Innovative design and development of attitude determination and control systems for CubeSats with reaction wheels

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ABSTRACT

Attitude determination and control systems (ADCS) represent a critical facet of CubeSat missions, orchestrating the precise orientation and stabilization of these small satellites in the space environment. This paper presents a comprehensive design and development of an ADCS tailored for CubeSats, harnessing a reaction wheel system to deliver a cost-effective and dependable solution for small satellite applications. The research begins by elucidating the requisites and specifications for the ADCS and then delves into the design phase, complemented by intricate modelling and simulation employing MATLAB Simulink and the Webots Simulator. The results of this study underscore the exceptional performance of the proposed ADCS configuration, leveraging the reaction wheel model. This system demonstrates an unparalleled capacity to achieve precise and controlled attitude adjustments, well within the defined parameters. Furthermore, this research underscores the pivotal role played by efficient system design, meticulous simulation, and rigorous testing in the triumphant implementation of ADCS, greatly enhancing CubeSat missions and their contributions to the realm of space exploration and technology innovation. This comprehensive approach to the design and testing of an ADCS for CubeSats ensures that these diminutive satellites continue to make significant strides in space missions, paving the way for an exciting future of space research and technology development.

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1. INTRODUCTION

In recent years, CubeSat missions have gained increasing popularity due to their cost effectiveness, rapid development cycles, and adaptability for various space applications. The attitude determination and control system (ADCS) play a crucial role in CubeSat missions by ensuring precise control of the satellite's orientation and stability [1]–[4]. However, designing and implementing a cost-effective and efficient ADCS for small satellite applications remains a challenge. The limited size, power, and resources available for CubeSats necessitate innovative solutions to meet their specific needs. Despite the growing adoption of CubeSat missions, there's a notable gap in economical and reliable ADCS solutions that cater to small spacecraft requirements [5].

A design guide for ADCS for Pico satellites [6] present a design technique for Pico satellite ADCS based on ECSS documentation, offering insights into implementing ECSS standards for practical Pico satellite projects. Design, simulation, and testing of a reaction wheel system for Pico/nano-class CubeSat systems [7] introduces a reaction wheel system with momentum storage of 30 mNms and a torque of 2.5 mNm, designed for small satellites weighing between 5 kg to 20 kg. Test bench for nanosatellite attitude determination and control system ground tests [8] proposes a three-degree-of-freedom (3DOF) test bench for CubeSats, providing a reliable platform for ground-based ADCS testing without motion interference. Prototype of micro reaction wheel for CubeSat [9] describes the design and validation of micro reaction wheels used in Tel-USat CubeSat, capable of generating 0.74 mNm of torque [10].

The paper underscores that a majority of CubeSats employ Sun Sensors, magnetometers, and magnetic coils, with over 50 percent utilizing the concept of reaction wheels [11]–[13]. ADCS model for preliminary design procedures within a concurrent design approach presents an ADCS model for CubeSat following the concurrent design approach of the European Space Agency. The paper attitude determination and control system for nadir pointing and detumbling using magnetorquer for 1U Bolivian CubeSat [14] discusses the integration of gyroscopes, sun sensors, and magnetorquers in the actuators and emphasizes the use of magnetometers as attitude sensors. Attitude determination and control system of the Uruguayan CubeSat, AntelSat [15] provides insights into the ADCS used for the Uruguayan Nanosatellite, AntelSat, a 2U CubeSat. This system utilizes magnetorquers as actuators and magnetometers as orientation sensors. Design and Implementation of active attitude determination and control subsystem for ISRASAT1 CubeSat [16]–[18] explain the components and design approach for CubeSat's ADCS used in remote sensing applications. ESTCube-2 attitude determination and control: step towards interplanetary CubeSats discusses the design approach to achieve a 360-degree per second angular velocity for a 3U CubeSat [19]–[22].

ADCS is a critical subsystem for small satellite missions, responsible for maintaining spacecraft orientation and steering accuracy through sensors, actuators, and control algorithms. Reaction wheels are widely adopted actuators due to their precision and continuous control capabilities without the need for propellant [23]. However, designing ADCS for CubeSats poses challenges, including constraints on size, weight, power, and computational resources, coupled with the harsh space environment that subjects' systems to radiation, thermal fluctuations, and vibrations. While many research efforts have been made to design and develop ADCS, the existing solutions for CubeSat missions often rely on expensive and complex components like star trackers, magnetometers, or gyroscopes, limiting their accessibility and scalability [24], [25].

