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Research opportunities in systems engineering applied to distributed spacecraft missions

Iván Felipe Rodríguez Barón

Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brasil

Aluno de Doutorado ETE/CSE

Fundación Universitaria los Libertadores, Bogotá D. C., Colombia.

Geilson Loureiro

Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brasil / ETE

ivan.baron@inpe.br

Abstract. *This document aims to identify gaps and research opportunities in the application of systems engineering in the development of distributed spacecraft systems missions from the beginning of the system life cycle, specifically satellites flying in formation. Through a theoretical background, concepts are defined mainly about Systems Engineering, distributed spacecraft missions, satellite constellations, systems flying in formation and attitude and orbit control systems. In addition, a literature review and research opportunities identification were carried out, describing the evolution of the application of systems engineering in the development of the attitude and orbit control system for satellite constellations flying in formation. Finally, possible research works based on this approach are proposed, on the successes and challenges of this type of space mission.*

Key words: Satellite Constellation; Formation Flying Systems; Systems Engineering; Distributed Spacecraft Missions; Attitude and Orbit Control System.

1. Introduction

The Concurrent Systems Engineering (CSE) (LOUREIRO et al, 2018) process has an integrated development approach that considers all life cycle processes in the development of a complete satellite. In this way, the contribution of this research is found in the application of systems engineering in the development of the attitude and orbit control system, for a constellation of satellites flying in formation, based on the needs of the mission. Since modern telecommunications (Internet of Things - IoT), remote sensing and meteorological needs can best be met by combining the characteristics of monolithic geostationary satellites and small low-orbiting satellites. Therefore, small satellites in multi-satellite missions or distributed spacecraft missions (DSM) can achieve some objectives that are not possible to achieve separately. (CHUNG et al., 2016). The objective of using satellite constellations for Earth observation missions is the advantage of having higher coverage performance through the combination of multiple satellites. Chan et al (2019) presented that the design of a proper satellite constellation can achieve global continuous coverage and multiple-fold coverage, thus meeting the requirements of global communication, navigation, meteorology, positioning, space exploration, and scientific experiments.

This document aims to present theoretical background and bibliographical research on the theme of the application of systems engineering in the development of satellite constellations in formation flying since the beginning of the system's life cycle, in order to identify research gaps and opportunities.

The document is organized in four principal parts, Initially, the introduction, research motivation and literature review, concepts are defined. The next section approaches the methodology based on a bibliometry structured. In Section 3, the results were presented, describing the evolution of the application of systems engineering in the development of the attitude and orbit control system for satellite constellations flying in formation, and possible research works based on this approach are proposed. The conclusions, in Section 4, report the trajectory and feasibility of this theme for doctoral research.

1.1. Motivation

In the case of Formation Flying System (FFS) defined by J. Le Moigne (2018) as "Two or more spacecraft that conduct a mission such that the relative distances and 3D spatial relationships (i.e., distances and angles between all spacecraft space) are controlled by direct detection by a spacecraft of at least one other state of the spacecraft", where states are coupled employing control laws. In this way, it involves new Guidance Navigation and Control (GNC) functions, which require that each satellite be controlled in attitude and position, for absolute references and concerning each other. However, the FFS requires specific sensors and communication for relative navigation and high precision control. Also, it requires highly stable positioning control and the ability to reorient in space to complete the mission. Therefore, it is a great challenge to develop projects that incorporate the AOCS / GNC functionality for such a complex system. The design of the Attitude and Orbit Control system (AOCS) and GNC systems has become a growing need for efficient tools in all domains involved in spaceship design.

1.2. Theoretical background.

NASA (2016) defines the Systems Engineering (SE) as "a methodical, multi-disciplinary approach for the design, realization, technical management, operations, and retirement of a system", considering the system as "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 life cycle of the space product, contributes to achieving the Stakeholders functional, physical and operational performance requirements, improving the life cycle cost and schedule within the stated constraints. (NASA, 2016). For space products, Loureiro et al (2018) proposed a Total View Framework (TVF), where the integration dimension is composed of product and services, considering the analysis of Stakeholders, requirements, functions and implementation, and finally the hierarchical structure of mission layer.

