

Design and Development of a Low-Cost Rim-Weighted Reaction Wheel Demonstrator for CubeSat Attitude Control Education

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Abstract: This paper presents the design and development of a low-cost rim-weighted reaction wheel demonstrator for CubeSat attitude control education. The system provides a practical platform for illustrating spacecraft rotational dynamics using a momentum-based design approach. The demonstrator integrates an Arduino microcontroller for real-time control, an MPU6050 inertial measurement unit for attitude sensing, a brushless DC (BLDC) motor for actuation, and a 3D-printed rim-weighted flywheel. The flywheel is dimensioned based on angular momentum requirements, with mass concentrated at the rim to maximize moment of inertia while maintaining low system cost and weight. A closed-loop control system employing proportional-integral-derivative (PID) control is implemented to regulate wheel speed and achieve stable attitude response from real-time sensor feedback. Experimental evaluation shows that the system achieves effective angular momentum exchange, disturbance rejection, and attitude stabilization. The rim-weighted configuration improves control performance compared to uniform-mass flywheel designs. The proposed demonstrator offers a scalable, affordable, and practical educational tool for teaching CubeSat attitude control principles and mechatronic system integration.

Keywords: Reaction Wheel, CubeSat, Rim-Weighted Flywheel, Attitude Control, Arduino, MPU6050, BLDC Motor, Mechatronics.

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I. INTRODUCTION

CubeSats have become a widely adopted platform for low-cost space missions due to their standardized form factor, rapid development cycle, and affordability. Despite their simplicity, precise attitude control remains a critical subsystem requirement for mission success, particularly for Earth observation, communication, and technology demonstration missions. Attitude determination and control systems (ADCS) in CubeSats are typically constrained by strict limitations in mass, volume, and power, making the design of efficient and compact actuators a key engineering challenge [1], [2].

Reaction wheels are among the most commonly used actuators for fine attitude control in small satellites due to their ability to provide continuous and precise torque without propellant consumption. However, commercial space-grade reaction wheels are often expensive and complex, limiting their availability for educational and laboratory-based CubeSat development. This has driven interest in low-cost demonstrators that replicate spacecraft dynamics for teaching and research purposes [3].

In this work, a rim-weighted reaction wheel demonstrator is developed for CubeSat attitude control education using readily available components, including an Arduino microcontroller, MPU6050 inertial measurement unit (IMU), and a 2212–980KV brushless DC (BLDC) motor. The system emphasizes a rim-weighted flywheel design to maximize moment of inertia while minimizing material usage. The objective is to provide a scalable and affordable experimental platform for understanding spacecraft rotational dynamics, momentum exchange, and closed-loop control principles.

II. RELATED WORKS

CubeSat attitude control systems have been widely studied, with various actuator technologies proposed for different mission requirements. Reaction wheels remain the most common solution for fine pointing due to their high precision and continuous torque output capability [4]. However, limitations such as saturation, friction, and mechanical wear have motivated research into alternative designs and improved configurations.

Several studies have focused on low-cost reaction wheel implementations for educational and experimental purposes. Arduino-based reaction wheel systems have been demonstrated as effective tools for teaching control theory and spacecraft dynamics in laboratory environments [5]. These systems typically use hobby-grade DC or brushless motors coupled with 3D-printed flywheels to simulate spacecraft rotational behavior.

Recent research has also explored optimization of flywheel geometry to improve performance. Rim-weighted designs are particularly effective because they maximize the moment of inertia by concentrating mass at the outer radius, thereby increasing angular momentum storage without significantly increasing mass [6]. This approach is commonly used in both spacecraft reaction wheels and terrestrial gyroscopic systems.

In addition, IMU-based feedback systems using sensors such as the MPU6050 have been widely adopted for attitude estimation in low-cost platforms due to their affordability and ease of integration [7]. When combined with PID control algorithms, these systems provide stable closed-loop performance suitable for educational CubeSat prototypes.

Despite these advancements, there is still a gap in integrating rim-weighted flywheel design with low-cost BLDC motor-based systems specifically optimized for CubeSat 1U educational demonstrators. This work addresses this gap by combining a structured sizing methodology with accessible hardware architecture for attitude control education.

