

Attitude Control Systems for Nanosatellites: A Systematic Review

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Abstract: As technology advances electronic components and devices get miniaturized, nanosatellites can hold denser payloads with more sensors, requiring attitude control to point precisely both sensors and antenna to send back to ground stations on Earth the acquired data. Such important techniques have been researched since the 90's to develop efficient technology due to lack of space, available energy to the tasks and their criticality, many techniques and designs have been developed and tested since then. In this review, using PRISMA methodology, some of this research will be presented focusing on the actual more used ones, like reaction wheels, magnetorquers and other perspectives as attitude control by shifting masses. A summary of findings was constructed to highlight these review points, and a discussion was made right after about the possible gaps. The presented techniques show some flaws when used as the only control device separately but have the tendency to minimize it when combined. However, using both methods requires more battery usage, processing and raises the nanosatellite's costs, since these dedicated actuators are highly expensive. In the other hand, experimental techniques, based in moving mass actuators presented promising results in terms of energy saving, precision, time to convergence, but requires more intricate calculations and a refined control due its non-linearities intrinsic to the systems construction and a single physical prototype haven't been displayed until the writing of this review. In conclusion, there's a clear preference for applying reaction wheels and magnetorquers together to Attitude Determination and Control Systems (ADCS), but its common problems could be solved by using another technique such as moving mass control, a field where still have great opportunities to innovative, equally efficient techniques and the possibility of pioneering the construction of a physical functional prototype, even with its own peculiarities.

Keywords: Attitude Control. Nanosatellites. Aerospace Engineering. Literature Review. CubeSat.

1. Introduction

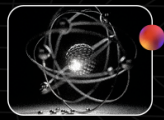
In 2025 there's at least 790 CubeSats launches predicted [1], and technologies aimed at aerospace engineering became a major importance subject in the international scenario recently.

One of the subjects of interest is the development of devices called nanosatellites for exploration and monitoring of Low Earth Orbit (LEO) and the Very Low Earth Orbit (VLEO) because of its overall of cost-effectiveness since the imagery are improved, payloads, antennas, transmission power are drastically reduced if compared with common high altitude satellites and the launcher needs less power and fuel to execute the missions [2]. On the other hand, low altitude means denser air and consequently more perturbations (Fortescue and Stark apud [2]) that need to be dealt with by

control systems to damp the oscillations and keep the cubic satellite stable.

The most used devices to integrate attitude control systems in nanosatellites are magnetorquers and reaction wheels (H. Polat and colleagues apud [1]), but at the same time they are still expensive devices when thinking about the allocated budget to researchers, students and minor institutions [3], especially in Brazil. Even in countries where there is more investment, the cost of these devices is still a concern to universities and laboratories, leading to research to develop solutions such as low-cost reaction wheels [3] or new concepts as moving mass actuators to control nanosatellites [4],[5].

In countries with low tradition and investment in technology research and low levels of



industrialization the development of devices based in marginal technologies can, besides the cost reduction, put it in an advantageous situation of dispute its place on the subject's technological vanguard by owning not only the intellectual property, but also the know-how to deal with the new technology, creating alternative paths to the goal.

The bigger challenges about moving mass control are connected to strong nonlinear behavior; the application of advanced nonlinear control techniques, such as Lyapunov stability theory [4]; the need of physical space to operate the moving parts; and positioning of the parts in must to be in trivial positions along the vehicle [6].

In this paper, the aim is to compile the last ten years contributions in the area of attitude control systems for nanosatellites, that fits the systematic review criteria, with emphasis in shifting mass. By means of this review, several documents about the current techniques and technologies already on the market are analyzed in terms of research and innovative interest in new studies.

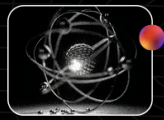
This document is segmented into the following content: Section 2 describes the systematic review approach applied. Section 3 presents the results obtained and a discussion about the methods and technologies used in attitude control systems. Section 4 presents the conclusions and future works.

2. Methodology

For this review, the literature systematic process referred as Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was adopted [7]. The queried databases were: ScienceDirect, Google Scholar, CAPES Periodic and IEEE Xplore, used as primary research sources, all known for their reliability and large number of relevant documents, however the adopted search string returned no results in the IEEE Xplore case .

The keywords used were Attitude Control, Shifting mass, CubeSats, Nanosatellites, Unbalanced and Center of mass, in this context, the constructed terms for the research using the connectives and, or and quotes were ("Shifting mass" OR (("moveable" OR "changeable" OR "unbalanced") AND "center of mass")) AND ("Attitude control" OR "Modeling") AND ("CubeSats" OR "nanosatellites"), used in the search box exactly this way for all the sources.

