Review

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CubeSats and Their On-Board Computers: Systematic Literature Review

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Abstract

CubeSats have revolutionized the exploration and utilization of near-space environments, particularly in low-earth orbit. In this study, we present a systematic review of the current literature to identify and discuss the main developments, research topics, and advancements in the development of nanosatellite avionics, with a focus on onboard computers—covering both hardware and software aspects. A systematic literature review was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. Of the 647 articles extracted from Science Direct and IEEE, 202 studies were selected based on rigorous inclusion and exclusion criteria, revealing six major thematic areas in nanosatellite design and operation. The findings are organized into six subsections that address the most frequently discussed topics in designing, developing, and operating nanosatellites. Topics start with the onboarding of the mission's analysis and overview and continue with the review of the hardware and software solutions for the onboard computers, their architecture and reliability assessment, and the system engineering around them. Two applied topics of telemetry and communication and the use of machine learning onboard nanosatellites are finishing the review topics. According to the results, CubeSat research and development continues growing rapidly, leveraging modern embedded technology advancements. The availability, robustness, and high integration level of commercial off-the-shelf components have introduced graphics processing units, field-programmable gate arrays, and multi-core computing systems into space. These powerful and energy-efficient computers, reinforced by modern machine learning models, enable the rapid and reliable development of complex, sophisticated missions. Finally, the conclusions highlight the major findings, potential future trends, and research topics in the field. Ultimately, this article serves as a comprehensive guide for scientists, developers, integrators, and enthusiasts engaged in space technology research and development.

Keywords: nanosatellites; CubeSat; on-board computer; cdhm; systematic literature review; OBC; software; hardware; system engineering; reliability; machine learning; AI; COTS

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1. Introduction

Since their introduction in 1999 by Cal Poly's Jordi Puig-Suari and Stanford's Bob Twiggs, CubeSats have transformed small satellite development. What began as a simple educational tool (a 10cm cube weighing about 1.33kg) has evolved into various sizes (1.5U, 2U, 3U, and beyond), supporting increasingly complex missions.

Before CubeSats came along, satellite development was restricted to government agencies and aerospace giants. The process was expensive and technically demanding, often taking years and massive funding. CubeSats changed this by introducing a modular, standardized approach that cut development time and costs. Using off-the-shelf components and encouraging collaboration between universities and industry has opened space access to a much wider community.

These tiny satellites now serve critical roles across scientific, educational, and commercial applications. CubeSats have proven their versatility from Earth observation to testing new technologies, telecommunications, and even deep-space exploration. NASA, ESA, JAXA, and countless private companies have embraced them for space research, expanding satellite networks, monitoring climate changes, supporting disaster response, and venturing to Mars and the Moon.

As miniaturized electronics, propulsion systems, and AI advance, CubeSats become even more capable. They're poised to play key roles in satellite constellations and space-based IoT networks that reshape global communications. The increasing availability of rideshare launches has made deploying these satellites easier than ever before.

In just two decades, CubeSats have gone from classroom projects to essential tools for commercial and scientific missions, demonstrating how quickly space technology can evolve. These small satellites will remain fundamental to our expanding space activities as innovation continues.

So far, almost 2600 CubeSats have been launched (Figure 1), and the forecast [116,117] says that it is expected to have roughly another 2000 CubeSats in 2025-2029.

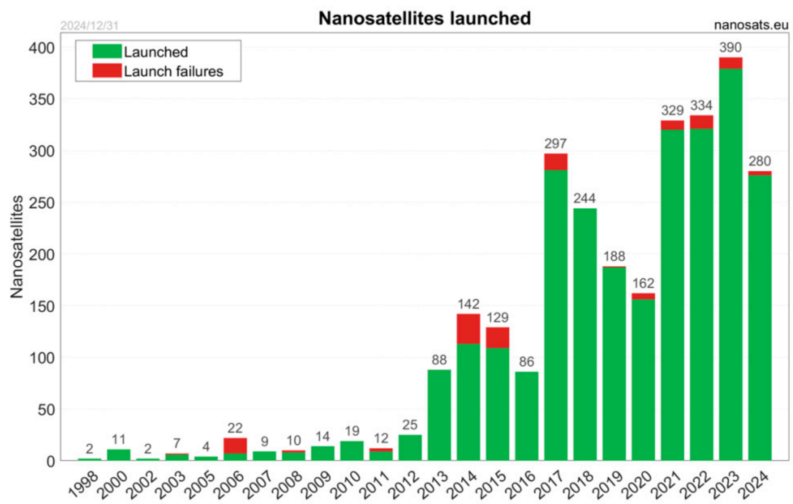

Figure 1. Statistics of CubeSats launch as per 31/12-2024 (Erik Kulu, www.nanosats.eu).

Academic interest in nanosatellites and space exploration is growing rapidly, thanks to the success of CubeSats technology and the technical advances in commercial launch vehicles such as SpaceX's Falcon 9. The number of research over the past 25 years (Figure 2) has grown almost exponentially, which proves the importance and feasibility of a systematic literature review.

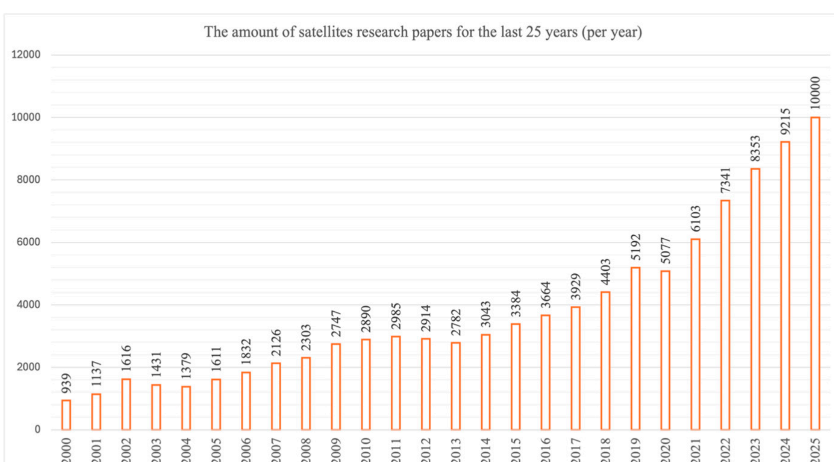

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Figure 2. The amount of IEEE Xplore publications about the research in space satellites (2000-2025).

