing on mitigating risks associated with satellite data transactions and ensuring integrity and authentication of data exchanged between satellites.
2022 China	Leyuan Sun, Jun Yang c,Wende Huang , Laping Xu, Shaochuan Cao, Haidong Shao Xichang Satellite Launch Center Shanghai Key Laboratory of Space Navigation and Positioning Techniques National University of Defense Technology Hunan University	**Inter-satellite Time Synchronization and Ranging Link Assignment for Autonomous Navigation Satellite Constellations** The research emphasizes the importance of time synchronization for the entire constellation and introduces the concept of link assignment matrices and visibility matrices to model the problem of link assignment combining time synchronization and ranging. The paper highlights the significance of self-maintaining the time-space reference of the navigation satellite constellation through autonomous orbit determination and communication. Additionally, it discusses the use of ISLs in the Ka band with narrow beams for successful operation in orbit, demonstrating the evolution of ISL features in navigation systems.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2022 United Kingdom USA	Joshua F Anderson, Michel-Alexandre Cardin, Paul T. Grogan Imperial College London Stevens Institute of Technology	**Design and Analysis of Flexible Multi-Layer Staged Deployment for Satellite Mega-Constellations under Demand Uncertainty** The research focuses on the potential benefits of staged deployment in addressing the challenges posed by fluctuating demand in internet satellite constellations. By exploring the integration of flexibility and adaptability into satellite system design, the authors aim to enhance economic performance, sustainability, and resilience in the face of uncertainty. Through a comprehensive analysis, the study sheds light on the strategic advantages of multi-layer satellite constellations and the value of incorporating real options to optimize the design of satellite mega-constellations.
2022 USA	David Arnas Richard Linares Purdue University Massachusetts Institute of Technology	**Uniform Satellite Constellation Reconfiguration** The study focuses on leveraging the properties of 2D Lattice Flower Constellations and uniform distributions to address the challenges associated with satellite constellation reconfiguration. The authors present analytical methods for defining the distribution of both uniform and nonuniform satellite constellations using a minimal number of distribution parameters, providing a compact formulation for designing satellite constellations. The research aims to contribute to the advancement of satellite constellation design and optimization for various space missions.
2023 USA	Matthew L. Marcus, Henock A. Legesse, David H. Richardson NASA Goddard Space Flight Center	**A Model-Based Framework for NASA Science Mission Formulation** This paper outlines the use of a Digital System Model (DSM) to implement NASA's systems engineering standards in early mission formulation stages. The framework supports the development of Master Equipment Lists (MELs), Science Traceability Matrices (STMs), and Mission Traceability Matrices (MTMs), facilitating enhanced project documentation and stakeholder communication.
2023 USA	Sean Marquez, Kevin Chiu, Sharanabasaweshwara Asundi Old Dominion University	**Model-Based CubeSat Flight-Software Architecture using a Docs-as-Code approach** The paper introduces a novel model-based systems engineering (MBSE) approach to developing flight software architectures for CubeSats, utilizing a documentation-as-code methodology. It details the process and benefits of integrating software development practices into the design and management of spacecraft systems documentation.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2023 USA United Arab Emirates Egypt	Mohammed Atallah, Mohamed Okasha, Haitham Elshimy Iowa State University United Arab Emirates University Beni Suef University	**Design and Implementation of an Attitude Determination and Control Subsystem testbed for up to 12-U CubeSat" (2023)** The document focuses on creating a testbed for attitude determination and control systems, applicable for up to 12-U CubeSats. This will allow practical experiments and testing of control strategies for small satellites, aiding in the advancement of CubeSat technologies.
2023 Republic of Korea	Desalegn Abebaw Zeleke Hae-Dong Kim University of Science and Technology Gyeongsang National University	**A New Strategy of Satellite Autonomy with Machine Learning for Efficient Resource Utilization of a Standard Performance CubeSat** This paper introduces a novel approach to satellite autonomy using machine learning to optimize resource utilization on CubeSats. It discusses the development and implementation of a machine learning model for image classification and task scheduling to enhance the efficiency of onboard resource management, particularly for Earth observation satellites covered frequently by clouds.
2023 China	Pei Chen, Xuejian Mao, Siyu Chen Beihang University	**LEO Satellite Navigation Based on Optical Measurements of a Cooperative Constellation** This research presents a cooperative constellation navigation system for LEO satellites utilizing optical measurements. It proposes a method to improve navigation precision through photometry and line-of-sight vector calculations, which supports a high-precision spacecraft orbit estimation with a least square batch filter, validated by simulation studies.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2023 Australia Italy Argentina United Arab Emirates	Kathiravan Thangavel, Pablo Servidia, Roberto Sabatini, Pier Marzocca, Haytham Fayek, Santiago Husain Cerruti, Martin España, Dario Spiller RMIT University Sapienza University of Rom Comisión Nacional de Actividades Espaciales (CONAE) Khalifa University SmartSat Cooperative Research Centre	**A Distributed Satellite System forMulti-baseline AT-InSAR: Constellation of Formations for Maritime Domain Awareness Using Autonomous Orbit Control** The paper explores a distributed satellite system design using multi-baseline AT-InSAR for maritime domain awareness. It discusses the integration of autonomous orbit control with synthetic aperture radar technologies to effectively manage satellite formations, aiming at enhancing the capabilities of maritime surveillance and monitoring.
2023 China	Yifei Jiang, Wanxia He, Wenzheng Liu, Shufan Wu, Xiao Wei, Qiankun Mo Shanghai Jiao Tong University Shanghai Aerospace Computer Technology Institute Shanghai Aerospace Systems Engineering Institute	**A B5G Non-Terrestrial-Network (NTN) and Hybrid Constellation Based Data Collection System (DCS)** This document proposes a B5G non-terrestrial network and hybrid constellation-based system for data collection. It utilizes CubeSats to achieve global coverage and incorporates a 5G terrestrial network as a data bearer, proposing a traffic load balance strategy and utilizing software-defined radio for compatibility with various sensor data models.
2023 Italy	Giovanni Zanotti, Michele Ceresoli, Andrea Pasquale, Jacopo Prinetto, Miche`le Lavagna Politecnico di Milano	**High-performance lunar constellation for navigation services to Moon orbiting users** This study presents a strategy for designing a small-sized lunar constellation to provide navigation services to Moon orbiting users. The design process involves multi-objective optimization to determine the optimal constellation configuration that can support critical Guidance, Navigation, and Control (GNC) tasks. Various optimized constellations are tested to evaluate their performance in assisting missions visiting the Moon. The results highlight the effectiveness of the proposed approach in designing a high-performance lunar constellation for navigation services.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2023 Republic of Korea	Mohammed Irfan Rashed, Hyochoong Bang Korea Advanced Institute of Science and Technology	**A study of Cognitive Computing in Nanosatellite Constellations for Synergic Autonomy in CisLunar Space** This study delves into the integration of cognitive computing technologies within nanosatellite constellations to achieve synergic autonomy in CisLunar space. Explore the potential benefits and challenges of implementing Artificial Intelligence in small satellite operations, aiming to enhance efficiency and productivity. By leveraging cognitive computing, these constellations can navigate the complexities of operations in Low Earth Orbit (LEO) and beyond, paving the way for innovative applications in disaster management, deep space exploration, and more.
