OPEN ACCESS

PAPER

Phys. Educ. **60** (2025) 035015 (7pp)

iopscience.org/ped

How to stabilize a satellite using the principle of conservation of angular momentum

J A Lira

Department of Science, Physics Section, Pontifical Catholic University of Peru (PUCP), Lima, Peru

E-mail: jalira@pucp.pe

Abstract

There are currently more than 9000 active satellites orbiting the Earth (2024 ESA Space Environment Report www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2024). Most of them are used for communications: radio, telephony, televisión and internet. Some of them help ships steer a safer course at sea. Others give us warnings about hurricanes and storms, and do the same for forest fires and icebergs. Some more have military applications. Many observation satellites take photographs of the Earth and then send them to a ground station for processing and dissemination. To take photographs it is first necessary to stabilize the satellite, avoiding oscillations or spins. The aim of this article is to show how to stabilize a satellite using the principle of conservation of angular momentum. Only basic knowledge of classical mechanics is necessary to understand how to achieve it. The applied method is especially relevant for the stabilization of small satellites, which are often used by colleges, universities and even some high schools for many different purposes. Pursuing this goal, we will use the motor with a coupled wheel from an old DVD drive, an angular rate sensor and a microcontroller. The experimental results are shown at the end of the article. Additionally there is a video that shows how stabilization takes place.

Keywords: satellite stabilization, angular momentum, CubeSat, DVD drive

1. Introduction

In 2023, the number of satellite launches was the highest in history. Most of them were launched for commercial communications purposes, with low-Earth orbit -500 to 2000 km- being the most used. The trend is to continue rising. In the last twenty years, students of universities, colleges and some high schools (such as Thomas Jefferson High School in Virginia and Merritt Island High School in Florida -both in the United States) have developed small satellites [1], which have then been put into orbit by space transportation companies. Even space agencies like NASA and the Japan Aerospace Exploration Agency have also taken on this task. The objectives of these launches have been diverse. Some satellites have been designed to conduct an engineering test in space, such as the DTUsat-1 of the Technical University of Denmark [2], others to detect earthquakes, such as the QuakeSat 1 of Stanford University [3], or even for biological research, such as the GeneSat-1 of NASA together with Santa Clara University [4]. The Pontifical Catholic University of Peru (PUCP) also sent a satellite into space in 2013, the PUCP-Sat-1, the mission's objective was to take photos of the Earth, as well as launch a smaller satellite from within it [5].

It is precisely one of the objectives that most attracts students to take a picture of the Earth from space as shown in figure 1 [6]. To achieve this task, it is useful first to stabilize the satellite so that the image can be focused.

Many of the small satellites used are the CubeSats, cubes with a side of 10 cm and a mass of up to 2 kg [7]. With the limited space available, it is necessary to have a compact but efficient stabilization solution with minimal cost and risk. A mechanism that can achieve this goal is made up of small wheels that rotate at high speed.

This article will allow readers to start with a blank sheet of paper and design a practical solution from start to finish. I have assumed that readers have a general knowledge of physics and mathematics. Programming knowledge is necessary for the development of the control algorithm. Physical and engineering data have been provided. The reader is not required to be familiar with space technology.

2. Principle of conservation of angular momentum

After a satellite is taken by a spacecraft to the required height above the Earth's surface, tumbling can occur as soon as the satellite is displayed [8, 9]. In general, the motion of a CubeSat around the Earth therefore consists of a translation motion, along a circular or elliptical orbit, and also rotation movements around the axes parallel to the edges of the cube (figure 2). Our goal now is to suspend the satellite's rotation movements around its axes.

To explain how to interrupt the satellite's rotation movements for a while, let us consider a lecture demostration related with rotational dynamics and the conservation of angular momentum according to figure 3. A student seated on a swivel stool in rotation holds a spinning bicycle wheel with its axis vertical. By simply turning the wheel through an angle of 180°, he can stop the swivel stool. To do this he must supply a torque. This torque is internal to the stool-student-wheel system. There are no external torques on the system about the vertical axis and therefore the vertical component of angular momentum of the system is conserved. Turning the wheel changes its angular momentum, which has to be compensated by braking the student and stool in order to conserve the total vertical angular momentum of the system at its initial value [10].