After considering the typical composition of nanosatellite avionics, we will focus on the onboard computer as the primary and central means of controlling the flight mission and onboard avionics. Due to the need for adaptation, the onboard computer and its software are the most frequently changed design components of the nanosatellite mission.

Many teams worldwide are trying to create their avionics for nanosatellites, motivated either by the need to educate students and doctoral students or by the limited budgets for equipment and dual-purpose equipment. The first tasks of creating avionics are building technical requirements, studying state-of-the-art solutions, and building the list of terms of reference. All these artifacts are not sufficiently covered in the existing literature, which leads to an increase in iterations for the development of both software and hardware, which in turn critically affects project timelines, budgets, and general project success.

The key target of this article is to provide a clear overview of the critical part of the nanosatellite avionics – On-Board Computer (OBC) by doing a systematic literature review task. This task will cover the subject of OBC's hardware and software, computing architectures, and reliability, as well as identify the trends in those areas of interest. Additionally, the task will review nearby topics like nanosatellite missions and recent developments to be able to find the limitations and trends in the modern use of nanosatellites.

2. Research Methodology

The research in this article was carried out through a systematic literature review to reflect existing research and to build a systematic view of the directions of such research and their potential focus in the near future.

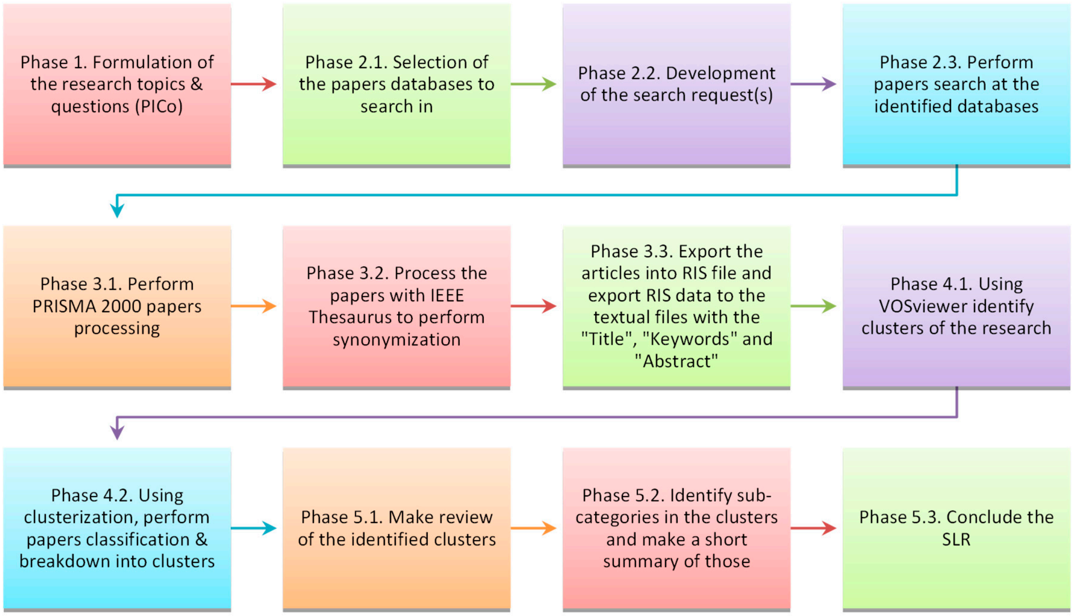

Figure 3. The algorithm of the planned systematic literature review process.

So, the process that is depicted on Figure 3 is broken down to the following main phases of the review process:

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1. Phase 1 - formulation of the research request using the PICo [31] methodology.
2. Phase 2 - selecting databases of scientific publications, articles and books and performing bibliometric analysis.
3. Phase 3 - processing the results of searches using the PRISMA [160] methodology (Preferred Items for Systematic Reviews and Meta-Analyses) and forming a short list of publications for further scientometric analysis.
4. Phase 4 - clustering based on the principle of synonymizing through the analysis of a short list of publications using the VOSviewer tool [200].
5. Phase 5 - systematic review of publications based on the results of clustering and the formation of a list: topics and areas of research, identified gaps and the formation of potential future research.

Phase 1. Formulation of the Research Request Using the Pico Methodology

To formulate the task of the literature review, we used the PICo (Population, Interest, Context) methodology [31] to formulate a research question.

Search terms such as “nanosatellites” and “CubeSat” are processed using IEEE Thesaurus 2022 [3] and we distinguish that CubeSat = NT (narrow term) from nanosatellites, nanosatellites = NT from satellites.

P - Population (Problem) = “nanosatellites” or “CubeSat”

I - Interest = “requirements”. Additionally, “lifecycle” or “cots” can be considered, but this, in the authors' opinion, greatly narrows the population of documents for search.

Since the review is focused on on-board computers and their hardware and software, we formulate the following search terms:

OBC - On-Board Computer, CDHM - Command and Data Handling Module, and its derivative abbreviation - CDH (Command and Data Handling) and generalize it to “computer.” [56] (We refer to the CubeSat 101 course from NASA to check the appropriateness of the terminology)

The search string can be defined as the following:

Co - Context = “obc” **OR** “cdhm” **OR** “cdh” **OR** “computer”.

Phase 2. Selecting Databases of Scientific Publications and Searching Them

Two online search and index databases were selected for the hardware search: IEEE Xplore [95] and Elsevier Scopus / Science Direct [177].

Since research in the field of satellite engineering is developing at an exponential rate (see Figure 2), we will use articles from the last 10 years, i.e. 2015-2025, for the search. More outdated articles will be considered inappropriate for study and analysis.