176 documents were found in the period from 2014 to 2024, among them articles, thesis, dissertations, papers and a survey. The citations archives were uploaded to Rayyan, an AI systematic review management platform. From this tool, 18 duplicates were detected and excluded. By reading the 157 remaining titles and abstracts, 139 were excluded because of their relevance and connection to the topic and among the 18 remaining, 5 required premium login to access the content. Finally 13 were selected for full reading based on their title and abstract's

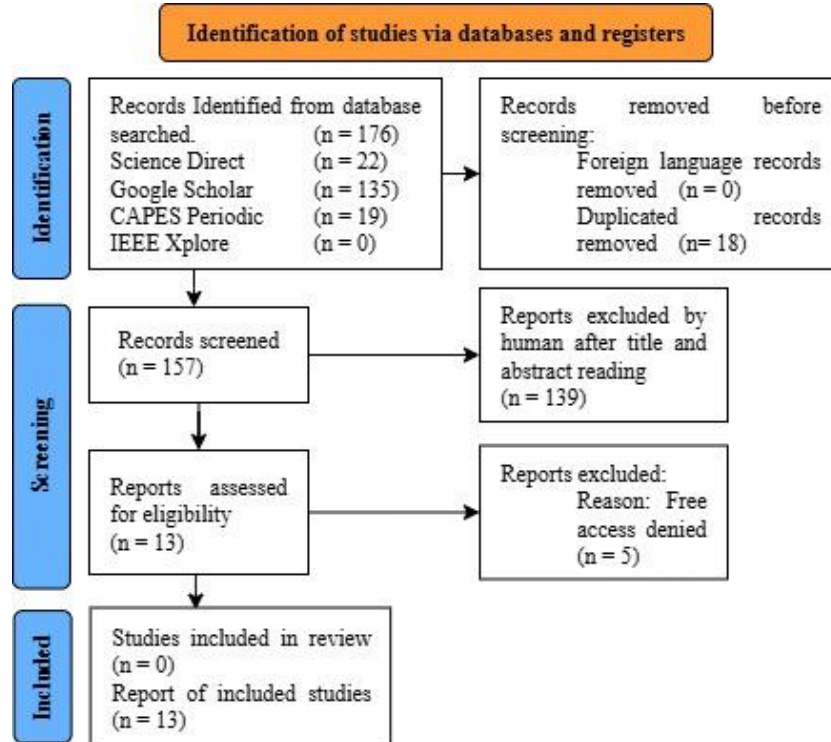


information. The figure 1 resumes the process and the number of documents excluded and remaining after each step. The following link redirects the

reader to a PRISMA Checklist 2009 version:

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Figure 1. PRISMA Diagram for attitude control system review

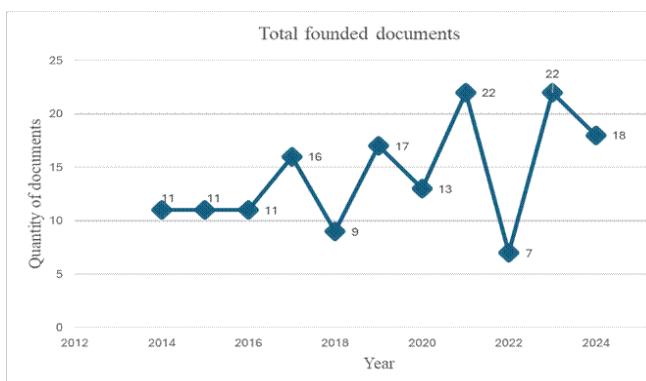


Source: Adapted from [7]

3. Results and Discussion

The quantity of published documents about CubeSats has had an ascendent tendency line since 2014, even reaching its lower point in 2022, as observed in Graphic 1.

Graphic 1. Studies found in research



An important point to note during this period is the change in terms used in research titles. Initially, the term “nanosatellite” was more used, but it led to less reach due to a more specific concept. After the term was back to “CubeSat” and, consequently, has more reach in research. Currently, the term “spacecraft” has gained prominence due to its more generic scope. Another thing to acknowledge is that 2022 the world felt the remaining problems caused by the COVID-19 Pandemic. These impacts closed laboratories, shortened the research budget to some entities which led to, in some sectors, delays in publications, unemployment and the premature ending of some research. All these factors combined may explain the phenomenon.