Based on NASA's and ECSS systems engineering philosophy, the project has broad areas of study to be developed. Both philosophies are similar, and the space mission design process must have an integrated development approach that considers the training lifecycle processes from design, development, testing, operation, and services to decommissioning the system. The Table 3.1 divides the space mission project life cycle into phases and defines the space mission project life cycle phases by NASA and ECSS systems engineering.

Table 1. Typical lifecycle of a space mission defined by ECSS and NASA. Source: Adapted from Malcolm Macdonald (2014)

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

On the other hand, according to Le Moinge (2018) a DSM is a "mission that involves multiple spacecraft to achieve one or more common goals". However, Danil Ivanov (2017) classify the DSM as constellations, swarm, and formation. In addition, Le Moigne et. al. (2020) it has proposed a taxonomy based on three main characteristics "organization", "Physical Configuration" and "Functional Organization"

Thus, the satellite constellation is characterized within the physical configuration and in turn within spatial relationship, and it can be defined as a mission composed of multiple spacecrafts with a common objective working as a system. A Formation Flying System (FFS) is defined by NASA (2017) as "Two or more spaceships that conduct a mission such that the relative distances and 3D spatial relationships (i.e., distances and angles between all spaceships) are controlled through direct detection by a spacecraft of at least one other state of the spacecraft".

The system of interest in this case is the AOCS, this system is responsible for carrying out two main functions, keeping the satellite in the desired orbital trajectory, and providing attitude control, that is essential to maintain the necessary pointing of specific equipment.

According to Bong Wie et al (2014) it is the integration of the GNC system and the Attitude Determination and Control System (ADCS). However, the ADCS system in turn is the integration between the Attitude Determination System (ADS) and the Attitude Control System (ACS), as shown in Figure 1.

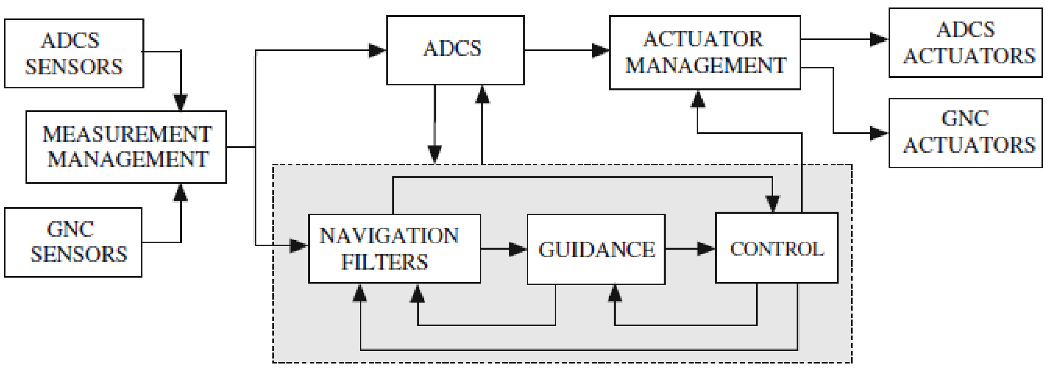

Figure 1. Block diagram illustration of the spacecraft AOCS. Source: Bong Wie et al (2014)

2. Methodology

Scientific articles, in indexed journal internationally classified at Scimago Journal & Country Rank (SJCR) greater than or equal to 0.5 were selected as a reliable source of information. From the JCR website, a search is made for journals in the engineering subject area and aerospace engineering subject category in all regions/countries (ranking of the year 2020), 40 Journals were found. The search was carried out initially from 4 main key words: Systems Engineering, constellation of satellites flying in formation, AOCS and Systems Engineering applied to AOCS of satellites flying in formation. In the search carried out, documents related to topics of SE applied to space products, FFS missions, FFS Control and SE concepts applied to FFS were found.

With the aim of delimiting the research, was proposed a process of selection of information. Initially the titles of the articles of interest are reviewed, followed by the abstract and later the content (Figure 2).