For a 2 kg CubeSat in circular orbit at 600 km altitude the disturbance torques (aerodynamic torque, gravity gradient torque and solar radiation torque [11]) are of the order of magnitude of 10^{-8} N·m and therefore it can be considered that its angular momentum remains constant for a time interval of about 2 min, during which we have in mind to stabilize the CubeSat by

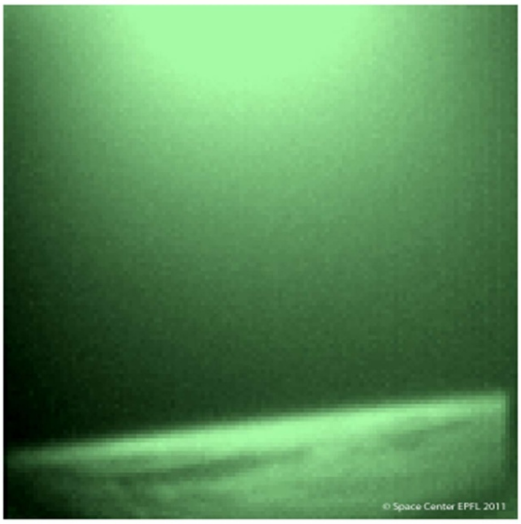

Figure 1. SwissCube's first image of earth's airglow. (Author: space center EPFL). Reproduced with permission from [7].

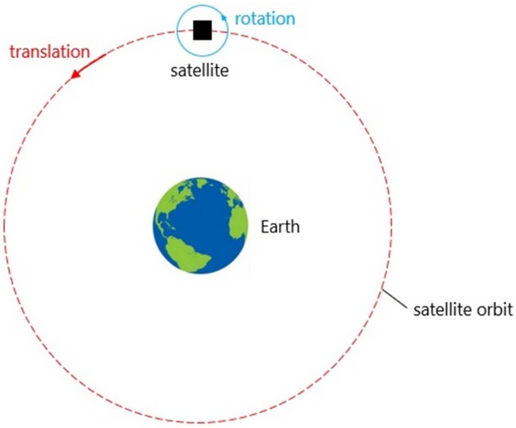

Figure 2. Motion of a CubeSat around the Earth: translation motion (dashed red line) and rotation movement (closed blue loop).

applying the principle of conservation of angular momentum.

3. Satellite stabilization

Now we will apply the principle of conservation of angular momentum to our satellite by operating wheels installed inside the CubeSat so that it can be stabilized. The steps to achieve this goal are shown in the block diagram in figure 4.

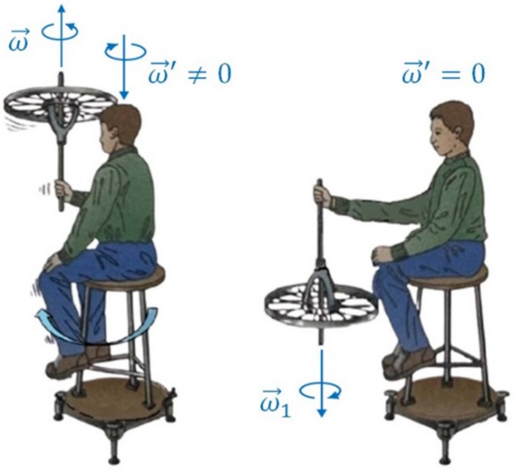

Figure 3. If the wheel is turned 180°, the swivel stool and the student come to a stop.

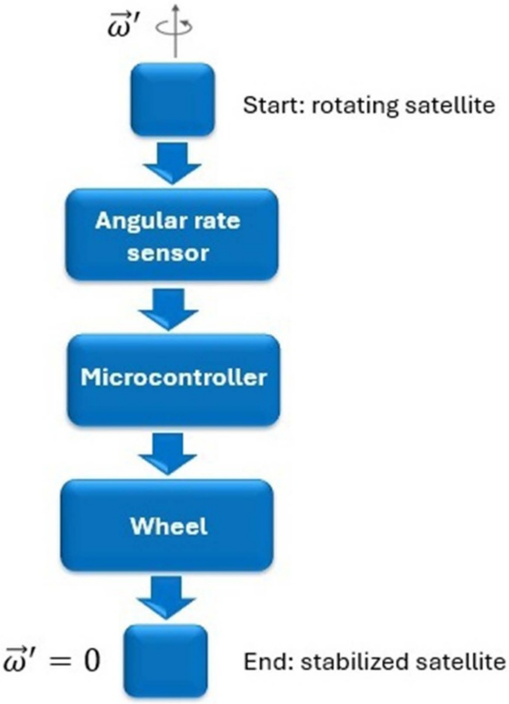

Figure 4. Satellite stabilization block diagram.

