14º WETE
Workshop em Engenharia e Tecnologia Espaciais

A brief review on systems engineering for Distributed Spacecraft missions

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Resumo. *This document aims to present a bibliographic review on the use of Systems Engineering as a tool for developing distributed spacecraft missions, focusing on the development of Attitude and Orbit Control Systems (AOCS) for small satellites in Flight Formation Systems (FFS). Through a bibliographic review, keywords such as Systems Engineering, satellite constellations in formation flight, AOCS, and Systems Engineering applied to AOCS of satellites flying in formation are utilized. High-quality scientific research based on Scimago Journal & Country Rank (JCR) with a ranking greater than or equal to 0.5 are considered. A search for journals in the thematic area of engineering and the category of aerospace engineering is conducted. The search results include Systems Engineering applied to space products, FFS missions, FFS control, and Systems Engineering concepts applied to FFS. The obtained results indicate significant growth in the areas of interest, particularly in the years 2009, 2013, and 2020.*

Keywords: Small Satellite, Formation Flight Systems, Systems Engineering, Attitude and Orbit Control System

1. Introduction

According to Dolgopolov et al. (2020), the global space economy between 2018 and 2019 experienced a growth of 1.7%, reaching revenues of 366 billion dollars, of which approximately 74% corresponded to the satellite industry. In 2020, the Satellite Industry Association (SAI) reported a similar trend (Bryce Tech, 2021).

The goal of using satellite constellations for Earth observation missions is to leverage the advantage of higher coverage performance by combining multiple satellites. Chan et al. (2007) state that the design of a satellite constellation can achieve continuous global coverage and multiple coverage, meeting requirements for global communication, navigation, meteorology, positioning, space exploration, and scientific experiments.

In the case of formation flight systems (FFS) of satellite constellations, highly stable positioning control and the ability to reorient in space are required to complete the mission. Therefore, the design of attitude and orbit control system (AOCS) and GNC systems has become a growing need for efficient tools in all domains involved in spacecraft design.

The high risks associated with this type of operation make it necessary to approach a multidisciplinary approach that allows identifying, proposing and designing the needs and solutions of real complex systems, as is the case of the concept of Systems Engineering (SE).

Thus, the objective of this research is to carry out a bibliographic analysis of the development of the AOCS for small satellites flying in formation within a distributed spacecraft mission from the SE.

2. Methodology

Through a bibliometric process of high-quality scientific research based on Scimago Journal & Country Rank (JCR) internationally classified greater than or equal to 0.5, a search is carried out for journals in the engineering subject area and the aerospace engineering subject category in all regions/countries. Subsequently, information filters are made by title, by summary and by content (Figure 1).

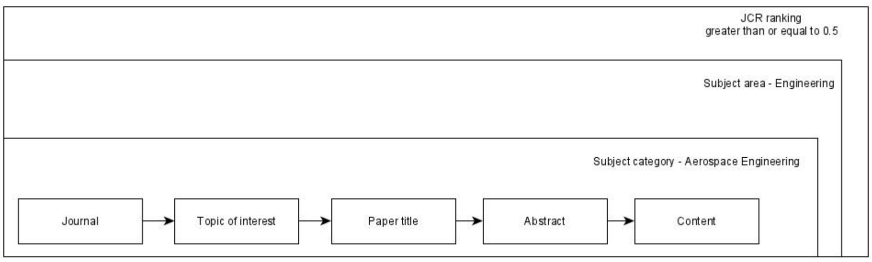

Figure 1. Research procedure

3. Results and Discussion

40 journals were found and the results are shown in Table 1.

Table1. 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
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

About 100 articles were selected by title, 50 by abstract and finally 20 articles were selected by their content, which are presented in table 2.

Table 2. bibliographic review about SE in DSM.

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 (CORAZZINI et al., 1998)	**Experimental Demonstration of GPS as a Relative Sensor for Formation Flying Spacecraft** The paper describes the application of carrier-phase differential GPS (CDGPS) techniques for high-accuracy positioning and attitude determination in a testbed of three vehicles in formation flying. Two architectures, distributed and centralized control, were considered in both static and dynamic cases.
1999 Brazil England	Geilson. Loureiro, Mr. and P. G. Leaney, Dr.	**A SYSTEMS ENGINEERING ENVIRONMENT FOR INTEGRATED SATELLITE DEVELOPMENT** The application of Systems Engineering in integrated satellite development is explored, taking into account functional and lifecycle process requirements. Applying Systems