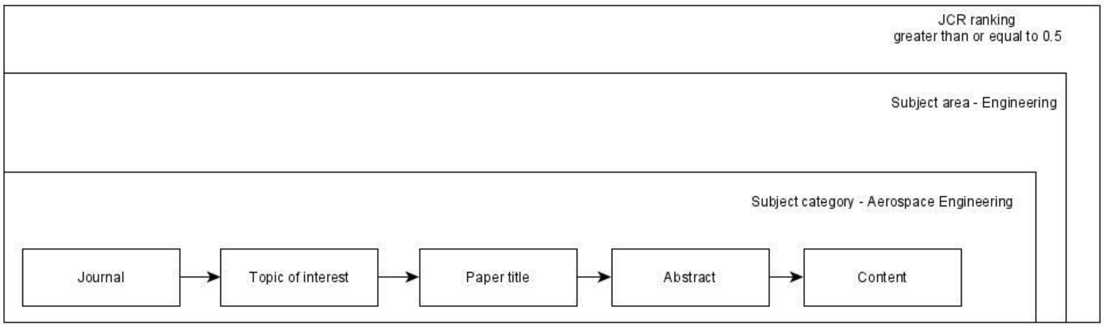

Figure 2. Search procedure proposal.

3. Results and Discussion

The results obtained shows the topics of interest has a significant growth in 2009, 2013 and 2020. are characterized by years, in the Figure 3.

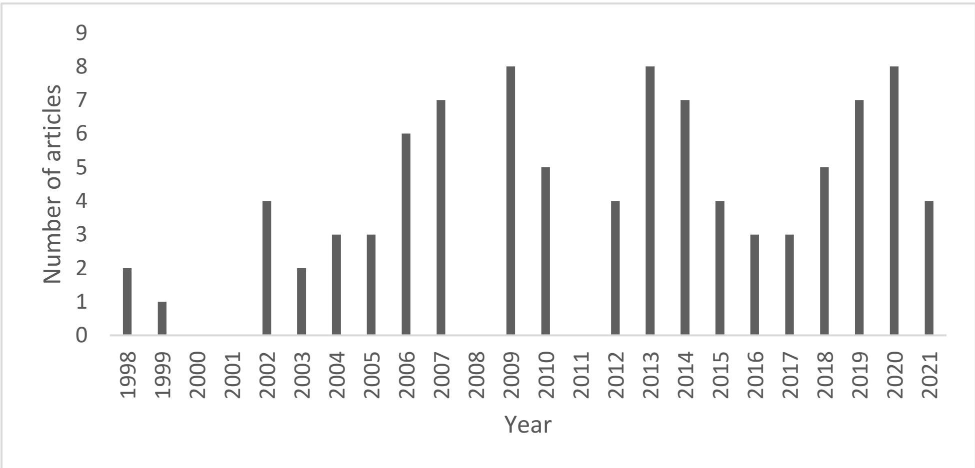

Figure 3. Scientific articles published by year. Scientific articles related to topics of interest published by year.

Additionally, the number of articles were characterized by countries as shown in figure 4. The Unites States of America (USA) have the higher number of articles published and an apparent interest in this research.

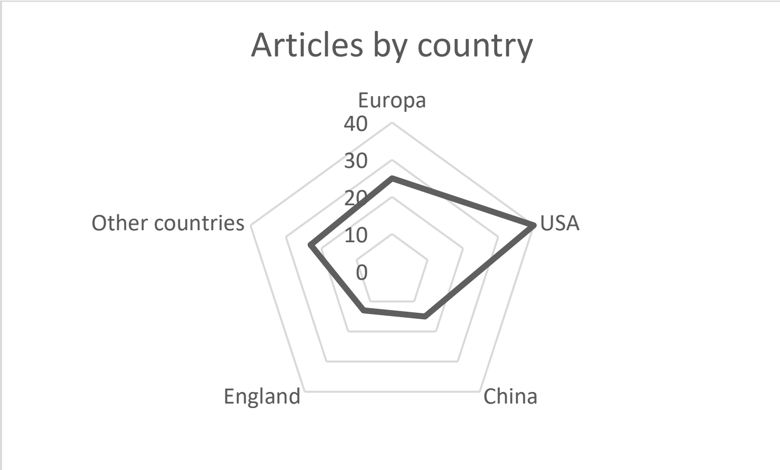

Figure 4. Scientific articles published by country. *

Europe represents the countries with of articles published in this area

On the other hand. The research shows principal interest in the SE applied in Space products development and principally in the control of FFS (Figure 5).