Graphic 2 illustrates in Mundi-Map how these documents are distributed in the world. From the most relevant papers, it is clear the polarization of this new space race between the United States and China, with six and four documents included, respectively. Besides, this graphic presents the necessity of more debate, publications and incentives to Brazil to dispute space in this new scenario to avoid too much technological

dependence. The development of research in this area of knowledge in Brazil still needs to grow in numbers and especially in innovative ways. In this search, for example, among all 157 not duplicated documents only 2 articles were from Brazil, which represents 1.27%. Table 1 summarizes all documents obtained in this research, chronologically displayed, and the summary of findings.

Graphic 2. World included articles distribution

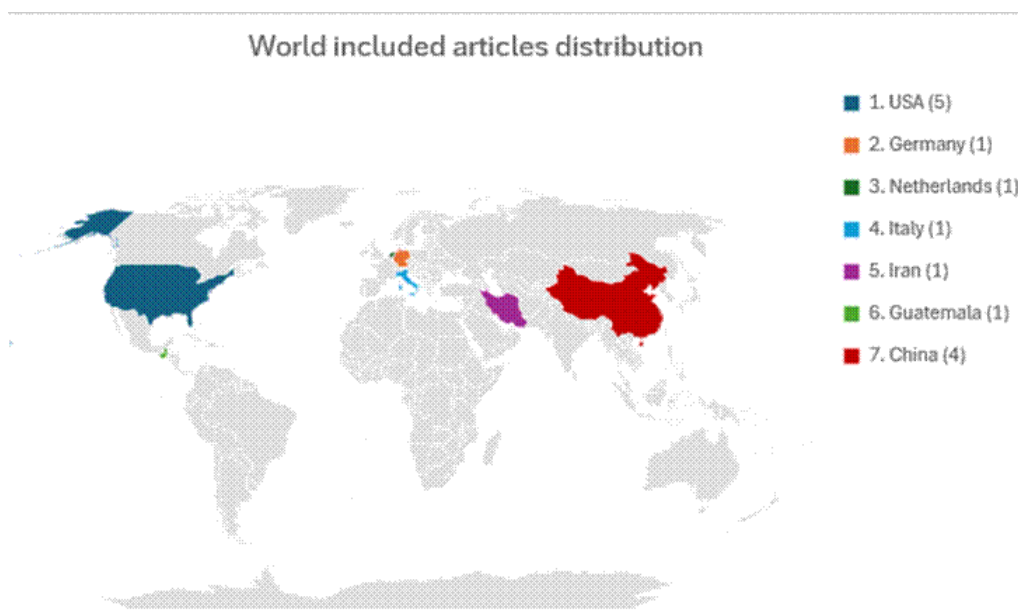
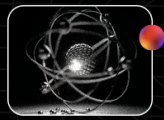


Table 1 - Articles compilation

Reference	Objective	Attitude Control Method	Summary of findings
[4]	Develop a novel attitude control system through shifting masses.	Shifting Mass	Technique based on shifting masses to variate aerodynamic torque. Use of Lyapunov stability theory.
[8]	MATLAB/Simulink application to test CubeSats hardware in a laboratory.	Reaction Wheels + Magnetorquers	Simulated environment in MATLAB/Simulink to test hardware-in-loop. Actuators, perturbations and physics modelled.



[2]	Shifting masses to reject aerodynamic disturbances and stabilize the spacecraft's attitude.	Shifting Mass	Departed from Ches's (2015 [6]). Disturbances' mitigation to stabilize CubeSats Computer Aided Design (CAD) of a 3U CubeSat.
[9]	Verify and validate the possibility to control the attitude of CubeSat with magnetic rods as actuators only.	Magnetorquers	Tested the system using MATLAB/Simulink and hardware in loop to stabilize spin in satellites.
[10]	Development of a CubeSat to Earth observation with stability and high accuracy using momentum wheels within a competitive cost.	Momentum Wheels	Tested an attitude control system with only two momentum wheels to provide to the spacecraft the capability of Earth pointing and spin stabilization in VLEO.
[11]	Attitude control to CubeSats based on center-of-mass shifting paired with reaction wheels or magnetorquers.	Shifting Mass + Reaction Wheels and Shifting Mass + Magnetorquers	Shifting mass techniques for stabilization of a spacecraft. Added a set of actuators based on conventional techniques.
[12]	Design, fabrication and modelling of a plug and play CubeSat with controllable center of mass and reaction wheels in a sphere.	Reaction Wheels + Shifting Mass	Built a floating spherical satellite designed to operate on an air bearing surface. Used reaction wheels and shifting mass to control the satellite. Detailed engineering choices.
[6]	Debates about moving mass technology and its applications in aerospace, military and naval areas and its challenges.	Shifting Mass	A survey about moving mass control technology in aerospace, military and naval areas, showing patents of its applications.
[13]	Investigate attitude stabilization using shifting mass technique in a two-dimensional plane.	Shifting Mass	Tested if it is possible to stabilize three-axis attitude moving masses with less than 10% of spacecraft's mass in two-axis.
[14]	Develop an eight-degree-freedom model of a 2U CubeSat propelled by solid rocket motors with two moving masses.	Solid Rocket Motors + Shifting Mass	Applied moving mass technique to control generated torque by thrust misalignment and fuel consumption. Developed a simulation of a 2U CubeSat within the objectives conditions.
[3]	Design, manufacture, assemble and test a 3-axis reaction wheel prototype to reduce expenses to Cal Poly CubeSat Laboratory.	Reaction Wheels	Reaction Wheels are expensive devices. Patent studies of reaction wheels. Catalog of existing products and suppliers. Designed, manufactured and assembled a 3-axis reaction wheel new device.