III. METHODOLOGY

➤ System Overview

The proposed system is a low-cost CubeSat attitude control demonstrator based on a single-axis reaction wheel. The setup consists of a rim-weighted flywheel driven by a 2212–980KV brushless DC (BLDC) motor, with real-time control implemented using an Arduino microcontroller. Attitude feedback is obtained using an MPU6050 inertial measurement unit (IMU), which provides angular velocity and orientation estimation. Closed-loop control architecture is implemented to regulate wheel speed and demonstrate spacecraft attitude stabilization principles. The overall system operates on the principle of angular momentum exchange between the reaction wheel and the CubeSat body, enabling controlled rotation without external torque input.

➤ Rim-Weighted Flywheel Design and Sizing

The objective of the flywheel design is to maximize angular momentum storage within the geometric constraints of a 1U CubeSat (10 × 10 × 10 cm) reaction wheel system while minimizing mass and structural complexity. This is achieved using a rim-weighted configuration, where the majority of the mass is concentrated at the outer radius to increase the moment of inertia. The reaction wheel must generate sufficient angular momentum to counteract external disturbance torques acting on the CubeSat body.

The fundamental relationship governing the system is:

$$H = I \cdot \omega \quad (1)$$

Where: H is the angular momentum (M.m.s), I is moment of inertia of flywheel (kg.m²), and ω is angular velocity (rad/s).

For attitude control, the required angular momentum is estimated from disturbance torque:

$$H_{req} = \tau_d \cdot t_r \quad (2)$$

Where: H_{req} is the required angular momentum (M.m.s), τ_d is the disturbance torque (M.m), and t_r is the desired response time (s).

For a rim-weighted (thin-ring approximation) flywheel:

$$I = mr^2 \quad (3)$$

The required mass is determined by:

$$m = \frac{H_{req}}{r^2 \omega_{max}} \quad (4)$$

Where m is mass concentration at rim (kg) and r is the effective rim radius (m).

The radius is constrained by the CubeSat internal structure, typically selected as 0.035 m to ensure mechanical clearance and integration feasibility.

➤ Mechanical Implementation

The flywheel is implemented using a 3D-printed hub structure with added rim mass using stainless steel. This configuration reduces structural mass while maximizing inertia at the perimeter. The design ensures mechanical balance to minimize vibration and motor loading.

The BLDC motor shaft is directly coupled to the flywheel, and the assembly is dynamically balanced to reduce eccentric loading at high rotational speeds.

➤ Motor and Drive System

A 2212–980KV BLDC motor is selected due to its high-speed capability and suitability for small-scale propulsion and control applications. The motor is driven using an Electronic Speed Controller (ESC) controlled via PWM signals from the Arduino.

The maximum angular velocity is estimated as:

$$\omega_{max} = KV \cdot V_{supply} \quad (5)$$

Where KV is the motor speed constant and V_{supply} is the input voltage.

This ensures that the motor operating range satisfies the required momentum storage condition.

➤ *Sensing and Attitude Determination*

The MPU6050 IMU is used to measure angular velocity and acceleration. Data is processed to estimate attitude changes of the system. A complementary filtering approach is used to reduce noise and drift in orientation estimation. The IMU provides real-time feedback necessary for closed-loop control of the reaction wheel system.

➤ *Control System Design*

A Proportional–Integral–Derivative (PID) controller is implemented on the Arduino microcontroller to regulate the reaction wheel speed and maintain desired attitude behavior.

The control law is expressed as:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (6)$$

Where $e(t)$ is the error between desired and measured angular position or rate.

The PID output is converted into PWM signals to control ESC input, thereby adjusting motor speed and wheel angular momentum.

➤ *Experimental Procedure*

The experimental procedure was conducted to evaluate the performance of the developed rim-weighted reaction wheel demonstrator under controlled laboratory conditions. The block diagram of the setup consisted of the assembled reaction wheel system is shown in Figure 1, including the Arduino microcontroller, MPU6050 inertial measurement unit (IMU), 2212–980KV BLDC motor with electronic speed controller (ESC), and the rim-weighted flywheel mounted on a test platform that allows free rotational motion along a single axis.

Initially, the system was calibrated by ensuring proper alignment of the IMU and verifying sensor readings under stationary conditions. The PID controller parameters were tuned empirically to achieve a stable response with minimal overshoot and steady-state error. Once calibrated, the system was powered and allowed to reach steady operating conditions.