Therefore, to stabilize the CubeSat we first have to know the angular velocity at which it is rotating in each axis in order to then be able to replace its angular momentum through rotating wheels. The angular velocity of the satellite can be known through commercial angular rate sensors such as the integrated dual-axis gyro IDG-500 [12]. The operation of these sensors is based on the measurement of centrifugal forces acting on small vibrating masses within these devices when they are rotating, and from there the angular velocity is determined. Knowing the angular velocity of the satellite, it is only necessary to activate the wheels through a microcontroller so that they reach the same amount of initial angular momentum of the satellite, thus stabilizing it. For our work we have used the MSP430F2618 microcontroller [13]. A detailed description of the use of the microcontroller and the wheel speed control algorithm can be found in the [14]. The stabilization wheels and the motors that drive them have been taken from old DVD drives (figure 5).

4. Simulating space on Earth

To determine how well the satellite stabilization system works it is necessary to measure the system response time in simulated zero-gravity conditions. To achieve this a gravity offset table was built at the PUCP´s Institute for radio astronomy Facility. It is basically a square plane surface of aluminium measuring 0.3 m on each side, which has a square lattice of drilled orifices of 1 mm diameter, separated from each other by a distance of 2 cm. Air bearings under the test satellite output a thin layer of air from a 0.5 hp air compressor allowing the test satellite to float (figure 6). Even though with multiple orifices the bearing face of the test satellite experiences an uneven pressure distribution that encourages rotation, our test satellite was able to remain stable for a time interval of a few seconds simulating how this moves in space. A video shows the stabilization of the test satellite using the gravity offset table [15].

5. Results and discussion

The table described in the previous section was used to test our satellite stabilization system. Initial tests showed that the table could support a load of 300 g. An acrylic parallelepiped with a square base of 10 cm on each side and 5 cm high was used as test satellite carrier. A motor with its stabilization wheel was fixed internally to the base of the test satellite. The wheel speed could reach up to 18 760 rpm. The stabilization tests were carried out with a load of 262 g. As we mentioned above, in order to carry out the stabilization, it is necessary that the angular momentum of the wheel is equal to the angular momentum of the satellite. Considering that the mass of the stabilization wheel is 10 g, and taking into account that the geometry of the wheel approximates the geometry of a circular disc with an external diameter of 2.9×10^{-2} m, a quick calculation allows us to determine that if a satellite were rotating at a speed of $60^{\circ}\,\mathrm{s}^{-1}$ the wheel would have to rotate at

Figure 5. Stabilization wheel (black) and motor (grey).