This highlights the necessity for a cost-effective and reliable ADCS system that meets CubeSat performance requirements while overcoming these limitations. Additionally, ensuring accurate and frictionless testing setups for CubeSats is crucial to mission success, but challenges related to fabrication errors must be addressed. Therefore, a new approach to designing and testing CubeSat ADCS systems is required to ensure subsystem accuracy and reliability.

2. DESIGN OF ADCS

2.1. CubeSat

CubeSats, a class of small satellites, have surged in popularity due to their cost-effectiveness and adaptability in recent years. These standardized, compact satellites, measuring 10 cm on each side (1U), offer a versatile platform for various space applications. The cube-shaped design of CubeSats makes them highly accessible, allowing for easy assembly and launch into orbit. CubeSats find applications in scientific research, Earth observation, communication, and more. They enable the study of diverse phenomena, from climate change to space weather, and can even provide internet connectivity to remote areas on Earth.

A significant advantage of CubeSats is their affordability, making them an attractive option for universities, research institutions, and start-ups with limited resources. CubeSats also serve as test beds for new space technologies and concepts, providing valuable experience and data for future satellite missions. However, their small size does pose limitations. CubeSats may have constraints on carrying larger, heavier equipment and shorter life spans due to limited power sources. Nevertheless, CubeSats represent a dynamic and evolving field in space technology, with numerous potential applications and room for innovation. CubeSats typically consist of payload, ADCS, on-board computer (OBC), communication system (Comm), electric power system (EPS) and antenna. The payload includes cameras and measurement instruments, serving as the primary components for CubeSat applications. ADCS is responsible for orienting the CubeSat in space, enabling it to point cameras or instruments in specific directions. OBC acts as the satellite's central processing unit, responsible for computations and decision-making, essentially serving as the brain of the CubeSat. Comm facilitates communication with Earth's ground stations and other CubeSats in space. EPS comprises batteries that power all CubeSat components. Solar panels are used to recharge the EPS batteries. The antenna transmits communication signals between the CubeSat and ground stations and other CubeSats.

3. DESIGN METHODOLOGY AND WORK DESCRIPTION

3.1. Design of CubeSat chassis

The CubeSat chassis plays a pivotal role as it offers structural support to all satellite components. A well-designed chassis is crucial for mission success, as it must withstand the stresses and vibrations of launch and operate reliably in outer space. This section provides an overview of the CubeSat chassis design and the considerations taken. The chassis design must adhere to various requirements and constraints, including size, weight, structural strength, and compatibility with other subsystems. For example, it must fit within specific volume and weight limits while protecting the sensitive electronics and instruments on board the CubeSat. The CubeSat chassis was conceived with a box-shaped architecture, measuring 10×10×10 cm. The structure comprises panels and supports made of an Aluminium alloy (A6061) and includes additional bracing for enhanced strength; the Figure 1 shows the CubeSat frame.

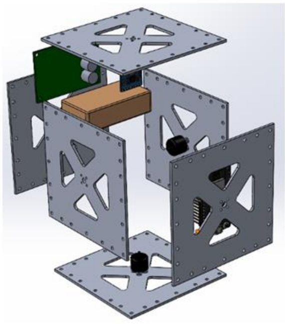

Figure 1. CubeSat frame

3.2. Design of ADCS architecture

The ADCS is designed using three reaction wheels and a gyroscopic plus accelerometer sensor for attitude determination. The reaction wheels are controlled using a proportional integral derivative (PID) controller, which adjusts the wheel speeds to the desired spacecraft orientation. This design approach was chosen based on its simplicity, reliability, and cost-effectiveness. Figure 2 block diagram of ADCS shows in Figure 2.