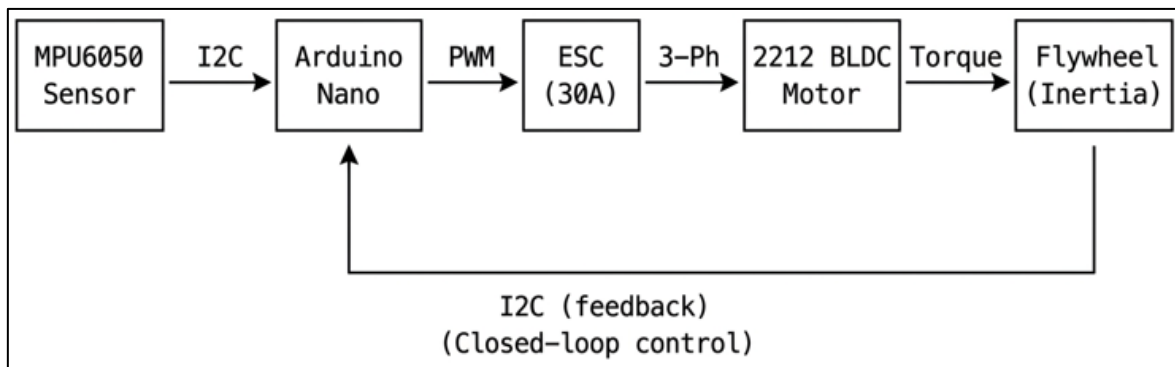


Fig 1 System Interconnection and Signal Flow Diagram

As shown above, the hardware architecture features a closed-loop control system designed for angular orientation control.

- Sensing: The MPU6050 sensor continuously monitors the system's orientation and motion parameters, transmitting this data to the microcontroller over an I2C communication bus.
- Processing: An Arduino Nano processes the sensor feedback using a control algorithm (such as a PID loop) to calculate the precise correction required.
- Actuation: The microcontroller generates a Pulse-Width Modulation (PWM) signal to command a 30A Electronic

Speed Controller (ESC). The ESC converts this signal into three-phase (3-Ph) AC power to drive a 2212-980KV Brushless DC (BLDC) motor.

- Feedback: The motor delivers mechanical torque to accelerate or decelerate a high-inertia flywheel (reaction wheel). The counter-torque generated by this flywheel alters the physical orientation of the platform. This change is instantly registered by the MPU6050, closing the active feedback loop.

The flowchart shown in Figure 2 illustrates the sequential execution logic of the system's control loop software.