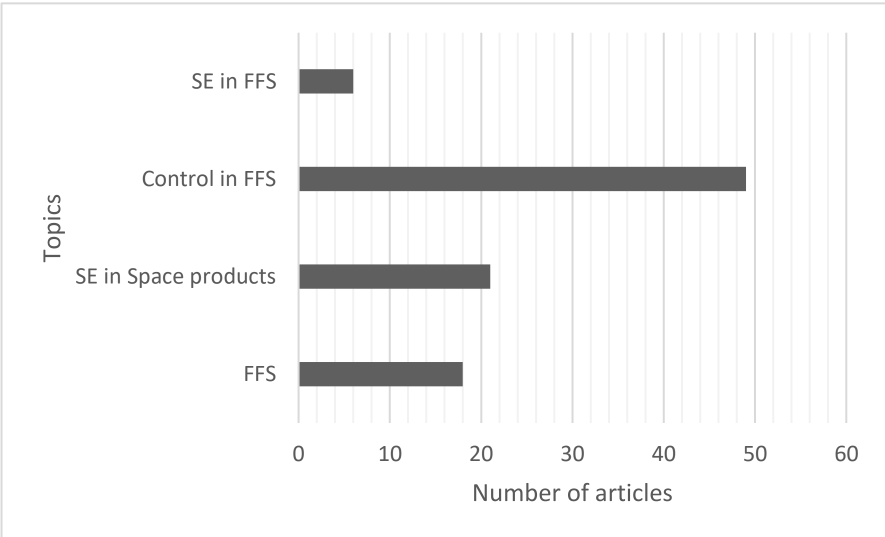

Figure 5. Number of articles by topic of interest

Thus, some research topics were generally found in FFS and the application of SE from 1998 to 2021.

Initially, since 1998 and in 2007 interest in testing high precision techniques for positioning and attitude in testbed was evidenced. proposing two main architectures, centralized and decentralized control. In this way, it is possible to visualize the need for the SE application in the Assembly. Integration and Tests (AIT) phase of FFS development, considering from the system, use and systems engineering and his interaction as figure 6 shows.

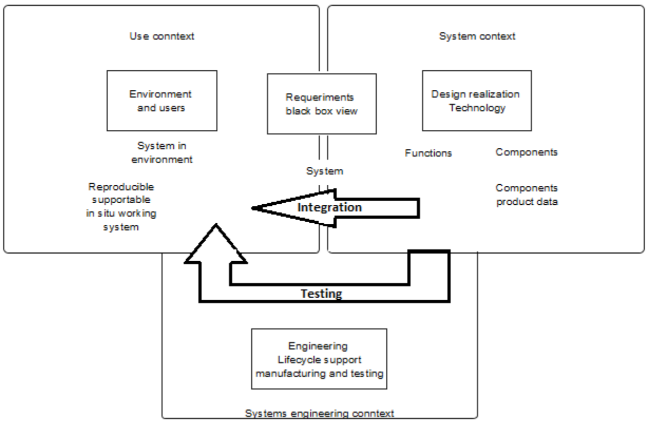

Figure 6 - Map of System Integration. The systems engineering context ties together the system integration effort. Source: Adapted from to Larson et. al. (2009)

However, around 75% of the documents were found to address the implementation of methods and techniques for the control of FFS, from CNG to AOCS, proposing different types of architecture, as centralized control, decentralized and reconfigurable control, from the reconfiguration of the architecture to the reconfiguration of its size and shape (Figure 7), generating interest in the analysis of the behavior and architecture of FFS services.