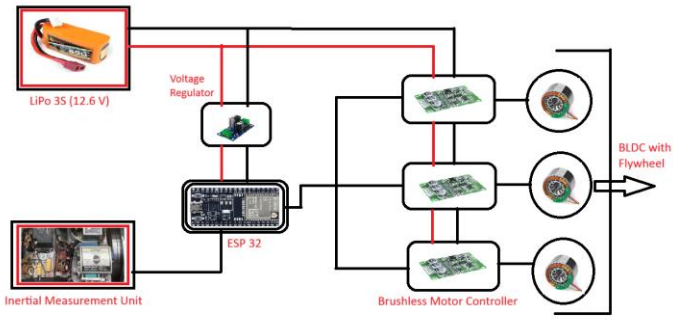

Figure 2. Block diagram of ADCS

3.2.1. Battery calculation

To estimate the duration for which the CubeSat will run on one battery charge cycle, the power ratings of all components must be considered. The calculation is as follows:

Total power consumed = power consumed by 3 BLDC motor + power consumed by ESP32 + power consumed by MPU6050

≈ Power consumed by 3 BLDC motor = 12 V×6 A×3 = 216 W.

Battery rating in W-h = 850 mAh×12 V = 10.2 W-h.

Duration for which the battery can provide power = 10.2/216 = 0.0472 h = 2.833 mins.

Since the system does not run continuously, the available duration will be sufficient for operation.

3.2.2. Connection diagram

The components are integrated into the CubeSat with the following connections:

- The battery supplies power to the motor controller and, via the voltage regulator, to the ESP32.
- The PWM pins of the ESP32 are connected to the speed reference pins of the ESC, and the DIR pin of the ESC is connected to the digital pins of the microcontroller.
- The ground of the battery is connected to all the components' ground.
- The MPU6050 is interfaced with the microcontroller via the I2C protocol, and the power (3.3 V) is drawn from the built-in voltage regulator of the ESP32.

3.3. Reaction wheel design

The selection of reaction wheels is critical in the ADCS module, as it determines the torque generated, which, in turn, affects the response of orientation actuation. With the estimated CubeSat mass from the computer-aided design (CAD) being approximately 1.2 kg, the required torque for each motor is as follows:

For a CubeSat with a mass of 1.2 kg and dimensions of 10 cm x 10 cm x 10 cm, the moment of inertia (I) can be estimated using the formula:

$$I = \left(\frac{1}{6}\right) \times m \times (L^2 + W^2)$$

where m is the mass of the CubeSat, L is the length, and W is the width. Putting the values, we get:

$$I = \frac{1}{6} \times 1.2 \times (0.1^2 + 0.1^2) = 0.004\ kgm^2$$

To achieve a desired angular acceleration (alpha) of 1 rad/s^2, the required torque (T) can be calculated using the formula:

$$T\ =\ I\ \times\ alpha$$

putting the values, we get:

$$T = 0.004kgm^2 \times 1\ rad/s^2 = 0.004Nm$$

so, each motor would need to produce a torque of at least 0.004 Nm to achieve an angular acceleration of 1 rad/s^2 for a 1.2 kg CubeSat. Assuming a solid cylindrical reaction wheel with uniform mass distribution, its moment of inertia (I) can be calculated using the formula, Figure 3 CAD of CubeSat with gimbal test rig.

$$I - (1/2) \times m \times r^2$$

where m is the mass of the wheel, and r is the radius.

To calculate the required radius for the reaction wheel, assuming a desired angular velocity (omega) of 1 rad/s, the angular momentum (H) of the reaction wheel can be calculated using the formula:

$$I\ =\ H/omega$$

putting the values, we get:

$$I\ =\ 0.004\ Nm\ /\ 100\ rad/s\ =\ 0.00004\ kg\ m^2$$

now, using the formula for the moment of inertia, we can solve for the radius:

$$r = \sqrt{(2I/m)}$$

assuming a reasonable mass for the reaction wheel, say 0.1 kg, we can calculate the radius:

r = √ (2×0.00004 kg m^2/0.1 kg)

r = 0.02 m or 2 cm

therefore, a reaction wheel with a diameter of 4 cm would generate the required torque of 0.004 Nm for a 1.2 kg CubeSat at an angular velocity of 100 rad/s.

3.4. Gimbal rig test bench

As mentioned earlier, the testing of CubeSat is difficult to perform on the ground as the gravity and friction will affect the result. The design of a test bench is proposed which will reduce the friction and allows the CubeSat 3 degrees of freedom around all the three axes. The test setup consists of 3 hoops which are connected through bearing and shaft in such a way that the CubeSat at the center can revolve around all the axes freely.