At the first stage, we will consider the total number of publications related to nanosatellites:

We use generalized words for queries, namely:

("All Metadata":"nanosatel*" OR "All Metadata":"cubesat")

The result of the IEEE Xplore database search is equal to 2866 articles.

To narrow down the search to the required research area, we specify that we are interested in requirements in the field of nanosatellites and CubeSats, namely their computers. So, the updated search query according to the following criteria, shall look like:

(“nanosatellite*” OR “CubeSat*”) AND “requirem*” AND (“obc” OR “cdh*” OR “comp*”).

The search is done in full metadata (all available fields in the database) and therefore chosen to be “All Metadata” since most articles are closed.

("All Metadata":"nanosatellite*" OR "All Metadata":"CubeSat*") AND "All Metadata":"requirem*" AND ("All Metadata":"obc" OR "All Metadata":"cdh*" OR "All Metadata":"comp*")

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The result is equal to 399 articles. These 399 articles are considered for the further processing.

The obtained results were saved using the export function to a bibliographic catalog with the RIS [164] (Research Information System) extension and divided into 4 files accordingly (due to the export limit of 100 references).

Let's perform the appropriate search in the Science Direct database. Since the search tools are less advanced in terms of complex search, we experimentally found that the following query provides the most relevant search results:

"satellite" AND "obc" AND “computer"

The result is equal to 248 articles. These articles are considered for the further analysis.

The overall amount of the articles from both IEEE Xplore and Science Direct that are eligible for the further analysis is 587.

Phase 3. Processing of Search Results According to the Prisma Methodology

The PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [160] was developed and implemented by Prof Joanne McKenzie and Dr Matthew Page at Monash University and provides a structured approach and methodology for analyzing multiple bibliometric references.

The PRISMA methodology distinguishes between full articles and articles where only keywords and abstracts are available. In our review, most of the articles are closed, so in the methodology checklist we will indicate a single list of articles, regardless of its openness.

For the screening steps, i.e. manual selection of relevant articles, the following stop-words/stop-abbreviations were used: ADCS (Attitude Determination and Control System), 5G, 6G, propulsion, radar, battery, SDR (Software Defined Radio), PPT (Power Point Tracking), EPS (Electric Power System), radio, attitude, thruster, robot, navigation, IoT (Internet of Things), thermal.

The terms “software”, “cyber”, “security” was retained during synonymizing and clustering to build links with an integral part of the On-Board Computer (OBC) – “software”.

In accordance with the PRISMA methodology, the following flowchart was built and processed:

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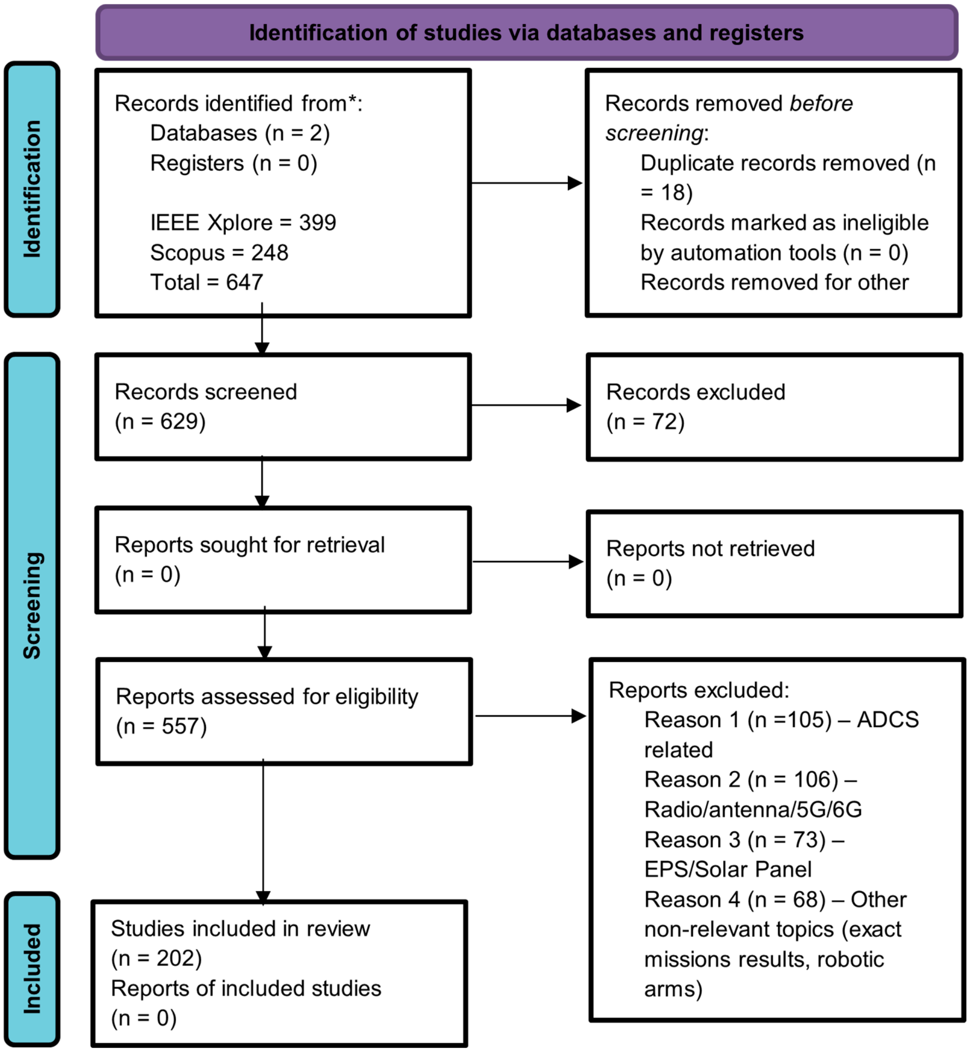

Figure 4. PRISMA diagram of the processing the selected 557 articles.

Thus, 202 articles from both libraries - IEEE Xplore and Science Direct - were selected for further work on the systematic review.

To improve further synonymizing and clustering, it was decided to replace the synonyms according to the IEEE 2022 thesaurus as follows:

Table 1. Synonymizing process in accordance with IEEE Thesaurus 2022.