2023 China Australia	Yixin Huang, Shufan Wu, Zeyu Kang, Zhongcheng Mu, Hai Huang, Xiaofeng Wu, Andrew Jack Tang, Xuebin Cheng Shanghai Jiao Tong University Beihang University The University of Sydney China Aerospace Science and Industry Corporation	**Reinforcement learning based dynamic distributed routing scheme for mega LEO satellite networks** Mega LEO satellite networks are gaining attention for their low latency, broadband communication, and global coverage. One of the main challenges in LSN systems is the calculation and maintenance of routing strategies due to the scale and dynamic network topology of LSN constellations. The QRLSN scheme aims to address these challenges by utilizing reinforcement learning to optimize routing strategies in a distributed and autonomous manner. By updating routing strategies in real-time, reducing computational resource consumption, and considering Quality of Service (QoS) requirements, QRLSN offers a promising solution for efficient communication in mega LEO satellite networks.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2023 Spain UK	Angel David Arcia Gil, Daniel Renwick, Chantal Cappelletti, Paul Blunt University of Vigo University of Nottingham	**Methodology for optimizing a Constellation of a Lunar Global Navigation System with a multi-objective optimization algorithm** Global Navigation Satellite Systems (GNSS) play a crucial role not only in terrestrial applications but also in space missions, including Low-Earth orbit satellites and higher altitude endeavors. This study focuses on optimizing a Constellation of a Lunar Global Navigation System using a multi-objective optimization algorithm. With the resurgence of plans for Lunar exploration by national space agencies, the need for accurate and reliable navigation systems has become paramount. The research methodology involves numerically simulating orbits and utilizing the Position Dilution of Precision (PDoP) as a metric to optimize a variety of constellation designs. Through 1864 generations and the evaluation of 12,000 unique designs, the study presents the top 10 optimized constellations, showcasing a 44% improvement in PdoP compared to existing literature. These optimized designs aim to meet the performance requirements of planned Lunar missions, emphasizing the potential of GNSS technology in space exploration.
2023 China	Jiaxin Zhang, Kaiwei Wang, Rui Li, Zhaoyang Chang, Xing Zhang, and Wenbo Wang Beijing University	**MaCRo: Mega-Constellations Routing Systems with Multi-Edge Cross-Domain Features** This work explores the complexities of non-terrestrial networks (NTN) and proposes a novel routing system that integrates multi-edge and cross-domain features. By leveraging the capabilities of Mega-Constellations, the MaCRo system aims to enhance network performance and flexibility, offering a promising solution for the evolving landscape of satellite communications in the era of 6G networks.
2024 USA	Yuri Shimane, Nicholas Gollins, Koki Ho Georgia Institute of Technology	**Orbital Facility Location Problem for Satellite Constellation Servicing Depots** This research introduces a new approach to the facility location problem in space, specifically for servicing satellite constellations. The authors developed a mathematical model to determine optimal locations for servicing depots, considering the dynamics of orbital mechanics and the logistical needs of satellite maintenance, effectively applying terrestrial logistics principles to space applications.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2024 Republic of Korea	Minkeon Lee, Seunghyeon Yu, Kybeom Kwon, Myungshin Lee, Junghyun Lee, Heungseob Kim Changwon National University Agency for Defense Development Korea Aerospace Research Institute	**Mixed-Integer Linear Programming Model for Scheduling Missions and Communications of Multiple Satellites** This study addresses the challenges of scheduling missions and communications for multiple satellites and ground stations. It proposes a mixed-integer linear programming (MILP) model that assigns time windows for missions and communications, optimizing satellite utilization. This is especially critical as the number of satellites and the diversity of their missions increase.
2024 Italy	Giacomo Borelli, Gabriella Gaias, Camilla Colombo Politecnico di Milano	**Guidance and Control for Safe Contactless Plume Impingement Operations to Detumble an Uncooperative Spacecraft** The article explores advanced guidance and control methods for performing safe, contactless plume impingement operations to stabilize uncooperative spacecraft. It details a strategy employing the differential pressure forces exerted by a servicer's thruster plume to control tumbling motions of a target spacecraft, enhancing the safety and feasibility of proximity operations without physical contact. The methodology involves detailed simulations and focuses on increasing the effectiveness of detumbling operations while managing the delta-v costs and ensuring operational safety during complex maneuvers.
2024 Switzerland	Lukas Muller, Kangkang Chen, Gregor Moller, Markus Rothacher, Benedikt Soja, Lola Lopez Institute of Geodesy and Photogrammetry Astrocast SA	**Real-time navigation solutions of low-cost off-the-shelf GNSS receivers on board the Astrocast constellation satellites** The analysis focuses on the performance of eight CubeSats equipped with multi-GNSS single-frequency payloads. The study examines the impact of varying interference signals emitted by the satellite platform during eclipse periods on the navigation solutions. The geometric distribution of GNSS observations from different antenna locations on the satellites is also analyzed. The findings provide insights into the effectiveness of these navigation solutions for constellation maintenance, formation flying, communication optimization, collision avoidance, and Earth observation using small satellites.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2024 Italy	Daniele Barberi Spirito, Jacopo Prinetto, Andrea Capannolo, Miche`le Lavagna Politecnico di Milano	**Data Relay Constellation for high-performance links supply to future Martian missions** The paper proposes a distributed Mars-based orbiting system servicing as a communication relay for any scientific and technological mission operating on the red planet's surface. The paper explores the design of a small satellites Martian constellation to maximise the surface coverage and visibility time with respect to ground users while reducing the station keeping efforts of the assets. A relatively novel proposed approach is to exploit the so-called Trans Areostationary Orbits (TASO), which allow low drift of the spacecraft with respect to Mars' surface, with an improved orbital stability than the perfectly stationary orbits. The paper aims at extending the available options by exploring trajectories that leverage the third body gravitation from the two Martian moons, Phobos and Deimos, to possibly further improve stability, coverage of the surface, communication datarates, and manoeuvres costs in general. The costs include the operative phase, as well as all the transfers from Earth to the Martian sphere of influence. As a final contribution, the paper explores the concept of Linked, Autonomous, Inter-planetary Satellite Orbit Navigation (LiAISON) for the proposed constellation configurations, to verify the possibility of reconstructing the spacecraft states through relative-only measurements.
2024 China	Yingkai Caia, Yichao Lia, Zhaokui Wang Tsinghua University	***Real-time High-precision Baseline Measurement of Satellite Formation Flying Based on GNSS*** The research focuses on the development of a GNSS-based real-time measurement module to enhance the accuracy and efficiency of satellite formation operations. By improving the Klobuchar model for GNSS single-frequency ionospheric delay corrections and implementing submillimeter-level relative navigation technology, the study demonstrates significant advancements in spacecraft formation flying in highly elliptical orbits. Furthermore, the evaluation of precise microwave ranging technology for low Earth orbit formation missions and the exploration of on-orbit space technology experiments near the Tiangong space station highlight the potential applications of satellite formations in space science missions. Overall, the findings contribute to the enhancement of GNSS-based measurement systems for precise satellite formation flying and space technology experiments.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2024 Germany Sweden	Bharadwaj Chintalapati, Arthur Precht, Sougata Hanra, Rene Laufer, Marcus Liwicki, Jens Eickhoff Lulea˚ University of Technology Airbus Defence and Space University of Stuttgart	**Opportunities and challenges of on-board AI-based image recognition for small satellite Earth observation missions** This paper delves into the opportunities and challenges associated with implementing AI-based image recognition on small satellites for Earth observation missions. The authors highlight the importance of innovative approaches and collaborations among stakeholders in the space industry and academia to overcome these challenges. By resolving these issues, significant advancements in the field of earth observation are expected, leading to improved insights into natural disaster response. The study emphasizes the need for on-board AI algorithms to enhance data analysis accuracy in remote sensing applications, ultimately contributing to better decision-making processes in satellite missions.
2024 China	Bohan JIAO, Qifan LIU, Zhaohui DANG, Xiaokui YUE, Yonghe ZHANG b, Yuanqing XIA, Li DUAN d , Qinglei HU, Chenglei YUE, Pengcheng WANG, Ming GUO, Zhansheng DUAN, Bing CUI, Chu ZHANG, Xiaodong SHAO Northwestern Polytechnical University Chinese Academy of Sciences Beijing Institute of Technology Beihang University Xi'an Jiaotong University	**A review on DFACS (I): System design and dynamics modeling** Provides a comprehensive overview of the System design and dynamics modeling of Drag-Free and Attitude Control Systems (DFACS) used in various space missions. The review covers a wide range of topics related to DFACS research, including system design, control modes, mission formations, and future prospects and challenges in the field. The authors discuss the evolution of DFACS technology over the years and highlight the importance of DFACS in enabling precise control and stabilization of spacecraft in different mission scenarios