3.5. Algorithm for ADCS

The algorithm chosen for the ADSC is as follows:

- The ESP initializes the GPIOs and enables the Bluetooth of the ESP32.
- Then it checks whether the connection is established with the device from which the command will be given.
- If it is connected, it checks for the serial data and if any angle value is given as input, further action is carried out, Figure 4. shows the Flowchart of proposed system.
- ESP reads the current angle and then decides which reaction wheel should get ON and if the desired angle is reached, it switches OFF the reaction wheel and gets ready for the next command.

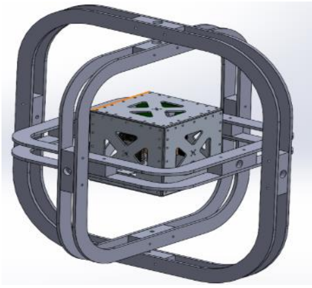

Figure 3. CAD of CubeSat with gimbal test rig

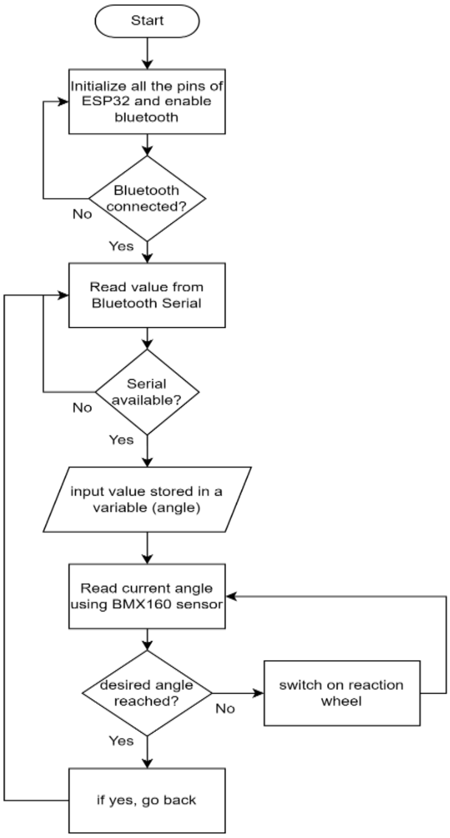

Figure 4. Flowchart of proposed system

The algorithm controls all three reaction wheels according to the need. The same algorithm is followed to code the microcontroller using Arduino IDE. The readings of the MPU can be seen through the serial monitor. The CubeSat has to follow a set of standards prescribed by ISO in the ISO17770:2017. It addresses CubeSats, CubeSat deployer, and related verification of assurance/quality terms and metrics. Maximum allowable weight is 1.33 kg and size should be 10×10×10 cm for each unit or 1U and they can be 1U, 2U, 3U, or 6U in size.

4. RESULTS AND DISCUSSION

4.1. Simulation in Webots

Before the fabrication process, it is essential to validate the feasibility of the CubeSat model through simulation. For this purpose, we utilized Webots simulation software, an open-source and cross-platform desktop application designed for robot simulation. Webots provides a comprehensive development environment for modeling, programming, and simulating robots. By configuring the simulation world, we were able to set the gravity to 0 m/s², replicating an environment similar to space. The initial CubeSat CAD was created using SolidWorks and later imported into Webots after converting it from the SolidWorks part file format (sldprt) to the stereolithography file format (STL). To simplify the simulation process, only the CubeSat frame was imported. The flywheels, vital for the attitude control system, were designed within Webots. These flywheels were represented as cylindrical objects with a radius of 2 cm and a mass of 50 grams.

The entire CubeSat assembly was treated as a 'Robot' node, visible in the Scene Tree Within this node, the structural components were grouped under the 'Solid' node, while the three reaction wheels were placed in the 'hinge joint' nodes. These hinge joint nodes contained information on joint parameters, the flywheel model, and the motor settings. The 'Robot' node also included a 'physics' node, set to the ON mode to ensure it behaved as a tangible object during simulation. A 'bounding object,' defined as a box with dimensions 104×104×104 mm, enclosed the entire CubeSat. An inertial measurement unit (IMU) was positioned at the geometric center of the CubeSat, providing roll, pitch, and yaw values in radians. Each robot in the simulation environment was equipped with a 'controller' sub-node, facilitating the execution of the algorithm.