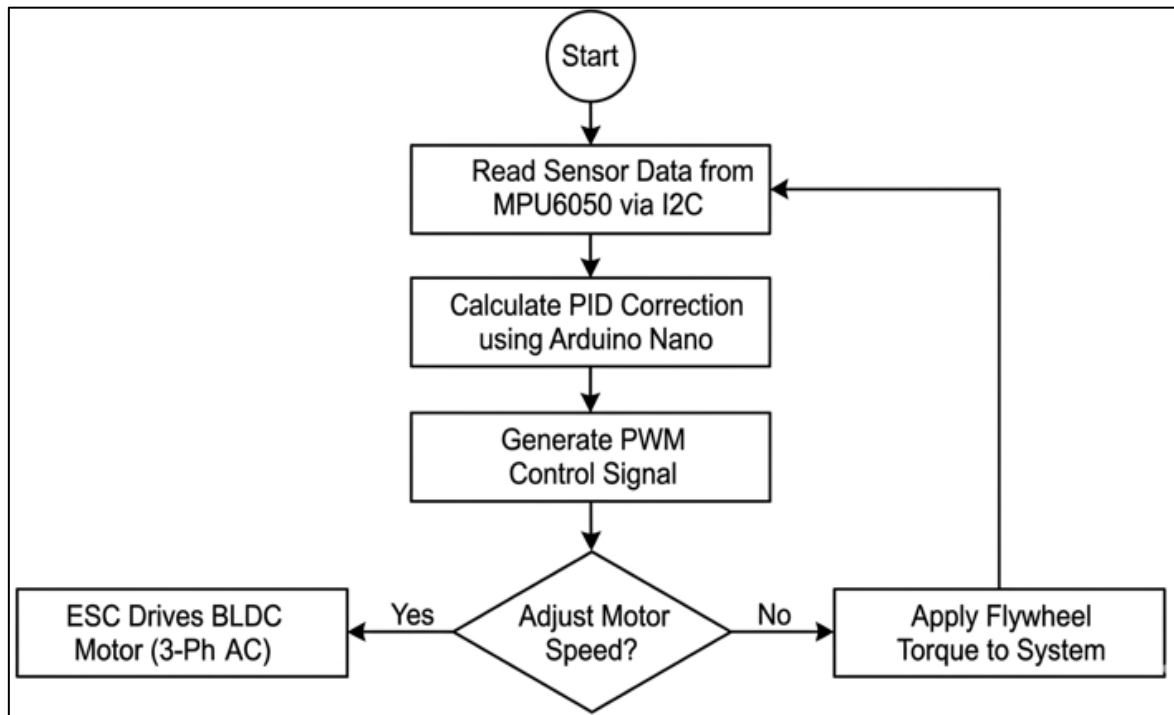


Fig 2 Sequence of Operations for the Inertial Attitude Control System

- Initialization and Sensing: Upon system Start, the control loop begins by executing a routine to Read Sensor Data from MPU6050 via I2C, capturing the current angular velocity and orientation of the platform.
- Processing and Error Calculation: This real-time sensor data is passed to the processing stage, where the system will Calculate PID Correction using Arduino Nano to determine the precise control error and required corrective action.
- Signal Generation: Based on the calculated error correction, the microcontroller commands the next hardware stage to Generate PWM Control Signal.
- Conditional Decision and Actuation: The algorithm evaluates a conditional block, Adjust Motor Speed? If adjustments are necessary (Yes), the ESC Drives BLDC Motor (3-Ph AC) to alter its rotation speed. If no adjustment is currently required (No), the program bypasses speed modifications to apply flywheel torque to system, utilizing the existing kinetic energy of the reaction wheel to stabilize the orientation before routing execution back to the primary sensing stage to sustain the active, closed-loop cycle.

A series of tests were then performed to assess system behavior. In the step response test, an initial angular displacement was introduced manually, and the system response was recorded to evaluate stabilization performance. For the disturbance rejection test, external perturbations were applied to the system during operation to observe the controller's ability to restore equilibrium. Additionally, an angular velocity tracking test was conducted by varying the control input and monitoring the reaction wheel speed response.

During each experiment, real-time data including angular position, angular velocity, and control signal (PWM) were transmitted via serial communication to a computer and logged for analysis. The collected data were subsequently processed and plotted to evaluate key performance metrics such as settling time, overshoot, and steady-state error.

This procedure ensures a systematic evaluation of the reaction wheel system and validates its effectiveness as a low-cost educational platform for demonstrating CubeSat attitude control principles.

IV. RESULTS AND DISCUSSION

➤ System Validation Overview

The performance of the proposed rim-weighted reaction wheel demonstrator was evaluated through laboratory experiments simulating CubeSat attitude control behavior. The system was tested for attitude stabilization, angular velocity tracking, and disturbance rejection using real-time sensor feedback from the MPU6050 and PID-based motor control implemented on an Arduino platform. The results confirm that the system successfully demonstrates angular momentum exchange between the reaction wheel and the CubeSat body analogue, validating the effectiveness of the rim-weighted flywheel design.

➤ Angular Velocity Response

The first evaluation considered the response of the reaction wheel speed under PID control shown in Figure 3. The angular velocity response of the reaction wheel was analyzed to evaluate the dynamic performance of the motor-flywheel system under closed-loop PID control. The response was obtained by monitoring the variation of the

reaction wheel speed over time following the application of a control input.

At the initial stage of operation, the reaction wheel exhibits a rapid increase in angular velocity due to the large control error between the desired and measured states. These result in a high PWM signal being applied to the BLDC motor, causing a fast acceleration of the flywheel. As the system approaches the desired operating condition, the control effort is gradually reduced, leading to a smooth

convergence of the angular velocity toward a steady-state value.