Synonym in the narrow term (NT)	**Result**
CubeSat	nanosatellite
CubeSats	nanosatellite
Synonym in the broader term (BT)	**Result**
satellite	nanosatellite
satellites	nanosatellite

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Synonym in the narrow term (NT)	**Result**
CubeSat	nanosatellite
CubeSats	nanosatellite
low earth orbit satellite	nanosatellite
space vehicle	nanosatellite
small satellite	nanosatellite
An equivalent synonym	**Result**
nano satellite	nanosatellite
nano satellites	nanosatellite

Phase 4. Processing and Clustering with the Vosviewer Analysis Tool

The good and ultimate way to define the research directions from a combined library of the research papers is to use synonymization and further clusterization approach. To do so, authors have identified the newly introduced (as late as in 2017) tool – VOSviewer.

VOSviewer is a software tool for creating maps based on network data and for visualizing and exploring these maps. The functionality of VOSviewer can be summarized as follows: Creating maps based on network data (i.e. networks based on the list of publications – in the author's case – a set of selected RIS files), Visualizing and exploring maps by generation of network, overlay and density visualization.

Using the VOSviewer, the following network diagram was built – Figure 5.

Via the built-in into the VOSviewer tool the following 6 clusters were identified:

- Cluster 1 - Nanosatellites, payloads and missions (21 elements) - red
- Cluster 2 - Software & Hardware (16 elements) - green
- Cluster 3 - System Engineering & Standards (15 elements) - blue
- Cluster 4 - Computer architecture & reliability (12 elements) - yellow
- Cluster 5 - Monitoring & Telemetry (7 elements) - purple
- Cluster 6 - AI/ML (4 elements) - turquoise

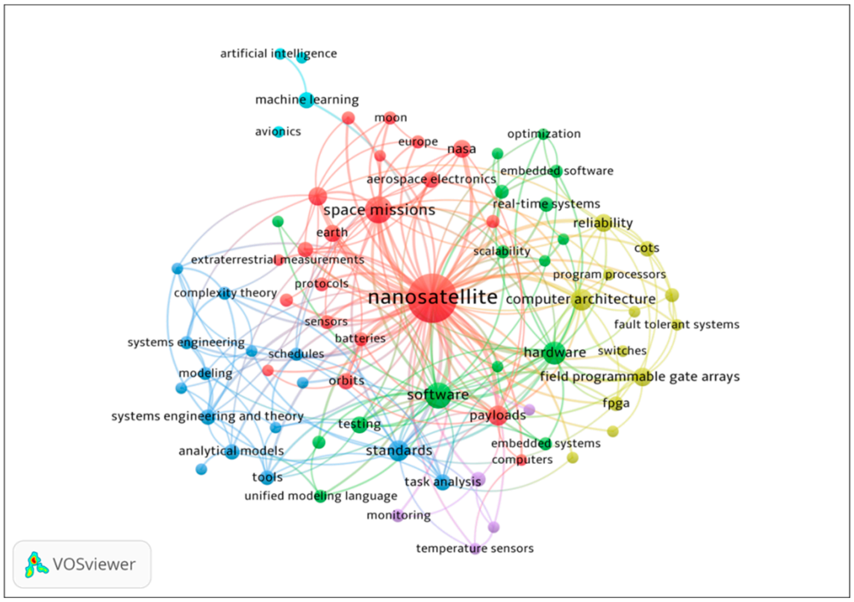

Figure 5. Network diagram done by the VOSviewer tool (generated by the authors).

The elements identified by the clustering are the terms that will be used for the further grouping of the papers and their further processing. Identification of the elements is done by VOSviewer tools and can be seen in the tab called "Items".

A quick glance on the popularity of the various terms (keywords) can be easily achieved via the density chart that has each identified term and its size and contrast that is proportional to the frequency of the term appearance during the publications analysis.

The obtained term density chart for the analyzed set of selected publications is shown of the Figure 6:

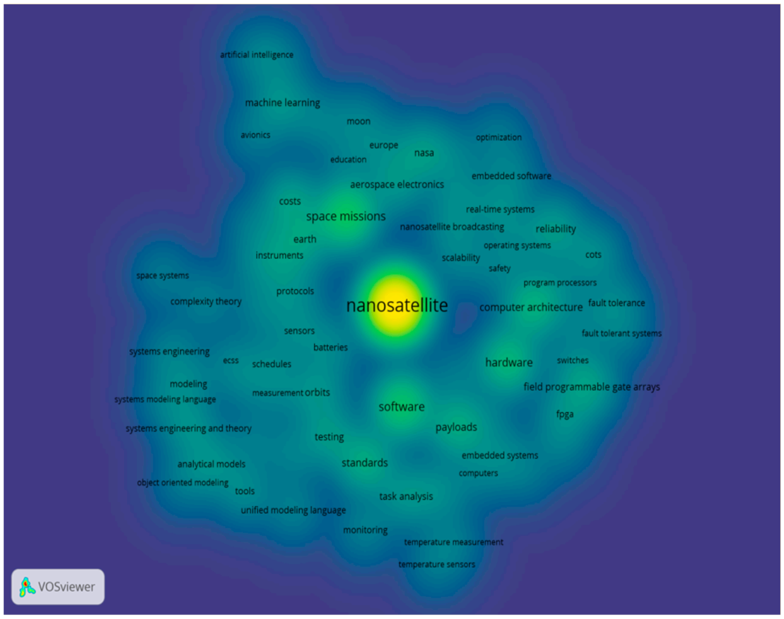

Figure 6. Term density chart done by the VOSviewer tool (generated by the authors).