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2024 China	Chenglei Yue, Bohan Jiao, Zhaohui Dang, Xiaokui Yue, Yonghe Zhang, Yuanqing Xia, Li Duan, Qinglei Hu, Qifan Liu, Pengcheng Wang, Ming Guo, Zhansheng Duan, Bing Cui, Chu Zhang, Xiaodong Shao Northwestern Polytechnical University Chinese Academy of Sciences Beijing Institute of Technology Beihang University Xi'an Jiaotong University	**A review on DFACS (II): Modeling and analysis of disturbances and noises** It focuses on the modeling and analysis of disturbances and noises in Drag-Free Attitude Control Systems (DFACS). The paper provides a detailed examination of how disturbances and noises impact DFACS systems and discusses various methods for analyzing and mitigating these interferences. The authors present insights into the performance evaluation of DFACS systems using techniques such as frequency domain analysis and disturbance analysis. The research is significant for understanding the challenges faced by DFACS systems and offers valuable information for improving the design and optimization of such systems in practical applications.
2024 China	Dong Wang, Jing Yang, Kai Xiong Beihang University Beijing Institute of Control Engineering	**Autonomous navigation method of satellite constellation based on adaptive forgetting factors** The research addresses the challenges posed by model uncertainty and unknown system noise in satellite navigation systems. The proposed method, known as UKF-AFF, incorporates adaptive adjustment strategies for forgetting factors to enhance adaptability and filtering accuracy. By introducing innovative approaches to covariance estimation and state correction, the study demonstrates significant improvements in estimation accuracy for satellite constellation navigation.
2024 United Kingdom	Onur Çelik, Colin R. McInnes University of Glasgow	**A Constellation Design for Orbiting Solar Reflectors to Enhance Terrestrial Solar Energy** The study focuses on the design and optimization process of a constellation of solar reflectors in low-Earth orbit to provide continuous illumination to solar power plants during periods of low or no sunlight. The optimization process involves parameters such as orbit geometry, reflector size, and location selection to maximize energy delivery. The authors discuss the potential benefits of this technology and its implications for enhancing terrestrial solar power generation.