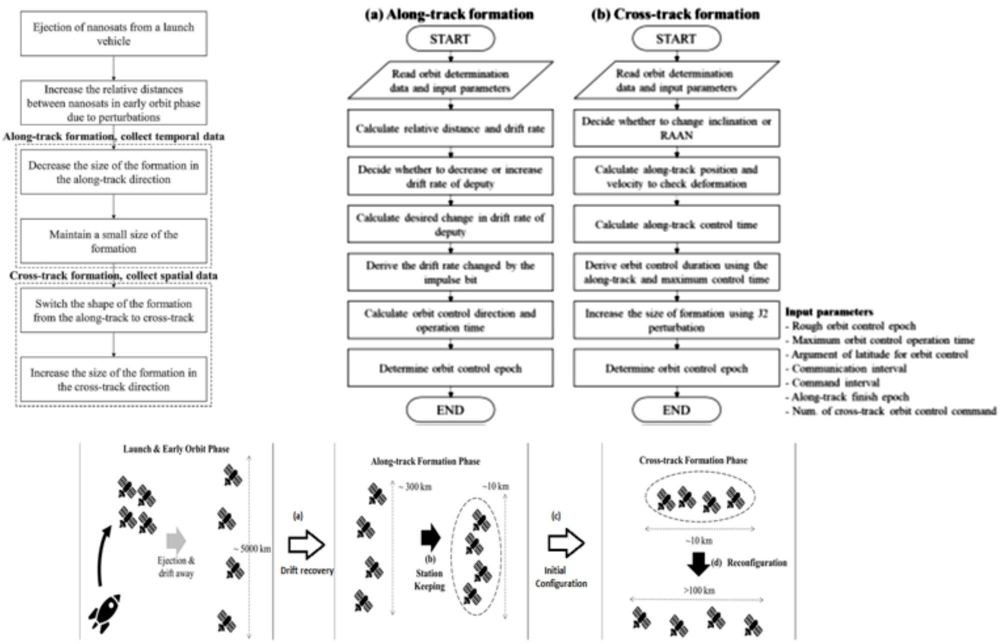

Figure 7. Change in the shape and size of the formation conducted by the four nanosats Source: Adapted from Song et al. (2021)

The foregoing is to minimize the fault tolerance of this type of mission, although only 5% of the information addressed the analysis of the Fault-Tolerant Controller Design to Ensure Operational Safety in FFS, this area should be explored.

On the other hand, the use of SE was evidenced in the development of space products, proposed since 1999. In this case, the application of SE, CSE, Unified Modeling Language (UML), Systems Modeling Language (SysML) and Model has been proposed. -Based System Engineering "MBSE", as well as the implementation of software and tools for the development of the SE in space products and the evolution until 2018. However, only 5% present the application of the SE directly in an FFS, in this case, an international mission called Telematics International Mission (TIM) composed of 9 pico-satellites for Earth observation. In this way, the application of SE in the development of FFS and AOCS is necessary to achieve the high precision requirements of this type of system. In this scope, a significant research opportunity is the implementation of Concurrent Systems Engineering from a Total View framework approach to satellites constellation Flying in Formation.

