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CubeSat Reaction Wheel Attitude Control Platform System Architecture

Justin Hartland
Embry-Riddle Aeronautical University, hartlanj@my.erau.edu

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Cover Page Footnote

The development of this research is a testament to the collective efforts of our dedicated team. Each member contributed significantly, making this paper possible. We are deeply grateful to Dr. Drakunov, Bryan Gonzalez, and Kyle Fox for their invaluable guidance throughout the course of our work. Our sincere appreciation goes to the Office of Undergraduate Research at ERAU for their financial support through an Ignite Grant. Special thanks to Liz Payne and Susan Adams for their indispensable assistance. Our team is comprised of the following dedicated individuals: Dylan Ballback, Ella Cheatham, Kesler Gerard, Vish Ramisetty, Vishwam Rathod, Jacob Salazar, Isaac Stitt, and Ryan Taylor.

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CubeSat Reaction Wheel Attitude Control Platform System Architecture

Justin Hartland, Sergey Drakunov, Ph.D.

Abstract

In the classroom, the physics behind spacecraft attitude dynamics and controls is abstract and difficult to comprehend. It is common that students struggle to develop the connection between the math they learn and how it can be applied in the real world. The goal of this project is to design and manufacture a 1U, 3U, and 6U CubeSat testbed for autonomous control systems utilizing reaction wheels. The testbed will include three separate reaction wheels each mounted on its own respective axis to control the attitude in three degrees of freedom. The end goal of the CubeSat Control Platform is to be integrated into a website where anyone can upload their own controls algorithm and watch a live stream of their algorithm performing on hardware in real-time.

1. Introduction

Attitude control is essential for spacecraft to carry out their mission objectives. Notable examples include ensuring an Earth-monitoring camera remains pointing towards Earth, and ensuring a satellite's solar panels remain oriented towards the Sun. Therefore, a robust attitude control system is essential for most spacecraft missions. One method many spacecrafts use to change their orientation is reaction wheels. Reaction wheels take advantage of the principle of conservation of angular momentum by accelerating and thus exerting an equal and opposite torque on the spacecraft itself.

Unfortunately, many spacecraft attitude dynamics and controls classes rely on 2-dimensional illustrations of 3-dimensional dynamics to educate students. Additionally, the intense mathematics and physics concepts applied compound the difficulty students face in gaining an intuitive sense of attitude dynamics and controls. By supplementing traditional lectures with a physical spacecraft attitude control demonstration, students may have an easier time building an intuitive understanding of spacecraft attitude dynamics and controls.

The purpose of the CubeSat Reaction Wheel Attitude Control Platform (henceforth referred to as the CubeSat Control Platform) is to design and manufacture a 1U, 3U, and 6U CubeSat testbed, all capable of autonomous attitude control about three Degrees of Freedom (DoF), utilizing reaction wheels, to be integrated into a website, which will allow anyone to upload their own control algorithm and watch a live stream to evaluate how their algorithm performs on hardware. By primarily utilizing off-the-shelf-components, a kit may be compiled for those interested in purchasing. The platform may support undergraduate students and independent researchers interested in learning spacecraft attitude dynamics and controls.

The scope of this paper includes a status report of the development of the physical CubeSat Control Platform itself by first describing general design requirements and considerations, the multi-platform design strategy utilized, testing methodology, and plans to continue development. Although they are eventual objectives of this project, development of the 3U and 6U CubeSat Control Platforms has yet to be commenced due to time constraints and is therefore outside of the scope of this paper.

2. Methods

This project was approached by designing and manufacturing a total of three control platforms increasing in complexity. These platforms include the following: an inverted pendulum, a 1-DoF CubeSat configuration, and a complete 3-DoF CubeSat configuration.

As mentioned, reaction wheels utilize the law of conservation of angular momentum to produce torque on a system. However, one common disadvantage of using reaction wheels is that they can become saturated. This occurs when the motors reach their maximum angular velocity and can no longer accelerate, and thus no longer produce torque. To avoid this, the moment of inertia of the reaction wheels may be increased to decrease the angular acceleration needed to produce an equivalent torque. For this purpose, point masses, in the form of nuts and bolts, were added along the outer radius of each reaction wheel (shown in Figure 1).

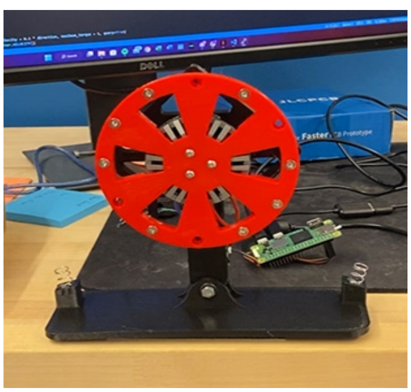

Figure 1: Inverted pendulum with fixed pivot point and reaction wheel

Each of the three systems is comprised of common electronics. The computer selected to manage each system is a Raspberry Pi Zero 2 W because of its small size and its capability to be remotely operated using a Secure Shell. To obtain orientation data, an Adafruit MPU-6050 6-DoF accelerometer and gyroscope was chosen due to its ease of use. The motor selected to drive each reaction wheel is the MJ5208 brushless motor because of its relatively high torque capability and flat dimensions to optimally fit within the constraints of the CubeSat. The motor controller selected is the Moteus Brushless Controller because of its velocity and torque control capability, small relative size, and onboard encoder.