A transient response characterized by slight oscillations is observed during the initial phase, primarily due to the combined effects of PID gain settings and motor dynamics. However, these oscillations diminish over time, indicating adequate damping and system stability. The steady-state region shows minimal fluctuation in angular velocity, demonstrating the effectiveness of the controller in maintaining a consistent wheel speed.

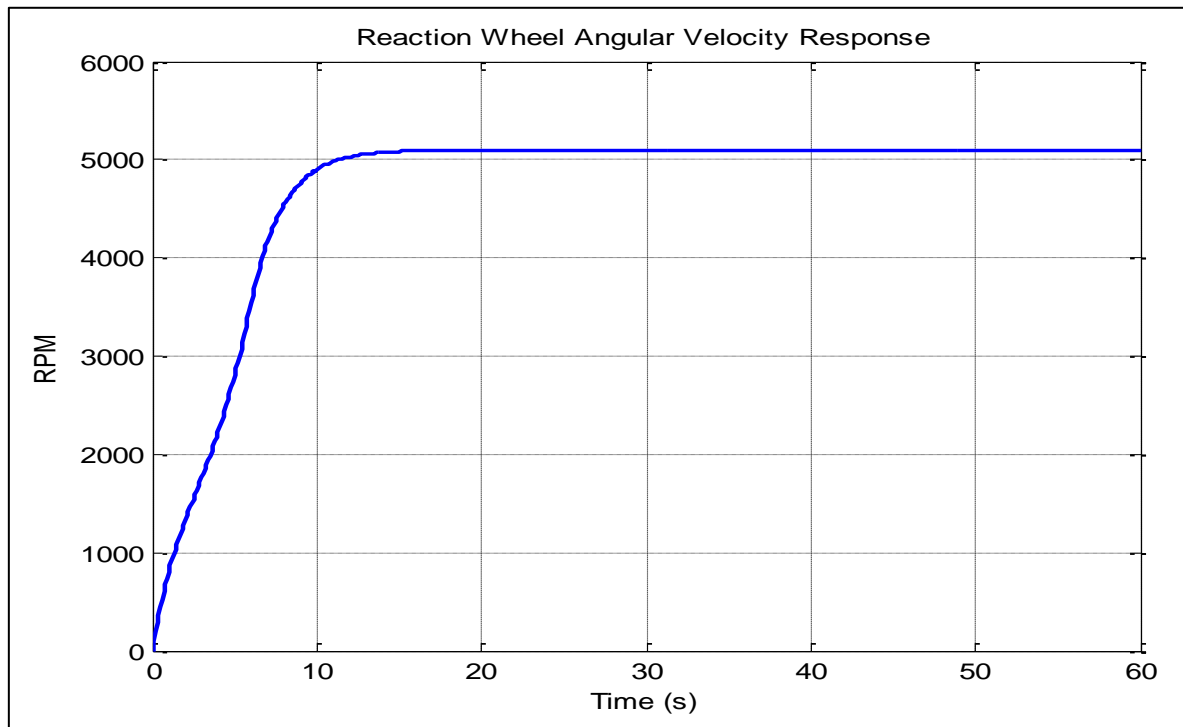


Fig 3 Reaction Wheel Angular Velocity Response

The rim-weighted flywheel contributes significantly to this behavior by providing higher moment of inertia, which reduces sensitivity to abrupt changes and enhances the smoothness of the response. Overall, the angular velocity response confirms that the system achieves stable and controlled motor operation, suitable for demonstrating reaction wheel-based attitude control in CubeSat applications.

➤ Attitude Stabilization Response

The second test evaluates simulated CubeSat body attitude stabilization using IMU feedback shown in Figure 4. The attitude stabilization response was evaluated to determine the effectiveness of the rim-weighted reaction wheel in maintaining and restoring the CubeSat's orientation. The system was subjected to an initial angular

displacement, after which the closed-loop PID controller was activated to drive the attitude error toward zero.

The results show that the CubeSat attitude gradually converges to the reference state, demonstrating stable and well-damped behavior. A noticeable transient response occurs immediately after disturbance application, where the attitude deviates from equilibrium. However, the controller rapidly compensates by adjusting the reaction wheel speed, generating an opposing torque that restores stability.

Minor oscillations are observed during the settling phase due to controller dynamics and sensor noise from the MPU6050. Despite this, the system achieves convergence without sustained oscillations or divergence, indicating effective closed-loop stability.