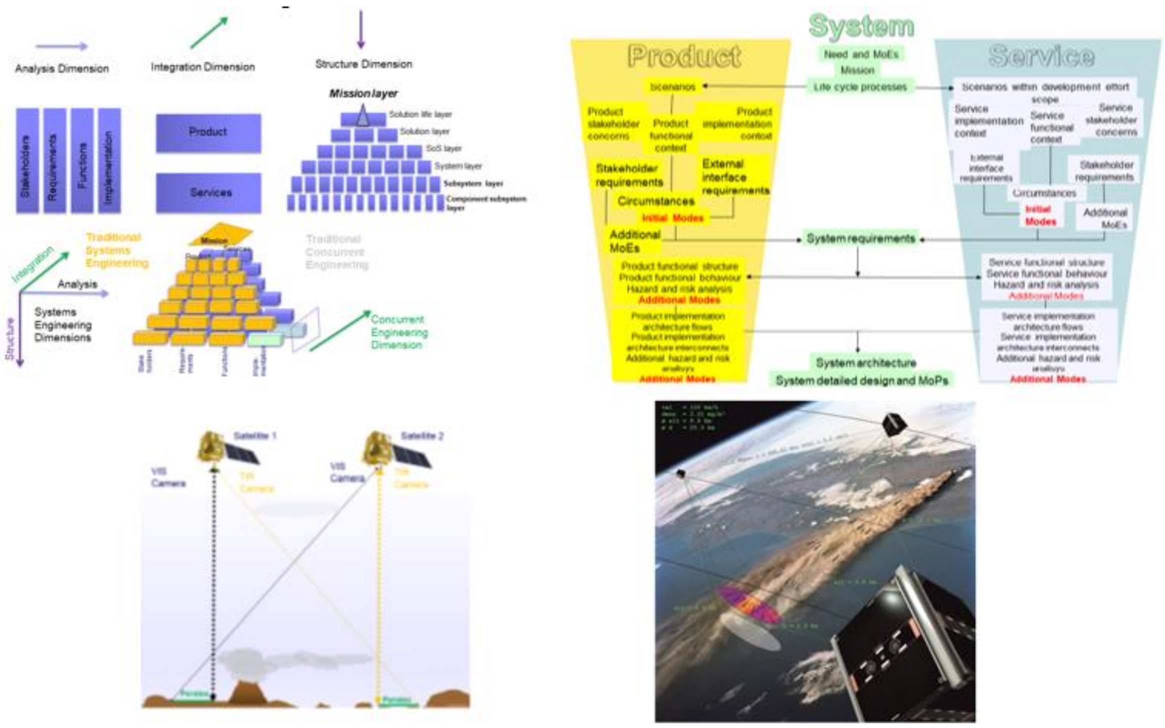

Figure 9. Total View framework and CSE in DSM. Source: Adapted from to Loureiro et. al. (2018)

Finally in 2020, is proposed a taxonomy of DSM from the point of view of three principal characteristics, the organization, the physical configuration and the functional configuration, additionally, some subcategories are proposed. Each of these configurations should have a functional and behavioral analysis. Thus, a decision-making from a formal process (Table 2) for the configuration of a DSM based on its taxonomy could be approached as a research opportunity.

Table 2 - Formal Process for Decision Making. Source: Adapted from to Larson et. al. (2009)

Decision Making Steps	Description
1.Identify what we need to decide	The first step in getting the right answer is asking the right question. What is the decision? What's at stake? In what context will the decision take place? Who should decide?
2.Frame the decision	Decisions aren't made in a vacuum. Define the environmental, organizational, mission - related, and major uncertainty factors that influence the right choice.
3.Select a method to evaluate alternatives	Establish criteria for evaluating t e alternatives. Which tools are best for this decision? Formal processes take more time and effort to document the decision, help establish a consensus, and apply an objective method.
4.Generate alternatives	Before settling on a single answer, look for several. Create backups in case the first- choice solution doesn't work
5.Evaluate alternatives	Select evaluation methods and tools, and examine the solutions in light of established criteria. Look for cognitive and perceptual biases that may distort the process.
6.Choose the best solution	Select the best solution. Document the process, alternatives considered and rejected, and rationales. List action steps required, and then carry out the decision.
7.Test and evaluate	Evaluate the applied decision's effects. Determine the likely outcome of rejected strategies. Prepare necessary documentation. Integrate lessons learned for future decisions.

4. Conclusions

In this document, the motivation to research the application of systems engineering in the AOCS of a constellation of satellites flying in formation was addressed, considering the high demands of the control system of this type of DSM. the literature review of subject of interest was presented, considering mainly documents published in journals with a classification of 0.5 or higher in the Schimago ranking. In this way, documents related to the research from 1998 to 2021 were found.

The research allows to visualize a strong trend in the study of the control of FFS, due to the high precision required by the maneuvers to keep the desired distance and relative position. However, there are gaps mainly in the field of application of methods and concepts of systems engineering for the development of satellite flying in formation and the control required.

In conclusion there is opportunity to carried out research in the SE application in FFS from a robust framework of analysis, mainly in order to contribute to the accuracy and reliability of the control between satellites flying in formation.

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