The time analysis chart (Figure 7) is an Overlay visualization that provides an idea of research trends:

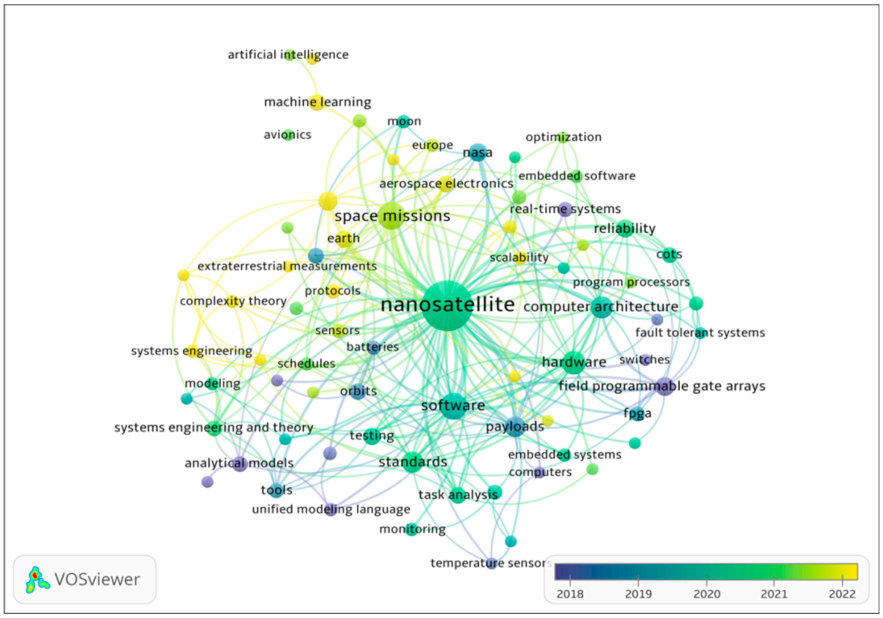

Figure 7. Overlay visualization chart done by the VOSviewer tool (generated by the authors).

The diagram shows that research in such areas as system modeling, requirements management, FPGA (field programmable gate array) and the use of analytical models for nanosatellite construction was active in 2015-2018 and is likely to have a stable research maturity today. In 2020-2022, the biggest trends in research were software and hardware, reliability, the use of systems engineering and modeling to build nanosatellites, and standardization of approaches to their development. In 2022-2023, the main research was focused on optimizing the price of nanosatellites, using machine learning and AI, as well as optimizing and researching embedded software. And the trends of 2023-2024 were focused on general issues of building space systems. It should also be added that during 2022-2024, the number of publications (and, accordingly, research) in Europe increased significantly, as evidenced by the involvement of the European Space Agency (ESA) and its bigger role in the CubeSat industry.

Phase 5. Review of Clustering and Related Scientific Publications

The identification of clusters and their synonymized terms were calculated by the VOSviewer tool, but for further analysis, it is necessary to perform manual operations to analyze the research areas and the number of publications corresponding to the synonymized terms.

The total number of publications and the breakdown by clusters by keywords is shown in Table 2 below.

Table 2. Breakdown of the researched papers and their distribution among the identified clusters.

Cluster #	Cluster Name	Number of papers assigned	The identified keywords
1	Nanosatellites & Missions	50	aerospace electronics, atmospheric modeling, batteries, computational modeling, computers, costs, earth, education, Europe, extraterrestrial measurements, instruments, moon, nanosatellite,

			NASA, orbits, payloads, protocols, sensors, space missions, and technological innovation
2	Hardware and Software	31	cyber-physical systems, embedded software, embedded systems, ESA, flight software, hardware, operating systems, optimization, real-time systems, requirements engineering, safety, scalability, software, software architecture, testing, and unified modeling language
3	System Engineering & Standards	58	analytical models, complexity theory, ECSS, MBSE, measurement, modeling, object-oriented modeling, project management, schedules, space systems, standards, system engineering (and theory), system modeling language, task analysis, tools
4	Computer Architecture & Reliability	44	computer architecture, cots, fault detection, fault tolerance, fault-tolerant systems, field programmable gate arrays (FPGA), microcontrollers, program processors, random access memory (RAM), reliability, switches
5	Monitoring & Telemetry	6	monitoring, telemetry, temperature measurements, temperature sensors, visualization
6	AI/ML (Artificial Intelligence / Machine Learning)	15	artificial intelligence, avionics, earth observation, machine learning

Cluster 1 - Nanosatellites & Missions – 50 Papers

The studies in the first cluster of the systematic review are mainly aimed at analyzing approaches to nanosatellite construction, processes and approaches to their development, as well as reviewing the specifics of specific missions and the corresponding payloads. The studies in this cluster provide a good overview of the overall process of developing and preparing nanosatellites for launch, and its components - from requirements gathering to testing, optimization and interaction with nanosatellite launch programs of leading agencies such as ESA (European Space Agency) and NASA (National Aeronautics and Space Administration).

The studies allow the reader to review the trends, tasks, and problems of nanosatellites, as well as to get acquainted with their structure. An additional component of this cluster's publications is the analysis of completed missions and lessons learned, which makes it possible to reduce the risks of successor space programs.

An important element of this cluster is to demonstrate how the concept of building and standardizing CubeSat nanosatellites has launched other projects in the fields of space robots [110,138], manipulators, and even stratospheric balloons.

Table 3. Identified sub-categories (research directions) in the cluster 1.

Name of the identified sub-category	**Relevant publications**
Embedded Systems & Software Testing	[22,42,51]

Communication & Networking	[159]
Hardware, Avionics & COTS	[19,25,55,60,72,83,85,124,205]
CubeSat/Nanosatellite Platform & Design	[1,21,57,64,81,82,86,91,93,96,98,101,127,128,206]
Mission Design, Analysis & Concept Studies	[2,10,11,13,28,30,35,38,47,122,152,165,179,181,193,210,213]
Security & Data Management	[109,133]
Robotics & Autonomous Operations	[110,138]
Navigation & Sensor Fusion	[66]

Embedded Systems & Software Testing: Papers [22,42,51] focus on software toolsets, mutation analysis as the software creation and testing approach, and testing strategies for embedded applications.

Communication & Networking: Paper [159] is centered on transitioning from legacy bus protocols to Ethernet in space launchers and rather a demonstrator of a conventional technology moves to the nanosatellites industry.