(continue)

Table B.1 – Continuation.

Year and place	Paper identification	Paper summary
2024 United Arab Emirates Australia Luxembourg	Kathiravan Thangavel, Raja Pandi Perumal, Khaja Faisal Hussain, Alessandro Gardi, Roberto Sabatini Khalifa University of Science and Technolog RMIT University University of Luxembourg SmartSat Cooperative Research Centre,	**Multidisciplinary design and optimization of intelligent Distributed Satellite Systems for Earth observation** Recent advancements in small, connected, and intelligent satellite systems have paved the way for the adoption of intelligent Distributed Satellite Systems (iDSS) in various missions, including communication, navigation, and Earth Observation (EO). This article delves into the multidisciplinary design and optimization of iDSS for Earth observation purposes. By leveraging Artificial Intelligence algorithms for onboard data processing and autonomy, iDSS aims to reduce the Telemetry, Tracking, and Control (TT&C) load while enhancing onboard capabilities for data sharing among platforms. The primary objective of iDSS is to provide a responsive and resilient solution to meet the evolving needs of the scientific community and defense sector in EO missions. The research presented in this article establishes a modeling, design, and operational framework to maximize the potential of iDSS, focusing on real-time self-reconfiguration and adaptation capabilities. Key contributions include a review of iDSS specificities, design optimization of an iDSS constellation for EO missions, and considerations for developing trusted autonomy within iDSS.
2024 China	Dong Wang, Jing Yang, Kai Xiong Beihang University Beijing Institute of Control Engineering	**Autonomous navigation method of satellite constellation based on adaptive forgetting factors** In this article, Wang, Yang, and Xiong propose an innovative autonomous navigation method for satellite constellations that addresses the challenges of model uncertainty and unknown system noise. The method, known as UKF-AFF, incorporates adaptive forgetting factors to enhance filtering accuracy and adaptability of the navigation system. By introducing an adaptive adjustment coefficient based on the squared Mahalanobis distance, the method achieves online regulation of forgetting factors, improving stability and estimation accuracy. The system also utilizes the Smooth Covariance Matrix for time-varying measurement dimensions and estimates the process noise covariance matrix recursively to reduce model uncertainty. The authors provide a detailed construction of the autonomous navigation system, algorithm derivation, simulation results, and stability analysis, highlighting the effectiveness of the proposed method in enhancing satellite constellation navigation.

(continue)

Table B.1 – Conclusion.