The same algorithm demonstrated in Figure 5 was successfully implemented within this simulation environment. The IMU data, visualized in Figure 6, accurately reflects the CubeSat's orientation and verifies roll, pitch, and yaw control. Through simulation, we have validated that the CubeSat functions as intended, providing confidence in its ability to control roll, pitch, and yaw effectively.

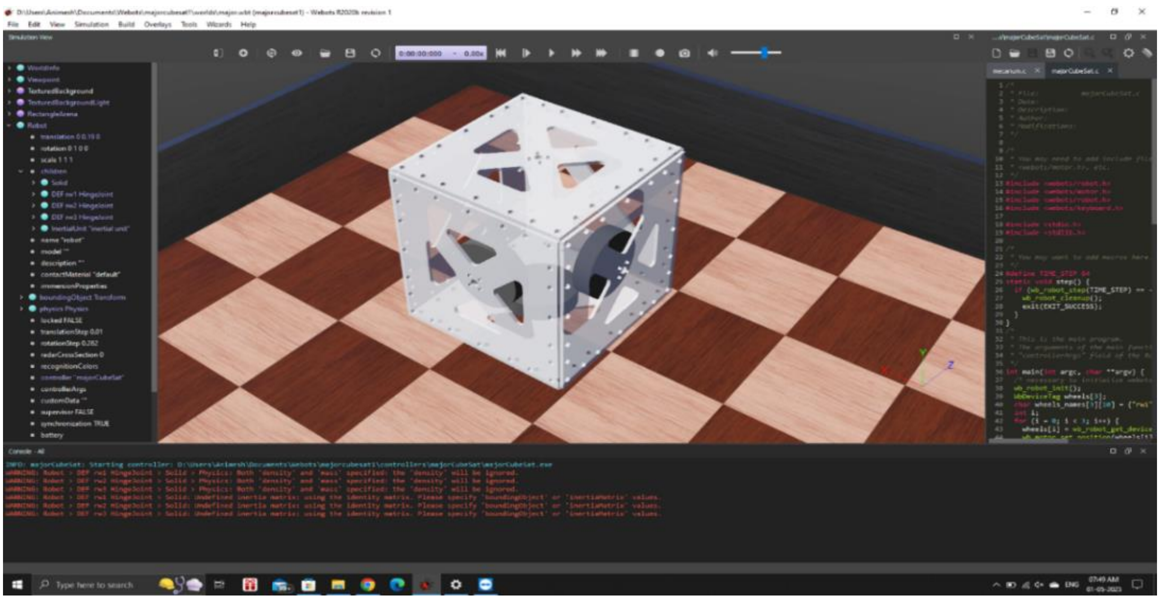

Figure 5. Webots Window with CubeSat simulation parameters

4.2. Hardware implementation

In this section, we delve into the details of hardware fabrication and integration. Before fabricating the frame components, a finite element (FE) analysis was conducted using SolidWorks. This analysis aimed to assess the structural integrity of the CubeSat chassis. The result of the analysis is presented in Figure 7.

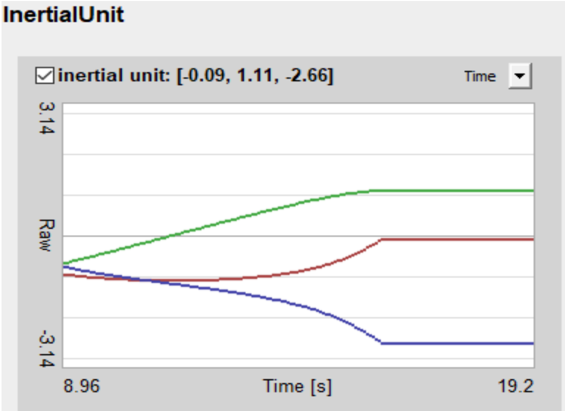

Figure 6. IMU data in graphical representation

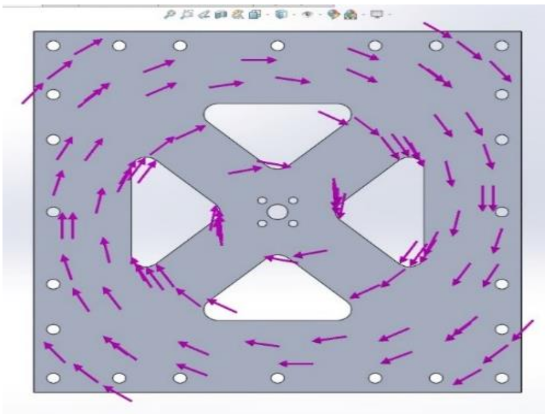

Figure 7. FE Analysis of CubeSat panel

Following the FE analysis, the next step was the fabrication of the CubeSat frame. The frame structure was constructed using an Aluminium alloy. To ensure precision in manufacturing, we utilized CNC laser cutting for metals. The DXF file format was input into the cutting machine, which then engraved the Aluminium according to the design using a CO2 laser. Subsequently, the motors were assembled onto the frame, and the flywheels were attached, as displayed in Figure 8.