Hardware, Avionics & COTS: Papers such as [19,25,55,60,72,83,85,124,205] emphasize hardware implementations, use of COTS components, avionics architectures, and similar topics.

CubeSat/Nanosatellite Platform & Design: A large sub-group of papers like [1,21,57,64,81,82,86,91,93,96,98,101,127,128,206] describes various CubeSat or nanosatellite development tools, design challenges, and platform innovations. This group of papers could be used as very fast-forward material for getting into the recent CubeSat development advancements and experience.

Mission Design, Analysis & Concept Studies: Papers [2,10,11,13,28,30,35,38,47,122,152,165,179,181,193,210,213] cover mission planning, performance analyses, concept studies, simulation, and related topics.

Security & Data Management: Papers [109,133] deal with satellite reference databases and digital security (e.g. encryption, data integrity).

Robotics & Autonomous Operations: Papers [110,138] focus on robotics aspects and autonomous operations (including lunar exploration elements).

Navigation & Sensor Fusion: Paper [66] is dedicated to sensor fusion and navigation filter challenges for spacecraft rendezvous. This papers more relates to the payload avionics but highlights some important points regarding the CubeSat specifics.

Cluster 2 - Hardware (18), Software (13) – 31 Papers

Cluster 2, consisting of research papers in the field of the hardware and software of the CubeSat avionics, mainly onboard computers. There are two key sub-clusters, namely "software" and "hardware". These could be broken down to the following sub-categories:

Table 4. Software sub-category from the Cluster 2 – HW & SW of CubeSats.

Name of the identified sub-category	**Relevant publications**
Software Frameworks & Architecture	[14,63,79,141,183,190,197]
Software Processes, Tools, Validation & Scheduling	[37,44,156,176,180,209]

Software Frameworks & Architecture: The papers [14,63,79,141,183,190,197] present modular frameworks, architecture-tracking approaches, command-centric and layered designs for flight

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software development – all aimed at improving reusability, reliability, and reducing development time.

Software Processes, Tools, Validation & Scheduling: Papers [37,44,156,176,180,209] focus on the development process and supporting tools (including iterative, agile, and model-based approaches), validation techniques (such as ility calculations), and methods for scheduling and task management in satellite missions.

Table 5. Hardware sub-category from the Cluster 2 – HW & SW of CubeSats.

Name of the identified sub-category	Relevant publications
Fault Tolerance & Radiation Hardening	[29,68,70,90,136,147,192,194]
Onboard Processing, Performance & Energy Efficiency	[100,123,134,167,187,208]
System Integration, EMC & Interface Standards	[36,39,166,211]

Fault Tolerance & Radiation Hardening: Papers such as [29,68,70,90,136,147,192,194] focus on architecture, tests, and techniques (e.g., SEL, SEU) to ensure reliable operation in the radiation-intensive space environment.

Onboard Processing, Performance & Energy Efficiency: Articles [100,123,134,167,187,208] address aspects of computing performance, energy efficiency, and on-board data processing via novel processors, performance monitors, or FPGA-based designs.

System Integration, EMC & Interface Standards: Papers [36,39,166,211] discuss the use of COTS devices, strategies for electromagnetic compatibility, and the development of standardized interfaces and satellite bus architectures.

Cluster 3 - System Engineering & Standards – 58 Papers

Cluster 3 focuses on looking into the research topics of model, requirement, simulation and modeling approaches to designing CubeSat. Additionally, this cluster covers topics of testing, V&V, CubeSat projects risk and project management as well as the role of such projects for the academic and educational use.

Table 6. Sub-categories identified in Cluster 3 – System Engineering & Standards.

Name of the identified sub-category	Relevant publications
MBSE & SysML Approaches	[15,18,53,76,103–107,175,188,203]
Requirements Engineering & Cyber-Physical Requirements	[9,154,162,163,170]
Agile, Scrum & Concurrent/Hybrid Development	[73,74,102,132,178]
Testing, Verification & FDIR	[8,67,79,84,89,114,184,201,207]
Simulation, Modeling, Optimization & Design Tools	[5,17,33,58,78,125,150,174,202,212]
Hardware, Avionics, On-Board Computers & Integration	[46,64,77,108,120,139,143–145,161,185]
Risk Management, Readiness & Safety	[155,182,204]
Educational & Project Management Approaches	[40,41,126,142,169]

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MBSE & SysML Approaches: These papers (e.g., [15,18,53,76,103–107,175,188,203]) focus on model-based systems engineering and use of SysML to develop CubeSat or satellite system models. It is worth mentioning that the approach of using MBSE and SysML had a major research interest in the period of 2016-2020 and had a major decline afterwards.

Requirements Engineering & Cyber-Physical Requirements: Papers [9,154,162,163,170] address the elicitation, specification, and modeling of system requirements—including non-functional aspects and cyber-physical scenarios.

Agile, Scrum & Concurrent/Hybrid Development: This sub-group of papers [73,74,102,132,178] covers modern Agile methodologies, Scrum practices, and approaches aimed at reducing development time and cost. The major development of the IT industry has its footprint here. Cluster covers research related to the use of non-waterfall development process.

Testing, Verification & FDIR: Papers [8,67,79,84,89,114,184,201,207] are dedicated to methods and platforms for testing, hardware-in-the-loop verification, fault detection (FDIR), and automated quality assurance.

Simulation, Modeling, Optimization & Design Tools: Papers [5,17,33,58,78,125,150,174,202,212] focus on simulation frameworks, calibration and optimization techniques, and design tools that help in predicting or enhancing system performance.

Hardware, Avionics, On-Board Computers & Integration: This group of papers [46,64,77,108,120,139,143–145,161,185] emphasizes the development, integration, and testing of hardware platforms, avionics, and embedded systems in the CubeSat domain.

Risk Management, Readiness & Safety: Papers [155,182,204] deal with frameworks for assessing assembly readiness, risk management plans, and approaches to reduce safety and compliance challenges.

Educational & Project Management Approaches: Articles [40,41,126,142,169] highlight experiences in education, project management, and concurrent engineering applied to satellite projects.