Year and place	Paper identification	Paper summary
2024	Cui-Qin Dai, Mingjian Zhang, Chong Li, Jian Zhao, Qianbin Chen "This article has been accepted for publication in a future issue of the journal" Citation information: DOI 10.1109/JIOT.2020.3030263	**QoE-Aware Intelligent Satellite Constellation Design in Satellite Internet of Things** The study focuses on optimizing Quality of Experience (QoE) factors in satellite constellation design to enhance user satisfaction. By formulating the problem with key parameters and constraints, the paper aims to maximize QoE by considering communication fluency, regional demand capacity, and profitability within the satellite constellation network. The proposed scheme involves a network model comprising Low Earth Orbit (LEO) satellites and ground IoT devices, emphasizing the importance of satellite coverage performance and communication efficiency. Through the integration of QoE metrics and optimization techniques, the research contributes to the advancement of intelligent satellite constellation design for improved SIoT services.
2024	Zhicheng Qu, Gengxin Zhang, and Jidong Xie, "This article has been accepted for publication in a future issue of the journal" Citation information: DOI 10.1109/ACCESS.2017.2735988	**LEO Satellite Constellation for Internet of Things** The study emphasizes the importance of protocol adaptations to ensure seamless integration between terrestrial IoT systems and LEO satellite-based IoT services. The paper sheds light on the potential benefits and challenges associated with deploying LEO satellite constellations for IoT connectivity.

APPENDIX C - EXTERNAL REVIEW AND FEEDBACK BY ZFT

Appendix C.1 - External Review And Feedback On The Tailored Systems Engineering Process By Zft.

- more emphasize on step 7 that this is your novelty

Chapter 5 would be very interesting!

Perhaps we have missed some points/explanations, and would like propose a meeting after fall break.
In this meeting you could tell us about the currently unaddressed points or explain something we have may have missed.
Do let us know :)

Best regards,

Prachit

[Quoted text hidden]

--
_____
ZfT - Zentrum für Telematik e.V.

M.Sc. Prachit Kamble
Systems Engineer [Space]

Magdalene-Schoch-Straße 5
97074 Würzburg

Tel: +49 (931) 615 633 - 48
Fax: +49 (931) 615 633 - 11

Email: prachit.kamble@telematik-zentrum.de
Web: http://www.telematik-zentrum.de

Vorstand:
Prof. Dr. Klaus Schilling, Hans-Joachim Leistner, Prof. Dr. Andreas Nüchter
Sitz: Würzburg
USt.-ID Nr.: DE 257 244 580, Steuer-Nr.: 257/111/70203 Amtsgericht Würzburg, Vereinsregister-Nr.: VR 200
167 Castell Bank, Würzburg
IBAN: DE24 7903 0001 0000 0042 28
BIC: FUCEDE77

Informationen über Ihre personenbezogene Daten erhalten Sie über unsere Webseite unter https://www.telematik-zentrum.de/index.php?id=17&L=0.
For information about your personal data please refer to our privacy statement under https://www.telematik-zentrum.de/index.php?id=17&L=1.

Diese Nachricht enthält vertrauliche und/oder rechtlich geschützte Informationen.
Wenn Sie nicht der richtige Adressat sind oder diese E-Mail irrtümlich erhalten haben, informieren Sie bitte sofort den Absender und vernichten diese E-Mail.Wir weisen darauf hin, dass die Verbreitung, das Kopieren oder der sonstige Gebrauch der E-Mail gesetzlich untersagt ist und gegebenenfalls Schadensersatzansprüche auslösen kann. Vielen Dank für Ihre Zusammenarbeit.

The information contained in this message and attachments is intended solely for the attention and use of the named addressee and may be confidential. If you are not the intended recipient, you are reminded that the information remains the property of the sender. You must not use, disclose, distribute, copy, print or rely on this e-mail . If you have received this message in error, please contact the sender immediately and irrevocably delete or destroy this message and any copies.

Ivan Baron <ivan.baron@inpe.br> Sun, Sep 29, 2024 at 10:04 PM
To: Alexander Kleinschrodt <alexander.kleinschrodt@telematik-zentrum.de>
Cc: Geilson Loureiro <geilson.loureiro@inpe.br>, Ivan Felipe Rodriguez Baron <ifrodriguezb@libertadores.edu.co>, prachit.kamble@telematik-zentrum.de, lisa.elsner@telematik-zentrum.de

Dear professors,

I hope this email finds you well. I am writing to kindly follow up on the document I submitted for review. I would greatly appreciate it if you could provide your feedback and observations at your earliest convenience. Your insights are invaluable to ensuring the quality and accuracy of the content, and I am eager to incorporate any suggestions you may have.

Additionally, I have a particular interest in applying the document's framework to a real-life example, specifically one based on a process or mission that has already been undertaken. I believe this approach will further clarify the document's practical applications, and I would be grateful for your guidance in this respect.

Please do not hesitate to let me know if any additional information or clarification is required.

Thank you very much for your time and consideration. I look forward to hearing from you soon.

Yours sincerely,
Iván

[Quoted text hidden]

Prachit Vijay Kamble <prachit.kamble@telematik-zentrum.de> Mon, Oct 28, 2024 at 6:59 AM
To: Ivan Baron <ivan.baron@inpe.br>
Cc: Geilson Loureiro <geilson.loureiro@inpe.br>, Ivan Felipe Rodriguez Baron <ifrodriguezb@libertadores.edu.co>, Alexander Kleinschrodt <Alexander.Kleinschrodt@telematik-zentrum.de>, lisa.elsner@telematik-zentrum.de

Hello Iván,

Thank you for the clarification about the document.