	Brazilian Institute for Space Research (INPE) Loughborough University, (Loureiro & Leaney, 1999)	Engineering principles in space product development leads to lower lifecycle costs and shorter development times.
2002 United Kingdom	S. M. Veres, S. B. Gabriel., D. Q. Mayne and E. Rogers. University of Southampton, D. Q. Mayne Imperial College (S. M. Veres et al., 2002)	**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.
2003 Brazil England	G. Loureiro, P.G. Leaney Brazilian Institute for Space Research – INPE Loughborough University, (Loureiro & Leaney, 2003)	**A systems and concurrent engineering framework for the integrated development of space products** was 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.
2006 UK	K.K.T. Thanapalan, S.M. Veres, E. Rogers and S.B. Gabriel University of Southampton (Thanapalan et al., 2006)	**Fault Tolerant Controller Design to Ensure Operational Safety in Satellite Formation Flying** Describes some benefits of using formation flying with several small satellites, including the advantage that the failure of one satellite does not necessarily result in the failure of the entire mission. Other benefits include the interchangeability of roles between satellites, reduced overall costs, and the ability to fulfill missions collectively, among others.
2007 Korea	Young-Keun Chang, Ki-Lyong Hwang and Suk-Jin Kang School of Aerospace and Mechanical Engineering Aerospace University (Chang et al., 2007)	**SEDT (System Engineering Design Tool) development and its application to small satellite conceptual design** The software tool 'Systems Engineering Design Tool' (SEDT) is introduced with the aim of minimizing the labor involved in the conceptual design phase of small satellites. While not directly related to formation flying systems.

2007 UK	Sandor Veres, Nick Lincoln and Steve Gabriel University of Southampton (S. Veres et al., 2007)	**Testbed for Satellite Formation Flying Under Ground Conditions** A formation flying testbed is introduced for ground-based testing of satellite formation control, utilizing two approaches: Ground-based Satellite Frames Testing (GSFT) and Hardware in the Loop Testing (HILT).
2009 Norway	Raymond Kristiansen and Per Johan Nicklasson Narvik University College. (Kristiansen & Nicklasson, 2009)	**Spacecraft formation flying: A review and new results on state feedback control.** The paper presents various works on spacecraft formation flying modeling approaches and controller designs. However, in formation flying systems, it is crucial to consider the strict and time-varying boundaries on spacecraft reference trajectories, and collisions between spacecraft should be avoided at all costs.
2012 Scotland, United Kingdom	Derek J. Bennet and Colin R. McInnes. University of Strathclyde (Bennet & McInnes, 2012)	**Pattern transition in spacecraft formation flying using bifurcating potential fields** In this case, a new methodology for controlling multiple spacecraft is developed. The approach is based on the artificial potential function method, utilizing bifurcation theory to control the transition between different formations.
2012 Germany Sweden	Simone D'Amic, J.-S. Ardaens and R. Larsson DLR, German Aerospace Center OHB Sweden (D'Amico et al., 2012)	**Spaceborne Autonomous Formation-Flying Experiment on the PRISMA Mission** This research focuses on the Prototype Research Instruments and Space Mission Technology Advancement (PRISMA), which stands as the first European technology demonstration of formation-flying and on-orbit-servicing techniques. The paper describes the guidance, navigation, and control (GNC) functionalities, as well as the Spaceborne Autonomous Formation-Flying Experiment (SAFE).
2013 Netherlands Belgium	E. Gill, P. Sundaramoorthy, J.Bouwmeester, B.Zandbergen And R. Reinhard Delft University of Technology von Karman Institute for Fluid Dynamics (Gill et al., 2013)	**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.
2014	Anna Guerman, Erick Lansard and Alfred Ng Guest editors - Acta Astronautica (Guerman et al., 2014)	**Satellite constellations and formation flying** This document discusses the growth of satellite constellations and the increasing interest in formation flying missions.