Cluster 4 - Computer Architecture & Reliability – 44 Papers

Cluster 4 is addressing the topic of computer architectures and their reliability in terms of the use of both COTS and non-COTS solutions for the CubeSat avionics design & development.

During the analysis of the papers the following sub-categories were identified:

Table 7. Sub-categories identified from the Cluster 4 – Computer Architecture & Reliability.

Name of the identified sub-category	Relevant publications
On-Board Computers (OBC) and Architecture Design	[6,54,87,100,135,148,172]
Fault Tolerance and Reliability in Space Systems	[12,62,69,71,151,168]
Radiation and Reliability Studies	[20,32,75,129–131,166,201]
FPGA-Based Architectures and Computing	[4,97,118,153,173,195,198]
Cybersecurity and Software Reliability	[16,23,52,59,61,92,186,191,196]
Dependability and Testing Approaches	[26,27,45,50,115,121]
Power Management and Energy Efficiency	[80,111,146]

On-Board Computers (OBC) and Architecture Design: This category investigates the specific ways of implementing computation architectures both for OBC and other electronic sub-systems of nanosatellites. Authors are discussing the commonalities in the OBC design for interoperable missions [54,148,172], improving OBC diagnostics and mission issues analysis [100,135] and trying to define the most applicable memory interfaces [87] and multi-core solutions [6]. Paper [54] provides very good state-of-the-art analysis of the details of the recent OBC architectures.

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Fault Tolerance and Reliability in Space Systems: The tolerance towards faults and errors that leads to the elevated reliability is the key topic for the investigation in this group of reviewed articles. It addresses dual processing approaches, combining FPGA and classical computation cores [69] to be able to identify issues in the computation context, as well as implementing a classical lock-step architecture [71], ending up in a distributed, so-called, multicell architectures [62]. There is a good numerical and simulation approach on identifying the diagnostics coverage [151]. The extra efforts in increasing reliability are seen in memory to CPU interfacing [168] and in addressing the most-typical avionics peripheral bus lockups (I2C) [12].

Radiation and Reliability Studies: Radiation in space is always the challenge. The fact that the vast majority of CubeSats operate on LEO is a little relaxing factor for the radiation hardening, however with the major use of COTS electronics in CubeSats, those are vulnerable to the radiation effects, especially at the Van Allen belt. To address this problem there are actual stress-testing approaches [20,75,130] simulation and injections of faults [129,131] and generally looking into reinforcing COTS electronics towards better reliability [32,166,201].

FPGA-Based Architectures and Computing: Using FPGA, and its simplified brother – CPLD, technologies is a design pattern that stands out in the industry. It allows flexible configuration (both in space [173] and during development [195]), provides parallel and deterministic computing, as well as allows great hardware level of integration to the memories, buses and interfaces, including adopting some open-source computing cores, i.e. RISC-V [118]. The idea of making an interoperable FPGA based OBC [198] and making it high reliability for NASA missions is highlighted in [97]. It connects to the same attempt where FPGA is coupled with GPU [4]. The challenges, findings and resource demands are also reviewed [153].

Cybersecurity and Software Reliability: Cybersecurity and impersonation in CubeSats control could potentially ruin the whole mission or deliver its value to someone else than the intended operator. One of the typical cyberattack analysis techniques is laying around system buses traffic anomalities detection [59] and further traffic transmitting to the ground station [23,92] and its management there [196]. Virtualization [61] and tasks isolation [16] is also considered, as it gives a computational context safety for the logically decoupled onboard software tasks and/or applications being ran on the OBC's CPU. The concept of FDIR approach to [26,191] the nanosatellites avionics architecting and its mission impact [52,186] is well covered here too.

Dependability and Testing Approaches: In the context of CubeSat systems, the term "dependability" refers to the ability of a system to deliver trusted and reliable service throughout its mission lifetime, despite the harsh space environment and limited intervention opportunities. Thorough and repeatable HIL testing [27,50] via model-based approach and fault & shock injection methods [121], and how it can help to elevate platform readiness towards specific equipment standards [115] is the key essence of this group of research papers. The use of formal functional safety approach is also considered in [45].

Power Management and Energy Efficiency: Power is the scarcest resource on the Earth orbit and its availability is directly coupled to the efficient and reliable operation and mission value delivery. Finding a balance between system reliability and power efficiency [111], correct computation planning [146] and implementing and trying it out [80], is the typical task that occurs during a CubeSat project development.

Cluster 5 - Monitoring & Telemetry - 7 Papers

Since telemetry, radio, and communication between nanosatellites and ground stations were removed from the analysis, the publications below refer to publications on hardware and software of the generalized telemetry data processing module and the ground station operation, and refer to the OBC topic.

The importance of the well-designed telemetry and its storage at the ground station can help to analyze the CubeSat reliability issues and the article [94] provide an overview of the ML approach for such an analysis.

Articles are reviewing the balancing of the power consumption and the telemetry data amount [7,133] as the telemetry and communication system are the most power demanding subsystems of a CubeSat.

Reputation handling for the inter-satellite telemetry and satellite to ground communication is researched in [49,88] and addresses the rising need of the cyber secure communications.

Complexities of laser high speed communications are discussed and the technical proposal on how it can be implemented is presented [149].

Some conceptual development of the LEO datacenters is proposed and reviewed in [34] and opens a new concept of sensitive data processing and storage at the orbit.

Cluster 6 - AI/ML (Artificial Intelligence / Machine Learning) – 15 Papers

Most articles on the use of AI and ML address the tasks of image and remote sensing processing, intelligent processing and recovery of telemetry data, and the latest developments to bridge the gap between cheap COTS solutions and radiation-resistant platforms that are not available as commercial products.

The systematically reviewed publications in Cluster 6, can be structured among the following sub-categories of research topics:

Table 8. The sub-categories identified in Cluster 6 – AI/ML.