We have compared it with previous one and have found following responses to the comments previously made by us.

- Define what are the outputs of the individual steps? More definition about the scope of the individual steps, maybe mentioning of examples could help ***[DONE FOR STEP 4.2.1 AND 1- 4 DSM ConOps AND 7. DSM Logical decomposition] [EXAMPLE GIVEN IS GOOD BUT STILL HAS PHILOSOPHY; NEEDS JUST IMPLEMENTATION; POINTS ABOUT ITIRATIONS NOT SUFFICIENT]***
- Why not talk about the outcomes of the different iterations? What is expected in the different iterations? What does 'review point validated' mean after every iteration? When does the iteration stop? ***[ADDRESSED IN SECTION 12 'Iterate and document'. THIS IS NOT SUFFICIENT. IF THE SUGGESTED METHOD WAS ENOUGH, WE WOULDN'T NEED ANOTER ITERATON]***
- A summary about chapter 4 would be helpful to explain the structure of it ***[Now addressed well!]***
- Suggestions on tools for the individual steps would be helpful, for example in step 2 a stakeholder chart ***[ONE SUGGESTION GIVEN IN 4.2 -> 1 -> 2. Identify all stakeholders involved] [ONE MORE TOOL IN 10]***
- In which step do we get mission requirement outputs? It is not clearly written down. ***[ADDRESSED IN SUMMARY OF 9]***
- What exactly are the considerations in step 5 & 9? Constraints? Write more details about it
- step 5 -> structure improvement, maybe categorizations? What requirements for LEO or interplanetary missions?
- step 6 -> what is outcome of the phases? when do you stop iteration?
- step 7
  - mismatching order of 7.2 and 7.3 in flow chart and text ***[Now fixed]***
  - Figure 4.4 -> it already shows a specific solution for ADCS but not really clear why the components are connected like this, suggestion: overall structure to know where ADCS is located within complete mission, additional ADCS diagram with more details and explanation, why only one spacecraft in diagram when talking about DSMs?
  - Figure 4.5 and 4.6 -> mission explanations of the arrows
  - this step is a little bit counterintuitive, all steps so far top-down and now it is bottom-up, how are these steps linked together? ***[CONCLUSION OF 7 AND 8]***
  - Is our understanding of 7.2 (distribution, what is every satellite doing on its own) and 7.3 (integration, what are the satellites doing together?) correct? ***[CONCLUSIONS OF 7 and 8]***

Iván Felipe Rodríguez Barón
PhD Student
INPE - National Institute for Space Research
ivan.baron@inpe.br
+57 3143478292
[Quoted text hidden]

Tesse_IFRB_TA_2.0.docx
3291K

Alexander Kleinschrodt <alexander.kleinschrodt@telematik-zentrum.de> Wed, Sep 4, 2024 at 2:10 AM
To: Ivan Baron <ivan.baron@inpe.br>, Geilson Loureiro <geilson.loureiro@inpe.br>
Cc: Ivan Felipe Rodriguez Baron <ifrodriguezb@libertadores.edu.co>, prachit.kamble@telematik-zentrum.de, lisa.elsner@telematik-zentrum.de

Hi Ivan,

We were just about to review your updated document, when we found out that you sent the same file that was already reviewed by us in June.

Maybe you made a mistake by sending the wrong file? Can you please fwd the up-to-date one. We will do our best to give some timely feedback.

Best Regards
Lisa, Prachit, Alex

[Quoted text hidden]

Ivan Baron <ivan.baron@inpe.br> Wed, Sep 4, 2024 at 4:50 PM
To: Alexander Kleinschrodt <alexander.kleinschrodt@telematik-zentrum.de>
Cc: Geilson Loureiro <geilson.loureiro@inpe.br>, Ivan Felipe Rodriguez Baron <ifrodriguezb@libertadores.edu.co>, prachit.kamble@telematik-zentrum.de, lisa.elsner@telematik-zentrum.de

Dear Lisa, Prachit, and Alex,

Thank you for reviewing the document. I would like to clarify that this is not the same file. Within the chapter of interest, I have added information based on the observations and recommendations made during the previous review. For example:

- Relating the potential outcomes of each proposed step.
- Providing a general summary at the beginning of the chapter.
- Detailing, clarifying, and reorganising certain steps, such as in the structuring and categorisation of requirements and constraints.
- Correcting and clarifying information in figures and flow diagrams.

Additionally, the chapter following the "tailoring" section, Chapter 5, which serves as an application example, is currently under development. This chapter is where we intend to demonstrate the outcomes of each proposed step. However, we aim to establish a clear and defined process for its application or comparison with existing methodologies.

I have attached the document of interest (Tesse_IFRB_TA_2.0) for your reference.

I would greatly appreciate it if you could review these changes and share your feedback.

I look forward to your comments.