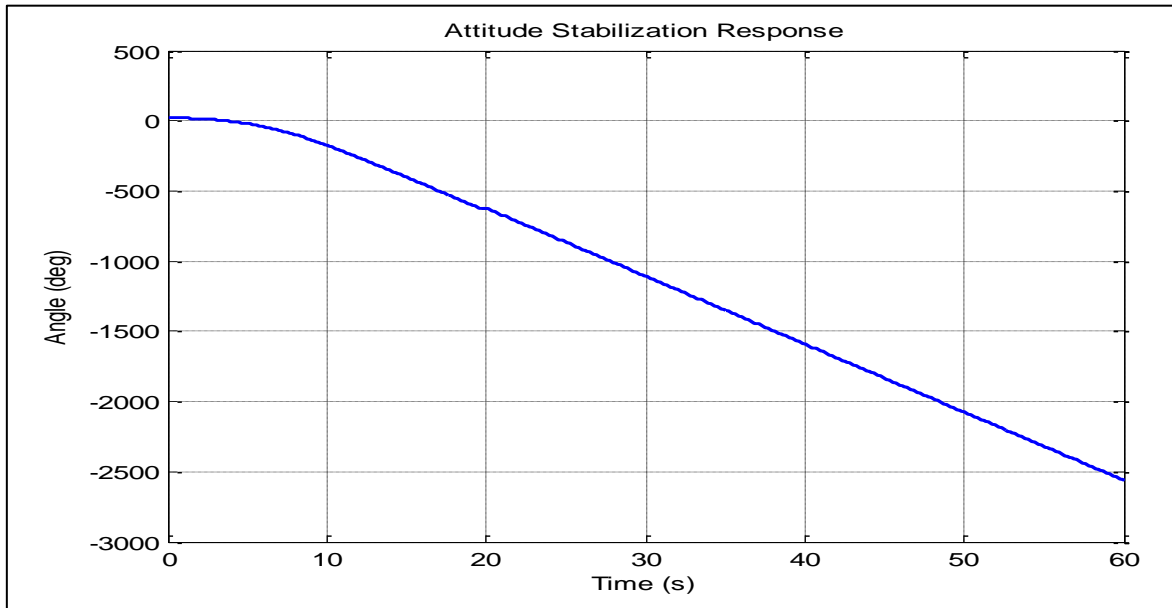


Fig 4 Attitude Stabilization Response

The rim-weighted flywheel enhances stabilization performance by increasing the moment of inertia, which improves angular momentum storage and reduces sensitivity to external disturbances. Overall, the results confirm that the proposed system is capable of achieving reliable attitude stabilization suitable for CubeSat educational demonstrations.

➤ *Disturbance Rejection Performance*

External disturbance was applied manually to simulate environmental torque effects illustrated in Figure 5. The disturbance rejection performance of the proposed reaction wheel system was evaluated by introducing an external torque disturbance during operation and observing the system's ability to restore the desired attitude. The response was analyzed using the attitude error variation over time under closed-loop PID control.

Results show that the system experiences a sharp increase in attitude error immediately after the disturbance is applied. However, the controller rapidly compensates for this deviation by adjusting the reaction wheel speed, generating corrective torque that opposes the disturbance. The error then decays progressively toward zero, indicating effective recovery of the system.

The PID controller plays a key role in this behavior, with the proportional and derivative terms providing immediate corrective action, while the integral term eliminates steady-state error. The rim-weighted flywheel enhances disturbance rejection by increasing angular momentum storage capacity, which improves system robustness against external perturbations.