Name of the identified sub-category	**Relevant publications**
ML for Satellite Operations & Analysis	[24,94,137,140]
AI for Autonomy and Decision Making	[65,99,119,189]
On-board Processing, Edge Computing & Hardware for AI	[112,157,158,171]
Computer Vision & Image Recognition in Space	[43,48,199]
Fault-Tolerant Model Updates & Maintenance	[113]

ML for Satellite Operations & Analysis: The papers [24,94,137,140] focus on using machine learning and deep learning for Earth observation, forecasting telemetry, optimizing resource use, and fault diagnosis.

AI for Autonomy and Decision Making: Articles such as [65,99,189,199] address autonomous decision-making and cognitive techniques (including deep reinforcement learning) to improve satellite operations and communication networks.

On-board Processing, Edge Computing & Hardware for AI: This group of papers [112,157,158,171] includes evaluations of new processor architectures (GPU, NPU, etc.) and on-board ML model deployment, emphasizing edge computing capabilities for space applications. The key essence of the edge computing for the space applications is its limited data communication back and forth with the ground station. Limiting the communication time and data amount leads to drastic power saving of the onboard energy.

Computer Vision & Image Recognition in Space: Papers [43,48,199] are dedicated to leveraging computer vision techniques for imaging payloads, object detection, and tracking on CubeSat platforms.

Fault-Tolerant Model Updates & Maintenance: Article [113] focuses on enhancing the resilience of onboard neural networks via fault-tolerant updates using vector quantization.

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3. Conclusions

Nanosatellites of a CubeSat class remain the booming topic in the modern space research, thanks to the modular architecture, low cost of the launch and buildup, as well as the accumulated know-how and research results. Use of nanosatellites both in commercial and academic organizations demonstrates the success of the technology.

As the main objective of the article is to conduct a systematic literature review on the design, development and testing of the on-board computers (OBC) of the nanosatellites, the key clusters to be concluded on are System Engineering and Standards, Hardware & Software, Computer Architecture & Reliability with a little glimpse on AI/ML topic.

Based on the review of the literature the following conclusions were done:

Hardware

1. The use of commercial electronics that are not radiation-resistant for the buildup of OBCs is spreading even more than before, including missions from big international space players like NASA. The use of conventional commercial processors such as STM32 from ST Microelectronics, ATSAMx/PIC32x from Atmel/Microchip or MSP430 series from Texas Instruments is a typical practice.
2. The use of dual architectures consisting of an FPGA and a processor is a steadily growing trend. At the same time, we are seeing an increase in the use of dual solutions combined in one chip, such as MPSoC, Xilinx Zynq, Microchip PolarFire. The key motivation for using FPGA-based architectures is their flexibility, reliability and performance.
3. The use of GPUs for more complex computational tasks is gaining popularity, especially for larger satellites or satellites where the OBC, ADCS and the payload are combined to save space. Initially the use of GPUs was popular choice for the AI/ML tasks in image processing at a payload module, but when it was adopted there – it was spreading out to the OBC solutions as well.
4. A separate branch of “highly reliable” missions is emerging that requires the use of radiation-resistant processors, FPGAs and electronics in general. Such solutions are normally intended to travel to higher orbits than LEO, orbits of Mars, or to deep space.
5. There are “middle” class of reliable mission computers follows the key principles and knowledge from the functional safety world and there are much research in the area of using lockstep cores (ARM Cortex-R as an example) or multi-channel redundant computers.
6. The open RISC-V architecture is becoming more and more popular, but today it is mostly at the level of IPU cores loaded into FPGAs (Microchip PolarFire or just a general purpose Xilix FPGA). This is due to the lack of physical processors that are properly commercialized. This trend requires further attention and research, as RISC-V is a very powerful and energy-efficient solution that will continue to grow.
7. Power consumption, efficiency and optimization techniques are still very much the topic for the research. Different methods and techniques are used to optimize both hardware but mainly flight software that is the key to the computational and electric efficiency. The amount of nanosatellite losses due to the power systems failure is still among the highest ones.

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Software (Flight Software)

1. The use of real-time operating systems (FreeRTOS, RTEMS, uCOS (Micrium)) is a de facto an industry standard. Operating systems allow for the safe implementation of more complex software systems and complexes.
2. The trend of increasing the share of nanosatellites performing missions under the Linux operating system (with or without real-time extension) is also noticeable. This is due to the large number of software available for use, as well as to the growing power of hardware and the increasing degree of integration.
3. Open-source software use is the industry standard.
4. A fairly large number of articles analyze the use of modern approaches to software development, such as Scrum/Agile and the movement towards modularity and reuse of software. Modularity and reuse is put into a spotlight of a future flight software development and the key method of reducing the complexity and mission failure rates.
5. Many projects and missions are still based on proprietary software solutions where software/firmware is developed in low-level programming languages like C, C++. At the same time more and more implementations are using higher level programming languages like Python and Rust.
6. The concept of virtualization and containerization is being actively considered and researched. In the nearest future, for the powerful OBCs it will most likely replace the concept of running the full monolithic binary software image. Virtualization and containerization are safer and more understandable for modern programmers and DevOps engineers, as well as generally more secure from stability and cybersecurity points of view.
7. Despite the availability of such well-known open-source software solutions as NASA's cFS and F'Prime, as well as ROS/ROS2 solutions, their use and consideration are very limited, which is most likely due to the short timeframe for software development in academic institutions.

System Engineering

The earlier trend of using MBSE and SysML approach for onboard software design and development seems to be less of a hot subject for research. This might be connected to the general maturity of the CubeSat technology and better unification of the different CubeSat avionics functions. In other words – the split on what each avionics unit of a CubeSat does, is way more clear and well-documented. In the late 2023 and onwards the interest to the use of MBSE approach has become interesting again.

On the testing side, the approach of using HIL/MIL/SIL testing is the main trend, and it resulted in creating relatively complex modular test platforms that are intended to help CubeSat developers to perform a V&V process during the development.

Cybersecurity, resilience and data protection is the rising research trend too. In the modern world of commercial solutions called Satellite-as-a-Service, there is huge need to preserve and limit access to the satellite data. Keeping the data secure and safe allows CubeSat developers to gain the full value of their missions and secure overall mission success.

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