Kind regards,
Iván

[Quoted text hidden]

Tesse_IFRB_TA_2.0.docx
3291K

Diese Nachricht enthält vertrauliche und/oder rechtlich geschützte Informationen.
Wenn Sie nicht der richtige Adressat sind oder diese E-Mail irrtümlich erhalten haben, informieren Sie bitte sofort den Absender und vernichten diese E-Mail.Wir weisen darauf hin, dass die Verbreitung, das Kopieren oder der sonstige Gebrauch der E-Mail gesetzlich untersagt ist und gegebenenfalls Schadensersatzansprüche auslösen kann. Vielen Dank für Ihre Zusammenarbeit.

The information contained in this message and attachments is intended solely for the attention and use of the named addressee and may be confidential. If you are not the intended recipient, you are reminded that the information remains the property of the sender. You must not use, disclose, distribute, copy, print or rely on this e-mail . If you have received this message in error, please contact the sender immediately and irrevocably delete or destroy this message and any copies.

Alexander Kleinschrodt <alexander.kleinschrodt@telematik-zentrum.de> Tue, Aug 27, 2024 at 10:02 AM
To: Ivan Baron <ivan.baron@inpe.br>
Cc: Geilson Loureiro <geilson.loureiro@inpe.br>, prachit.kamble@telematik-zentrum.de, lisa.elsner@telematik-zentrum.de

Hi Ivan,

we are now back from the summer break and meanwhile launched our Qube satellite successfully to orbit (see https://www.telematik-zentrum.de/projects/qube/). As calendars are clearing up marginally we could now look at your latest document. In case you still require our inputs.

If you still need us, can you please share your latest version? we would most likely find time for a review next week.

Best Regards
Alex

[Quoted text hidden]

Geilson Loureiro <geilson.loureiro@inpe.br> Tue, Aug 27, 2024 at 4:19 PM
To: Alexander Kleinschrodt <alexander.kleinschrodt@telematik-zentrum.de>, Ivan Baron <ivan.baron@inpe.br>, Ivan Felipe Rodriguez Baron <ifrodriguezb@libertadores.edu.co>
Cc: prachit.kamble@telematik-zentrum.de, lisa.elsner@telematik-zentrum.de

Dear Alex and colleagues,
Many thanks for your message.
We are still interested in your inputs. I am sending this message to Ivan´s other email.
I let him know that you contacted him via Whatsapp.
Best regards,
Geilson
[Quoted text hidden]

Ivan Baron <ivan.baron@inpe.br> Wed, Aug 28, 2024 at 5:25 PM
To: Geilson Loureiro <geilson.loureiro@inpe.br>
Cc: Alexander Kleinschrodt <alexander.kleinschrodt@telematik-zentrum.de>, Ivan Felipe Rodriguez Baron <ifrodriguezb@libertadores.edu.co>, prachit.kamble@telematik-zentrum.de, lisa.elsner@telematik-zentrum.de

Dear Professors,

I hope this email finds you well. As previously agreed, I am sending the attached new document for your review. In this case, I have endeavoured to address all the recommendations you made in Chapter 4.

I look forward to receiving your comments, suggestions, and to knowing your availability to review your new observations.

Thank you for your time and consideration.

Best regards,

I hope this email finds you well. As previously agreed, I am sending you the attached new document for your review. In this case, I have endeavoured to address all the recommendations made by you in Chapter 4.

I look forward to receiving your feedback and suggestions.

Thank you for your time and consideration.

Best regards,

Iván Felipe Rodríguez Barón

PhD Student

INPE - National Institute for Space Research
ivan.baron@inpe.br
+57 3143478292

[Quoted text hidden]

Tesse_IFRB_TA_2.0.docx
3291K

Alexander Kleinschrodt <alexander.kleinschrodt@telematik-zentrum.de> Fri, Jul 26, 2024 at 6:27 AM
To: Ivan Baron <ivan.baron@inpe.br>
Cc: Geilson Loureiro <geilson.loureiro@inpe.br>, prachit.kamble@telematik-zentrum.de, lisa.elsner@telematik-zentrum.de

Hi Ivan,

thanks for the updated Version! Unfortunately, we are right now quite busy with the launch of our Qube satellite. Also it is right now holiday season for us. I think we may only be able to come back to you with a meaningful review in September. I hope this still works for you!

Best Regards from Würzburg
Alex & ZfT+s4-Team

[Quoted text hidden]

--
_____
ZfT - Zentrum für Telematik e.V.
Dipl. Inform. Alexander Kleinschrodt
- Leiter Raumfahrtsysteme -
Magdalene-Schoch-Straße 5
97074 Würzburg

Tel: +49 (0) 931 615 633 - 63
Fax: +49 (0) 931 615 633 – 11
Email: alexander.kleinschrodt@telematik-zentrum.de
Web: http://www.telematik-zentrum.de
_____
Vorstand:
Prof. Dr. Klaus Schilling, Hans-Joachim Leistner, Prof. Dr. Andreas Nüchter
Sitz: Würzburg
USt.-ID Nr.: DE 257 244 580, Steuer-Nr.: 257/111/70203 Amtsgericht Würzburg, Vereinsregister-Nr.: VR 200
167 Castell Bank, Würzburg
IBAN: DE24 7903 0001 0000 0042 28
BIC: FUCEDE77

Informationen über Ihre personenbezogene Daten erhalten Sie über unsere Webseite unter https://www.telematik-zentrum.de/index.php?id=17&L=0.
For information about your personal data please refer to our privacy statement under https://www.telematik-zentrum.de/index.php?id=17&L=1.