2016 Germany.	Johannes Gross and Stephan Rudolph University of Stuttgart (Gross & Rudolph, 2016)	**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 (Loureiro et al., 2018)	**Lessons learned in 20 years of application of Systems Concurrent Engineering to space products** The paper presents the lessons learned from 20 years of applying Concurrent Systems Engineering (CSE) in the Brazilian Strategic Program for Space Systems (PESE) and the satellite formation 'Telematics International Mission' (TIM).
2020 South Africa	Dr. Rudolph Oosthuizen and Prof. Leon Pretorius University of Pretoria and CSIR (Oosthuizen & Pretorius, 2020)	**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.
2020 United States	Jacqueline Le Moigne, John Carl Adams, and Sreeja Nag NASA (Le Moigne et al., 2020)	**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.
2020 United States	Melanie L. Grande, Ashish S. Patel, Liam D. Durbin, and Daniel DeLaurentis School of Aeronautics and Astronautics, Purdue University (Grande et al., 2020)	**Modeling Architectures and Parameterization for Spacecraft** In this paper, the Modeling Architectures and Parameterization for Spacecraft (MAPS) environment is introduced to implement a model-based systems engineering (MBSE) approach for spacecraft applications using Systems Modeling Language (SysML) and orbital trajectory analysis for mission simulations.
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 (Song et al., 2021)	**Spacecraft formation flying system design and controls for four nanosats mission** This research aims to design a spacecraft formation flying system composed of four nanosats, referred to as the 'Ionosphere Plasma Experiment (SNIPE) mission.' The proposed design involves changing the formation flying shapes and sizes in two phases: the Cross-track and Along-track phases.

Among the most relevant investigations, it was observed that the use of Systems Engineering (SE) in the development of space products was proposed as early as 1999. In this context, the application of SE, Concurrent Systems Engineering (CSE), Unified Modeling Language (UML), Systems Modeling Language (SysML), and Model-Based System Engineering (MBSE) has been suggested. Additionally, the implementation of software and tools for SE development in space products has evolved until 2018. However, only 5% of the studies directly apply SE in a Formation Flying System (FFS), specifically in an international mission called Telematics International Mission (TIM), which consists of 9 pico-satellites for Earth observation. Therefore, applying SE in the development of FFS and Attitude and Orbit Control Systems (AOCS) is essential to meet the high precision requirements of these systems. In this context, a significant research opportunity lies in the implementation of Concurrent Systems Engineering within a Total View framework approach for satellite constellation Flying in Formation.

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.

The case of autonomous FF in Low Earth Orbit (LEO), according to D'amico is characterized by a high level of multidisciplinary, principally GNC and AOCS. From GNC for satellite rendezvous in 1960, GNC for FFS and autonomous FF technology demonstration as PRISMA mission in 2006, TerraSARX/TanDEM-X missions in 2007 to a realistic demonstration of a complete GNC system for formation flying spacecraft in LEO in 2010 (D'Amico, 2010). In 2013 De Florio proposed "Precise Autonomous Orbit Control in Low Earth Orbit: from Design to Flight Validation" focused on software development (FLORIO, 2013).

In 2020, a taxonomy of Design Structure Matrix (DSM) was proposed, focusing on three principal characteristics: organization, physical configuration, and functional configuration. Additionally, various subcategories were introduced. Each of these configurations should undergo functional and behavioral analysis.

Systems Engineering (SE) applied in Formation Flying Systems (FFS) is also discussed, as seen in the case of Subramanian et al. in 2015, where they conducted a Systems Engineering Study of a Formation Flying Demonstration Mission using CubeSats (Subramanian et al., 2015). Additionally, Concurrent Systems Engineering (CSE) applications for the conception of Attitude and Orbit Control Systems (AOCS) were explored by De Souza et al. in 2011, proposing a systematic process to develop systems according to stakeholders' expectations (De Souza et al., 2011).

Finally, Anyanhum and Edmonson (2017) proposed a design framework for Inter-satellite Communications (ICS) systems for small satellites using Model-Based Systems Engineering (MBSE). They presented an architectural framework for defining and representing ISC system architecture for Small Satellite Systems based on an MBSE approach (Anyanhum & Edmonson, 2017).

4. Conclusions

The scientific articles selected, presents the evolution of the control of FFS missions and the SE applied to space products.

Various research topics related to Formation Flying Systems (FFS) and the application of Systems Engineering (SE) have been explored from 1998 to 2021. Initially, starting from 1998 and continuing into 2007, there was a noticeable interest in testing high precision techniques for positioning and attitude in testbeds. Two main architectures, centralized and decentralized control, were proposed during this period. This highlights the necessity of SE application in the Assembly, Integration, and Testing (AIT) phase of FFS development.

However, approximately 75% of the documents focused on implementing methods and techniques for controlling FFS, ranging from Command and Guidance (CNG) to Attitude and Orbit Control Systems (AOCS). These studies proposed different control architectures, including centralized and decentralized control, as well as reconfigurable control architectures. This generated interest in analyzing the behavior and architecture of FFS services. Although only 5% of the information addressed the analysis of Fault-Tolerant Controller Design to Ensure Operational Safety in FFS, this area remains underexplored and warrants further research. Finally, it is recommended to undertake a study of publication trends in this area of research carried out at conferences, seminars, workshops, among others.

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