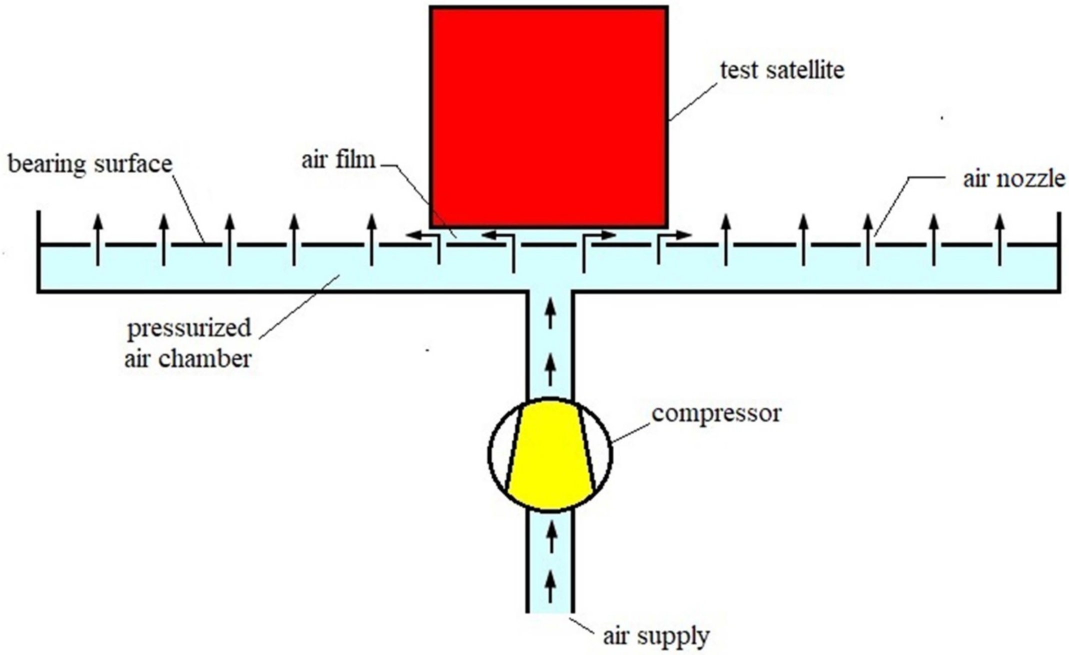

Figure 6. Gravity offset table for testing satellite stabilization.

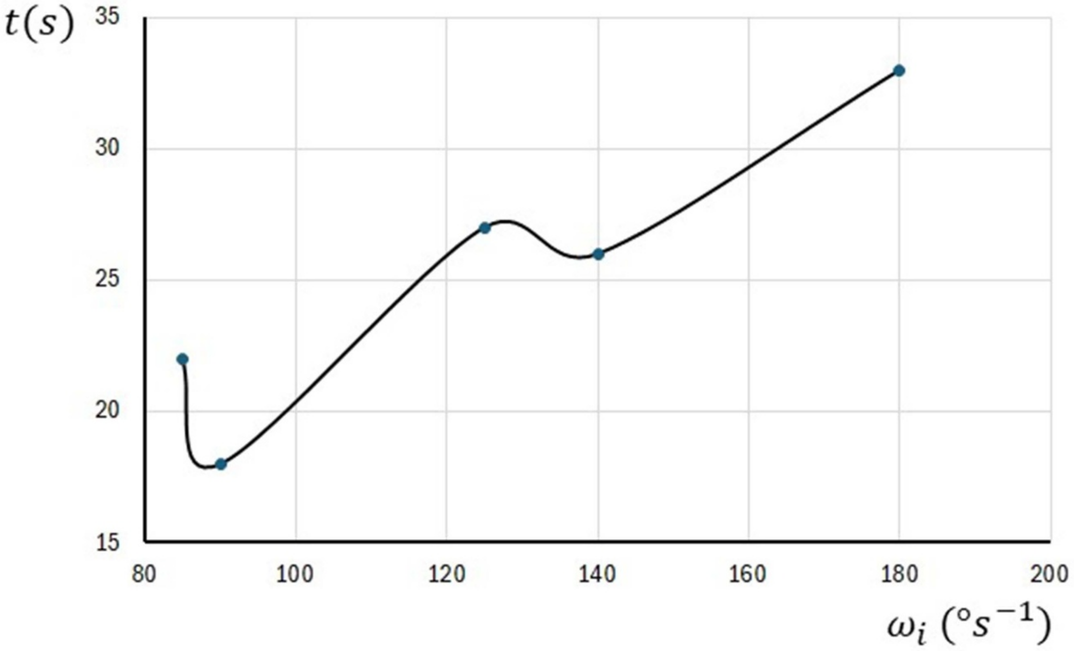

Figure 7. Braking time of the test satellite as a function of its initial angular velocity. The solid line represents the result of a fourth-degree polynomial trend fit to the data.

4153 rpm to achieve stabilization, which would be easy to achieve.

Breaking time measurements were made for initial angular velocities of the test satellite between 85 and $180^\circ\mathrm{s}^{-1}$. The experimental results are shown in figure 7. The observed braking times tend to increase as the initial angular velocities of the test satellite increase; however, a monotonic function was not observed over the whole velocity range studied. In order to achieve the stabilization of the satellite that will operate in space, it is necessary to fix three wheels inside the satellite, so that they can rotate around the three axes parallel to the edges of the CubeSat. It is important to note that the stabilization tests were performed with a load of 262 g, which refers only to the equipment needed to stabilize the satellite. If the CubeSat had a mass of 2 kg, the stabilization wheel at maximum rotation speed would be able to stabilize the satellite with an initial angular velocity of $35.49^\circ\mathrm{s}^{-1}$.