Tel: +49 (0) 931 615 633 - 42
Fax: +49 (0) 931 615 633 – 11
Email: lisa.elsner@telematik-zentrum.de
Web: http://www.telematik-zentrum.de

Vorstand:
Prof. Dr. Klaus Schilling, Hans-Joachim Leistner, Prof. Dr. Andreas Nüchter
Sitz: Würzburg
USt.-ID Nr.: DE 257 244 580, Steuer-Nr.: 257/111/70203 Amtsgericht Würzburg, Vereinsregister-Nr.: VR 200 167
Castell Bank, Würzburg
IBAN: DE24 7903 0001 0000 0042 28
BIC: FUCEDE77

Informationen über Ihre personenbezogene Daten erhalten Sie über unsere Webseite unter
https://www.telematik-zentrum.de/dataprotection/
For information about your personal data please refer to our privacy statement under
https://www.telematik-zentrum.de/en/dataprotection/

Diese Nachricht enthält vertrauliche und/oder rechtlich geschützte Informationen.
Wenn Sie nicht der richtige Adressat sind oder diese E-Mail irrtümlich erhalten haben, informieren Sie bitte sofort
den Absender und vernichten diese E-Mail.Wir weisen darauf hin, dass die Verbreitung, das Kopieren oder der
sonstige Gebrauch der E-Mail gesetzlich untersagt ist und gegebenenfalls Schadensersatzansprüche auslösen
kann. Vielen Dank für Ihre Zusammenarbeit.

The information contained in this message and attachments is intended solely for the attention and use of the
named addressee and may be confidential. If you are not the intended recipient, you are reminded that the
information remains the property of the sender. You must not use, disclose, distribute, copy, print or rely on this e-
mail . If you have received this message in error, please contact the sender immediately and irrevocably delete or
destroy this message and any copies.

Geilson Loureiro <geilson.loureiro@inpe.br> Thu, Jun 13, 2024 at 10:25 AM
To: lisa.elsner@telematik-zentrum.de, Ivan Felipe Rodriguez Baron <ivan.baron@inpe.br>
Cc: prachit.kamble@telematik-zentrum.de, Alexander Kleinschrodt <alexander.kleinschrodt@telematik-zentrum.de>

Many thanks, Lisa, Alexander and Prachit.
Geilson
[Quoted text hidden]

Ivan Baron <ivan.baron@inpe.br> Wed, Jul 24, 2024 at 6:51 PM
To: lisa.elsner@telematik-zentrum.de
Cc: Geilson Loureiro <geilson.loureiro@inpe.br>, prachit.kamble@telematik-zentrum.de, Alexander Kleinschrodt <alexander.kleinschrodt@telematik-zentrum.de>

Dear Professors,

Ivan Baron <ivan.baron@inpe.br>

Contact with student Ivan Baron on systems engineering process for AOCS for flight formation satellites

11 messages

lisa.elsner@telematik-zentrum.de <lisa.elsner@telematik-zentrum.de> Thu, Jun 13, 2024 at 7:24 AM
To: Ivan Felipe Rodriguez Baron <ivan.baron@inpe.br>, Geilson Loureiro <geilson.loureiro@inpe.br>
Cc: prachit.kamble@telematik-zentrum.de, Alexander Kleinschrodt <alexander.kleinschrodt@telematik-zentrum.de>

Dear Ivan,

thanks again for sharing your thesis with us. Below you can find our comments on chapter 4. I hope they are helpful for you.

Questions/Comments

- Define what are the outputs of the individual steps? More definition about the scope of the individual steps, maybe mentioning of examples could help
- Why not talk about the outcomes of the different iterations? What is expected in the different iterations? What does 'review point validated' mean after every iteration? When does the iteration stop?
- A summary about chapter 4 would be helpful to explain the structure of it
- Suggestions on tools for the individual steps would be helpful, for example in step 2 a stakeholder chart
- In which step do we get mission requirement outputs? It is not clearly written down
- What exactly are the considerations in step 5 & 9? Constraints? Write more details about it
- step 5 -> structure improvement, maybe categorizations? What requirements for LEO or interplanetary missions?
- step 6 -> what is outcome of the phases? when do you stop iteration?
- step 7
    - mismatching order of 7.2 and 7.3 in flow chart and text
    - Figure 4.4 -> it already shows a specific solution for ADCS but not really clear why the components are connected like this, suggestion: overall structure to know where ADCS is located within complete mission, additional ADCS diagram with more details and explanation, why only one spacecraft in diagram when talking about DSMs?
    - Figure 4.5 and 4.6 -> mission explanations of the arrows
    - this step is a little bit counterintuitive, all steps so far top-down and now it is bottom-up, how are these steps linked together?
    - Is our understanding of 7.2 (distribution, what is every satellite doing on its own) and 7.3 (integration, what are the satellites doing together?) correct?
    - more emphasize on step 7 that this is your novelty

I am looking forward to read the next iteration.

Best regards,

Lisa

ZfT - Zentrum für Telematik e.V.
M. Sc. Lisa Elsner

- Wissenschaftliche Mitarbeiterin -
Magdalene-Schoch-Straße 5
97074 Würzburg