One notable design requirement demanded by the Moteus motor controller is that the magnet attached to the motor shaft must be ~1 mm from the onboard encoder chip on the Moteus board. Therefore, a 3 mm thick plate must be situated between the motor and the Moteus controller.

Another commonality among the three systems is the hardware manufacturing process. Additive manufacturing (3D printing) was utilized due to the short amount of time required to print new iterations. All parts were printed using Polyactic Acid (PLA) filament. An inverted pendulum is a classic controls problem which consists of a pendulum with its center of mass positioned above its pivot point. Since this system is inherently unstable, it requires an additional torque to balance upright. In this application, the pivot point is fixed, and a reaction wheel is mounted at the end of the pendulum arm. This is an ideal initial control platform because it only requires one actively driven reaction wheel and provides an initial look at acquiring orientation data from the MPU-6050.

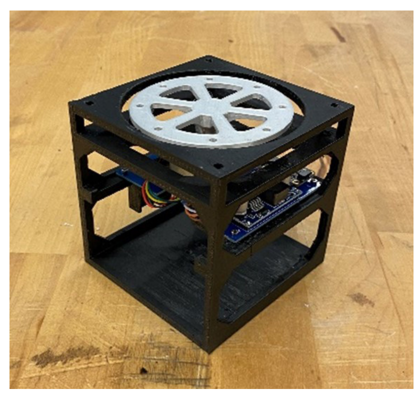

Figure 2: 1U, 1-DoF CubeSat

After completion of the inverted pendulum, a 1-DoF CubeSat configuration was designed. Rather than a complete 3-DoF configuration, the 1-DoF configuration attitude control system consists of only one reaction wheel. The purpose of this platform is to construct a system analogous to the 3-DoF CubeSat, but with simpler electrical system demands. This configuration was designed to adhere to the standard 1U CubeSat dimensions (10 cm by 10 cm by 10 cm) and secured by two rotary claws attached to a bearing which provides low friction rotation about one axis.

The next step was to design the complete 3-DoF CubeSat configuration. This system is the most complex of the three for multiple reasons. First, a reaction wheel subassembly, comprised of the reaction wheel, motor, and motor controller, must be positioned on three orthogonal faces of the CubeSat. This primarily poses a challenge because of the proximity requirement between the motor shaft magnet and motor controller's onboard encoder. Next, the center of mass must be located near the geometric center of the system to minimize torque created by the weight of the CubeSat. To adhere to these design parameters and fit the electrical system within the typical 1U CubeSat dimensions is a challenge outside the scope of this project. Due to this, an "expanded" 1U CubeSat was adapted with dimensions of 15 cm by 15 cm by 15 cm. This increase in volume allows development to be focused on integrating the hardware and electrical system without volume constraint issues.

To control multiple motors at a time, more electrical components were required. These components include the MJBots Pi3Hat, which allows the Raspberry Pi to communicate with multiple Moteus controllers at a time, and the MJBots power distribution board.

To test the 3-DoF CubeSat configuration, a gimbal system, consisting of three rings for 3-DoF, must also be designed. As the Engineering Physics Propulsion Lab (EPPL) has access to a Modix Big-60 3D printer with a print area of 600 mm by 600 mm, additive manufacturing again presents an optimal solution to manufacturing the rings (seen in Figure 3).

At this stage of development, the primary focus is to create a platform in which a control algorithm may be applied; it is not to design the platform and the control algorithm. However, to ensure each system's electrical and hardware subsystems were optimally integrated, a simple Proportional-Integral-Derivative (PID) controller was applied.

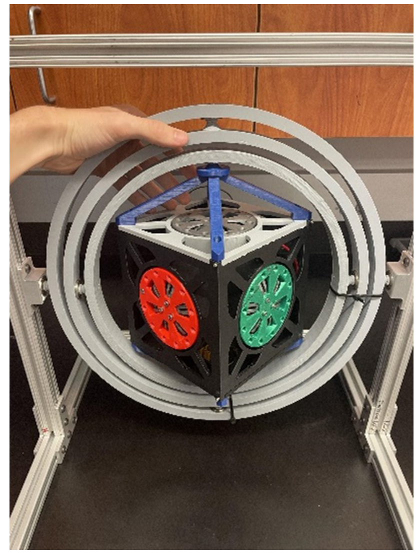

Figure 3: "Expanded" 1U, 3-DoF CubeSat in a gimbal ring system

3. Results

Each of the three control platforms and the 3-DoF CubeSat configuration have been successfully manufactured. Testing of the inverted pendulum and 1-DoF CubeSat configuration proved successful. However, issues related to Moteus brushless motor controllers led to an unsuccessful completion of the 3-DoF CubeSat configuration. The open-source practicality of the CubeSat Control Platform, other difficulties, and plans for future development are further discussed.