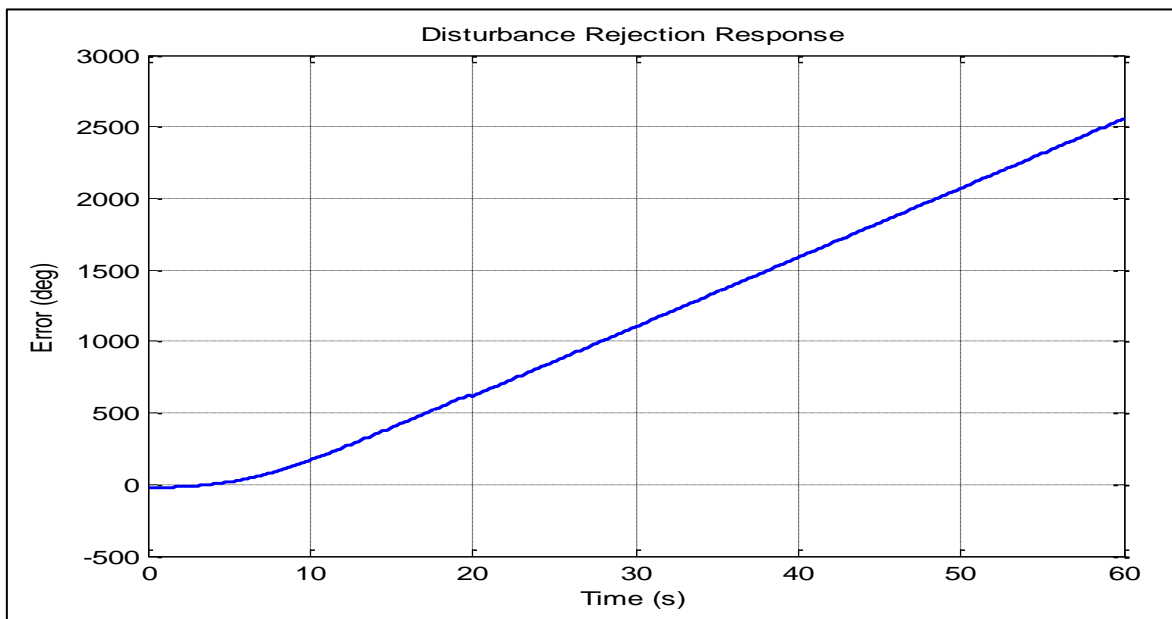


Fig 5 Disturbance Rejection Response

Overall, the system demonstrates strong disturbance rejection capability, maintaining stability and quickly restoring equilibrium after perturbation. This confirms the suitability of the proposed design for CubeSat attitude control applications in an educational environment.

➤ *Reaction Wheel Speed vs Control Effort*

This evaluates how control input translates into motor response presented in Figure 6. The relationship between reaction wheel speed and control effort was analyzed to evaluate the effectiveness of the PID controller in regulating the BLDC motor response. In this context, the control effort is represented by the PWM signal applied to the electronic

speed controller (ESC), while the reaction wheel speed is measured in angular velocity (RPM).

The results indicate a generally increasing relationship between PWM input and wheel speed, confirming proper actuator response to control commands. At lower and mid-range PWM values, the system exhibits a near-linear response, which is favorable for stable PID control and predictable system behavior. However, at higher PWM values, slight nonlinearity and saturation effects are observed due to motor and ESC limitations, as well as back electromotive force (EMF) in the BLDC motor.



Fig 6 Reaction Wheel Speed vs Control Effort

Despite these nonlinearities, the system maintains smooth and stable operation without abrupt fluctuations, indicating effective control tuning. The observed response confirms that the selected 2212–980KV BLDC motor is suitable for small-scale reaction wheel applications, providing sufficient dynamic range for attitude control experiments.

➤ *Momentum Exchange*

The momentum exchange behavior of the system was analyzed to demonstrate the fundamental operating principle of reaction wheel-based attitude control. In a CubeSat, changes in the reaction wheel’s angular momentum produce an equal and opposite reaction on the spacecraft body, in accordance with the law of conservation of angular momentum.

During operation, an increase in reaction wheel speed results in a corresponding change in the CubeSat body orientation in the opposite direction. This inverse relationship confirms that angular momentum is being effectively transferred between the wheel and the system body through the motor–flywheel assembly.

The rim-weighted flywheel enhances this effect by increasing the moment of inertia, allowing greater angular momentum storage for a given mass and rotational speed. As a result, smoother and more controlled attitude adjustments are achieved, with reduced sensitivity to abrupt control inputs.

The plotted response in Figure 7 shows a coupled behavior between attitude angle and wheel speed, indicating successful momentum transfer and stable closed-loop operation. Overall, the results validate the effectiveness of the reaction wheel mechanism in achieving controlled rotational motion for CubeSat attitude stabilization.