For the stabilization of small satellites there are also passive techniques such as the gravity-gradient control, however, this is only efficient in near-Earth orbits. Another purely passive control makes use of permanent magnets, but is only effective in near-equatorial orbits. The satellite stabilization method used in this article is quite efficient for small satellites such as CubeSats due to the little space and mass it requires for its operation, in addition to being independent of the type of orbit.

The satellite stabilization equipment is shown to 18 year-old students who had previously attended an introductory course in classical mechanics. They learned about the conservation of the angular momentum of a system in the absence of external torques. Their knowledge is assessed by a written test in which students must calculate the rotation speeds of the stabilization wheel for different angular velocities of the test satellite. The average score was 65 points, the maximum possible score was 100 points. The pass rate was 70%, the minimum passing score was 55 points.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgment

The figures were made by Guillermo Lira, which is gratefully acknowledged.

ORCID iD

J A Lira https://orcid.org/0000-0002-8834-1576

Received 19 December 2024, in final form 21 February 2025
Accepted for publication 7 March 2025
https://doi.org/10.1088/1361-6552/adbe1f

References

[1] MIHS StangSat 2019 Merritt Island High School (available at: www.facebook.com/profile.php?id=100054215122221)
[2] DTUsat-1 2006 (available at: https://web.archive.org/web/20130825072303/http://dtusat1.dtusat.dtu.dk/)
[3] Krebs G D 2003 Gunter´s Space Page QuakeSat 1 (available at: https://space.skyrocket.de/doc_sdat/quakesat-1.htm)
[4] Newsletter of NASA Ames Research Center 2007 Moffett Field, California (available at: www.nasa.gov/wp-content/uploads/2023/09/167988main_07_01astrogram.pdf)
[5] PUCP-Sat-1 & Pocket-PUCP 2023 (available at: https://inras.pucp.edu.pe/project/pucp-sat-1-pocket-pucp)
[6] eSpace—EPFL Space Center SwissCube-1 (available at: https://de.wikipedia.org/wiki/Datei:Figure_7.png)
[7] Johnstone A 2022 CubeSat design spezification Rev. 14.1 chapter 1 p 7 (available at: https://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/62193b7fc9e72e0053f00910/1645820809779/CDS+REV14_1+2022-02-09.pdf)
[8] Chen H, Cao X, Dai H and Yue X 2024 *Adv. Space Res.* **73** 187
[9] Khan S A, Shiyou Y, Ali A, Tahir M, Fahad S and Rao S 2023 *Adv. Space Res.* **71** 2140
[10] Cooray A 2023 JoVE science education database *Physics I. Angular Momentum* (JoVE)
[11] Wertz J R and Larson W J 1999 Space mission analysis and design chapter 10 p 324
[12] InvenSense Integrated dual-axis Gyro IDG-500 (available at: https://datasheetspdf.com/pdf-file/1350162/InvenSense/IDG-500/1)
[13] MPS430F2xx 2022 MSP430G2xx family user's guide (Rev. K) (available at: www.ti.com/lit/ug/slau144k/slau144k.pdf?ts=16935109

63282&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252Fes-mx%252FMSP430F2618)

[14] Menéndez D A 2010 Diseño e implementación del sistema de estabilización en el espacio para el picosatélite PUCP-Sat-1 chapter 3 p 20, chapter 4 p 39 (available at: https://tesis.pucp.edu.pe/repositorio/bitstream/handle/20.500.12404/516/MENENDEZ_QUINTO_DANIEL_DISENO_SISTEMA_ESTABILIZACION_PICOSATELITE.pdf?sequence=1&isAllowed=y)

[15] Lira J A 2024 Video about stabilization of the test satellite using the gravity compensation table (available at: https://youtu.be/7PaSMLcXWU0)

[16] European Space Agency 2024 ESA space environment report (available at: www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2024)

Juan Antonio Lira is a professor of physics at the Pontifical Catholic University of Peru. He regularly gives lectures on classical mechanics, thermodynamics and electromagnetism. His current research focuses on Earth sciences, particularly electromagnetic radiation related to major earthquakes.