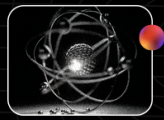
[1]	Develop an attitude control for CubeSat with three magnetorquers and one reaction wheel.	Reaction Wheels + Magnetorquers	Focused on numerical methods. Consider the orbit to determine the best results. Pondered three different control laws to choose and opted for the Linear Quadratic Regulator method.
[5]	Investigate a control technique based on moving masses to operate formations with CubeSats.	Shifting Mass + Magnetorquers	Proposed to create formations with moving mass technology as primary attitude control technique. Used Nash game theory to analyze the formation with two CubeSats.

Chesi [4] presented in his work a concept of attitude control of nanosatellites using shifting masses by creating distance between the center of pressure and center of mass to use the disturbance force of atmospheric drag as control force. Although mathematically this technique is possible it was proved using only math simulation and there's no visual concept of this system or how it would be if constructed. Even only published in 2017, in 2015 Shaik's [12] work presented a final assembly CubeSat using moving mass technique, but his spherical prototype had 198 mm diameter which is almost double far from the nanosatellite's dimensions specification proposed by the previous research cited, turning it impractical for conventional launchers.

Virgili-Llop and colleagues [2] studies proposed a 3U CubeSat concept with the shape of real devices in CAD, but there's no information if it was manufactured. Even with co-authors in common, Chesi and colleagues [11] kept the work in the theoretical field and the same hypothesis from his PhD thesis were maintained to facilitate the calculations and applications of the theorems. This increased interest about moving mass encouraged

Li and colleagues [6] to conduct a survey about it. They concluded that despite the shifting mass method showing great advantages most works in this field stayed at theoretical design and simulations because it is non-linear behavior and the mechanical engineering practical difficulties. This survey paved the way to Qian and colleagues [5] research, now with Li as second author. They also presented a theoretical model without engineering implementation. Moreover, they just cited the use of magnetorquers to compose the system but did not present more modelling or detail on it.

Chait and colleagues [8] also pointed out that reaction wheels and magnetorquers are well-known and modelled since 2015 which means it is a consolidated technology and there's few contributions to be made, no other than design and manufacturing to lower budget. In sequence, Curatolo [1] integrated reaction wheel and magnetorquer technologies in CubeSat considering in research three different control methods. However, this configuration lacks innovation in the aerospace market. Not by chance, Lee and colleagues [3] were able to design, manufacture



and assemble a reaction wheel technology device based on their authorial motor concept. Reaction wheels are shown as a well-established product in a way that research in this field leads, most of the time, to budget reductions.

Ousaloo and colleagues [9] successfully applied only magnetorquers to control attitude, but the convergence time was about 20 minutes in the experiment and the hardware is far from CubeSat's shape or size. Nonetheless this research stated that only magnetic actuators can provide more accurate results, but at a slower pace. In almost the same way, Ju [10] concluded that the momentum wheels technique, as the only control method, is not suitable for the task due to its inability to provide adequate transverse angular momentum levels, essential for the spacecraft's active attitude control.

He and colleagues [13] succeeded in applying moveable mass technology to attitude control using it in-plane, however, their control strategy has three defined steps to achieve it. Moreover, the movement around the Y-axis needs to be damped by aerodynamic drag to reach a controllable value. Similarly, years later, the study of Lu and colleagues [14] applied in-plane moving mass attitude control to thruster propelled CubeSats and although the simulations showed the feasibility of this method the general hardware is completely different than the majority of launched CubeSats and, again, it stayed in theoretical field.

4. Conclusions

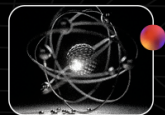
In this review was shown the actual relevance of research about attitude control for nanosatellites

internationally. The debate around the optimized control laws and methods is still open [1]. Although reaction wheels and magnetorquers already became consolidated products, they keep high prices [3], and are not the only way to achieve the final goal.