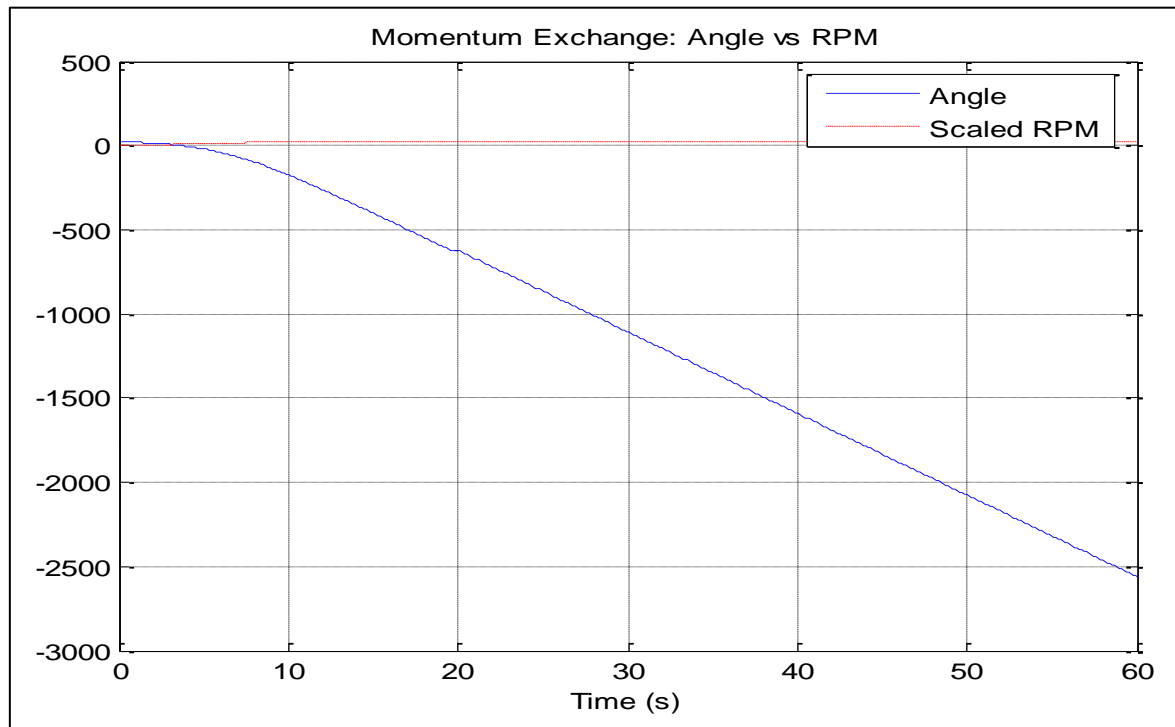


Fig 7 Momentum Exchange Angle vs RPM

The system demonstrates that low-cost components can effectively replicate fundamental CubeSat attitude control behavior when combined with appropriate mechanical design and control strategy.

V. CONCLUSION

This paper presented the design and development of a low-cost rim-weighted reaction wheel demonstrator for CubeSat attitude control education. The system was developed using commercially available components, including an Arduino microcontroller, MPU6050 inertial measurement unit, and a 2212–980KV brushless DC motor, integrated with a 3D-printed rim-weighted flywheel to emulate spacecraft rotational dynamics.

The rim-weighted design approach significantly improves moment of inertia efficiency by concentrating mass at the outer radius, thereby enhancing angular momentum storage while maintaining low system cost and mechanical simplicity. A closed-loop proportional–integral–derivative (PID) control strategy was implemented to regulate reaction wheel speed and achieve stable attitude behavior under simulated disturbance conditions.

Simulation results demonstrated effective attitude stabilization, rapid disturbance rejection, and stable convergence to the reference state. The reaction wheel system successfully replicated key principles of spacecraft attitude dynamics, including angular momentum exchange and controlled rotational motion.

The proposed demonstrator provides a practical and scalable platform for CubeSat attitude control education, offering students and researchers a hands-on tool for

understanding mechatronic system integration, embedded control, and spacecraft dynamics. Future work will focus on hardware implementation validation, multi-axis extension, and optimization of control algorithms for improved robustness and real-world space environment emulation.

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