Applying a PID controller to the inverted pendulum and 1-DoF CubeSat configuration proved to be straightforward. The platform orientation, defined as angular position in Euler angles, is fed into the PID controller as the process variable and motor torque is produced as the control variable. In the case of the inverted pendulum, the setpoint is such that the pendulum is balanced upright. As the pendulum arm accelerates due to the torque created by the weight of the system, the motor accelerates the reaction wheel to exert an appropriate torque to balance the system. A nearly identical process was applied to the 1-DoF CubeSat with the notable exception being the setpoint (an arbitrary orientation angle as opposed to an upright system).

Development of the 3-DoF CubeSat

configuration was impeded by an electrical failure on behalf of the Moteus brushless motor controllers, hindering communication between it and the Raspberry Pi. Another issue with the current iteration is the location of the system's center of mass. Due to the positioning of the reaction wheel subassemblies on orthogonal faces of the CubeSat, the center of mass is located in one corner of the system. The distance between the center of mass and geometric center is drastic enough for the weight of the CubeSat to overpower any torque created by the reaction wheels.

Shown in Table 1 are the necessary electrical components (assuming the Moteus motor controllers are in use) and the total price of the electrical subsystem. For printing each part of the hardware subsystem, around 500 g of PLA filament and 47 hours of printing time is required for the CubeSat platform itself (assuming 15% infill). To print each ring of the gimbal system, a total of 370 g and 25 hours of printing time is required. Considering other hardware components, such as bolts, threaded inserts, and bearings, it is safe to assume that the complete platform can be constructed for less than $1,000.00.

Table 1: Electrical Component Price Breakdown

Component	Quantity	Price Per Unit ($)	Total Price ($)
Rasp. Pi 2 W Zero	1	$35.00	$35.00
Adafruit MPU-6050	1	$13.00	$13.00
MJ5208 Brushless Motor	3	$65.00	$195.00
Moteus Motor Controller	3	$104.00	$312.00
MJBots Pi3Hat	1	$149.00	$149.00
MJBots Power Dist.	1	$149.00	$149.00
Ovonic 6S LiPo Battery	1	$20.00	$20.00
Electrical Subsystem	NA	NA	**$873.00**

4. Discussion

The foundation for future development of the CubeSat Reaction Wheel Attitude Control Platform has been laid. Functional platforms exist, the inverted pendulum and 1-DoF CubeSat configuration, which will provide insight into the design of the next 3-DoF CubeSat configuration iteration.

Given the estimated total price of the CubeSat Control Platform (<$1000.00), university utilization of the platform is practical.

Development of the 3-DoF CubeSat configuration will continue utilizing ODrive S1 controllers as opposed to the Moteus controllers. The ODrive S1 was selected because of an abundance of online documentation and example work to streamline troubleshooting. A 1-DoF CubeSat configuration (Figure 4) has already been manufactured and testing is underway. Following this, development of the 3U and 6U CubeSat will commence.

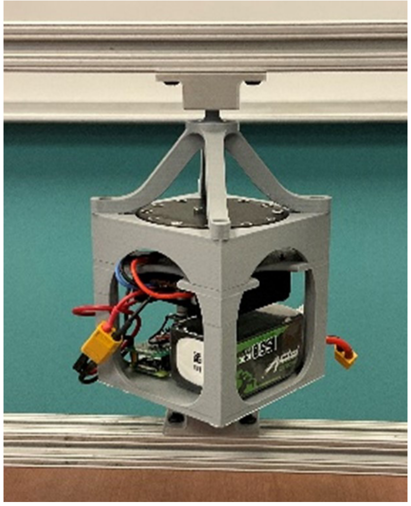

Figure 4: 1U, 1-DoF CubeSat with Odrive Pro motor controller

Aside from the CubeSat platforms themselves, an actively driven gimbal to simulate micro-gravity conditions for testing CubeSats (ACTIV) is underway in conjunction with the CubeSat Control Platform project. This testbed will provide a more realistic micro-gravity environment by compensating for friction within the bearings and for the weight of the CubeSat itself. The two projects will be mutually beneficial as ACTIV will provide a testbed for the CubeSat Control Platforms and the CubeSat Control Platforms will provide test spacecraft to tune ACTIV. As development of these platforms continues, the infrastructure of Easy Controls too will expand.