Thinking in the national scenario the currency exchange and tariffs make the importation of these devices even more expensive and starting a local manufacturing to reduce these costs is years away from the reality. The alternative is research innovative technologies to detain patents and production nationally, bringing new alternatives to compete for space, both scientific and economic.

A viable option appears to be shifting mass technologies, recent research showed its possibilities and applications [5], and yet there is no established market or products pointed to them. Of course, some engineering challenges may be surpassed, especially in the non-linear control field, but that is the researcher's primary objective.

The work presented in [2] in 2016 showed that back in the day using the simulations, CAD and devices' drawings of the era it was already feasible doing an assembly concept. In 2017 [12] proved that it is possible to use movable masses in a satisfactory way to control meant to be spacecraft smaller devices. From 2017 to now there's 8 years of advances in engineering overall and miniaturization of electronics that facilitates the development of movable mass technologies that fit in nanosatellites requirements. Not by chance, more recently [5] in 2023 applied this same technology to propose a formation control.



This whole scenario shows that even not being a consecrated technology it is still relevant and taking it out of computer simulations to more fit prototypes may create new technological paths to the subject.

References

- [1] Curatolo A., Development and experimental testing of nanosatellites attitude control using mixed magnetic/mechanical actuation [Master's thesis]. Forlì (Italy): University of Bologna; 2021.
- [2] Virgili-Llop J., Polat H.C., Romano M., "Using shifting masses to reject aerodynamic perturbations and to maintain a stable attitude in very low earth orbit," *Advances in the Astronautical Sciences*, vol. 158, pp. 2129–2148, 2016.
- [3] Lee A.M., Leon D., Casillas C.P., McCarver R., 3-Axis Reaction Wheel System for CubeSats [Senior project]. San Luis Obispo (CA): California Polytechnic State University; 2021.
- [4] Chesi S., Attitude control of nanosatellites using shifting masses [PhD thesis]. Santa Cruz (CA): University of California, Santa Cruz; 2015.
- [5] Qian Y., Li J., Zhang H., "Formation control of satellites in low Earth orbit by using moving masses," *Aerospace Science and Technology*, vol. 132, pp. 108073, 2023. DOI: 10.1016/j.ast.2022.108073.
- [6] Li J., Gao C., Li C., Jing W., "A survey on moving mass control technology," *Aerospace Science and Technology*, vol. 82, pp. 594–606, 2018. DOI: 10.1016/j.ast.2018.09.033.
- [7] Moher D., Liberati A., Tetzlaff J., Altman D.G., The PRISMA Group, "Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement," *PLOS Medicine*, vol. 6, no. 7, p. e1000097, Jul. 2009. DOI: 10.1371/journal.pmed.1000097.
- [8] Chait S.B., Spencer D.A., Georgia Tech Small Satellite Real-Time Hardware-in-the-Loop Simulation Environment: SoftSim6D [Master's project report]. Atlanta (GA): Georgia Institute of Technology; 2015.
- [9] Ousaloo H.S., Nodeh M.T., Mehrabian R., "Verification of Spin Magnetic Attitude Control System using air-bearing-based attitude control simulator," *Acta Astronautica*, vol. 126, pp. 546–553, 2016. DOI: 10.1016/j.actaastro.2016.03.028.
- [10] Ju D., Attitude Control Subsystem Design of the Stable and Highly Accurate Pointing Earth-imager [Master's thesis]. Delft (The Netherlands): Delft University of Technology; 2017.
- [11] Chesi S., Gong Q., Romano M., "Aerodynamic three-axis attitude stabilization of a spacecraft by center-of-mass shifting," *Journal of Guidance, Control, and Dynamics*, vol. 40, no. 7, pp. 1613–1626, 2017. DOI: 10.2514/1.G002460.
- [12] Shaik F.J., Design, Fabrication and Modelling of Three Axis Floating Satellite Simulator [Thesis]. Luleå (Sweden): Luleå University of Technology; 2017.
- [13] He L., Chen X., Kumar K.D., Sheng T., Yue C., "A novel three-axis attitude stabilization method using in-plane internal mass-shifting," *Aerospace Science and Technology*, vol. 92, pp. 489–500, 2019. DOI: 10.1016/j.ast.2019.06.019.
- [14] Lu Z., Hu Y., Liao W., Zhang X., "Modeling and attitude control of CubeSat utilizing moving mass actuators," *Advances in Space Research*, vol. 67, no. 1, pp. 521–530, 2021. DOI: 10.1016/j.asr.2020.09.027.