The subsequent step involved integrating all the motors with electronic components. For this purpose, a breakout board for ESP32 was created. The board facilitated the connection of control pins, including 3 PWM pins for speed and 3 digital pins for direction, from the ESP32 to the ESC pins via male headers. Power distribution was managed through a separate board. In this setup, the 12 V battery powered the 3 electronic speed controllers (ESCs), while the ESP32 received its power through the LM7805 voltage regulator. The MPU was connected to the ESP32 using jumper cables, operating via the I2C protocol. Power for the MPU was sourced from the ESP32, utilizing its internal 3.3 V voltage regulator. The assembled hardware, including all electronic components, is depicted in Figure 9.

Figure 8. CubeSat Frame with BLDC motor and flywheels

Figure 9. Assembled CubeSat with mechanical and electronic components

The initial testing phase focused on verifying the proper functionality of all motors. Once this was confirmed, the system underwent testing on a single-axis rotary setup. The system exhibited the desired behavior, whereby adjusting the motor's speed command caused the motor on the horizontal plane to start rotating, generating torque that enabled the CubeSat to orient at a particular angle. Altering the speed command led to different orientations of the CubeSat. By changing the direction parameter from clockwise to anticlockwise, the CubeSat could achieve various orientations. IMU data was also validated by visualizing the data in the serial monitor. The top-level implementation of the entire project is presented in Figure 10. The figure illustrates the establishment of a communication link between the CubeSat and a smartphone via Bluetooth. Direction values were transmitted via the Bluetooth serial monitor with the CubeSat sending feedback regarding whether the desired orientation had been achieved. The final overall assembled CubeSat is shown in Figure 11.

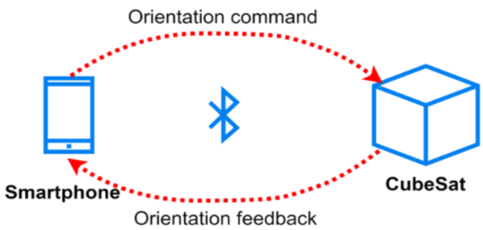

Figure 10. Toplevel block diagram

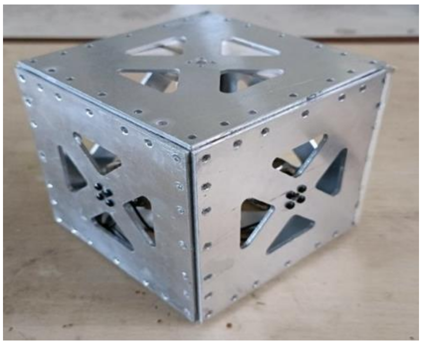

Figure 11. Assembled CubeSat

5. CONCLUSION

The report began with the problem formulation and the definition of objectives. It introduced the concept of CubeSat, ADCS, and its components. The methods and parameters used to achieve the objectives were thoroughly discussed in the following chapters. Finally, the results and discussions were presented, highlighting the project's outcomes. The primary objective of the project was to develop a cost-effective and efficient ADCS for CubeSat, and this goal was successfully achieved. The typical cost of a CubeSat's ADCS can amount to approximately $1000 or around INR 80,000, which can increase even further to meet space application standards, taking into account various constraints. In contrast, the prototype of the CubeSat ADCS with a reaction wheel developed in this project had a cost of $380 or around INR 30,000. This system enables extensive data acquisition and testing before making a significant investment in an ADCS built to space standards. One limitation, however, is the accuracy of the results. The manufacturing of such small and complex systems demands precision in fabrication, and the unavailability of certain services resulted in a less accurate assembly, particularly in the actuation of the CubeSat. Nevertheless, the primary objective was met, and the hardware's behavior aligned with expectations.

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