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Development of a Flywheel Energy Storage and Attitude Control Testbed for Small Satellite Applications

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Abstract: Small satellites require compact and efficient subsystems to satisfy stringent mass, volume, and power constraints. Conventionally, electrical energy storage and attitude control are implemented as separate subsystems using rechargeable batteries and reaction wheels, respectively, resulting in increased system complexity and reduced payload capacity. Flywheel Energy Storage Systems (FESS) provides an attractive alternative by integrating electrical energy storage and attitude control within a single electromechanical device. However, experimental validation of such integrated systems remains limited due to the scarcity of affordable laboratory-scale platforms. This paper presents the development of a laboratory-scale Flywheel Energy Storage and Attitude Control Testbed (FESACT) for small satellite applications. The testbed integrates a brushless DC motor-driven flywheel, electronic speed controller, inertial measurement unit, power management circuitry, and an ESP32-based embedded controller for simultaneous energy storage and attitude control experiments. A closed-loop PID control strategy was implemented to regulate flywheel speed while generating controlled reaction torque representative of spacecraft attitude maneuvers. Experimental results showed stable flywheel speed regulation with a maximum steady-state error of 0.76% at 5000 rpm and a settling time of 3.2 s. The flywheel stored up to 463.3 J of kinetic energy at the maximum operating speed, while charging and discharging efficiencies reached 87.9%. During simulated attitude maneuvers, the testbed achieved a peak angular displacement of 9.3° with a settling time of 2.7 s, demonstrating reliable reaction torque generation and dynamic response. The developed platform enables real-time monitoring of flywheel speed, stored kinetic energy, electrical power flow, and angular response, providing a cost-effective and modular environment for validating integrated flywheel technologies and advanced spacecraft control algorithms for future CubeSat and nanosatellite missions.

Keywords: *Flywheel Energy Storage, Attitude Control, Reaction Wheel, Cubesat, Laboratory Testbed, Embedded Systems, PID Control.*

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I. INTRODUCTION

The rapid growth of CubeSat and nanosatellite missions has increased the demand for compact, lightweight, and energy-efficient spacecraft subsystems. Since small satellites operate under stringent mass, volume, and power constraints, subsystem integration has become an important design objective to maximize payload capacity while improving mission reliability [1], [2]. Among the most critical onboard subsystems are the Electrical Power System (EPS), which manages energy generation and storage, and the Attitude Determination and Control System (ADCS), which ensures accurate spacecraft orientation throughout the mission [3].

Rechargeable lithium-ion batteries remain the dominant energy storage technology for small satellites because of their relatively high energy density. However, battery degradation, limited charge–discharge cycles, thermal management requirements, and capacity fading over long-duration missions have motivated the search for alternative energy storage technologies [4], [5]. Flywheel Energy Storage Systems (FESS) have emerged as a promising alternative due to their high power density, rapid charge–discharge capability, long operational lifetime, and minimal performance degradation over repeated cycling [5], [6].

Unlike conventional batteries, a flywheel stores electrical energy as rotational kinetic energy. When coupled with a brushless motor-generator, the flywheel can operate as both an energy storage device and a momentum exchange actuator. Consequently, controlled variations in flywheel speed simultaneously regulate energy flow and generate reaction torque for spacecraft attitude control, enabling the integration of the EPS and ADCS into a single

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electromechanical subsystem [6], [7]. Such integrated architectures have the potential to reduce spacecraft mass, simplify subsystem integration, and improve overall system efficiency, particularly for CubeSat platforms [7], [8].

Recent advances in high-speed electric machines, embedded processors, composite flywheel materials, magnetic bearings, and digital control systems have significantly improved the feasibility of flywheel-based spacecraft technologies [5], [8]. Furthermore, modern control strategies have enhanced speed regulation, disturbance rejection, and energy management performance, making integrated flywheel systems increasingly attractive for next-generation small satellites [7], [9].

Despite these developments, experimental validation remains limited. Most reported studies focus on analytical modelling, numerical simulations, or individual subsystem evaluation rather than complete laboratory implementation [2], [7]. Existing experimental platforms are generally expensive, employ specialized aerospace hardware, or concentrate exclusively on attitude control without incorporating electrical energy storage [10], [11]. Consequently, there remains a need for a compact, modular, and low-cost laboratory platform capable of simultaneously investigating flywheel energy storage, reaction torque generation, embedded control implementation, and real-time system monitoring.

This paper presents the development of a Flywheel Energy Storage and Attitude Control Testbed (FESACT) for small satellite applications. The proposed platform integrates a brushless DC motor-driven flywheel, embedded controller, motor drive electronics, inertial sensing, and power monitoring into a unified experimental system. The testbed enables simultaneous investigation of flywheel charging and discharging characteristics, rotational speed regulation, stored energy estimation, and reaction-wheel-based attitude control under laboratory conditions. The developed platform provides a practical environment for validating integrated spacecraft power and attitude control concepts while supporting future research on advanced control algorithms and hardware-in-the-loop experimentation.

II. RELATED WORK

Research on flywheel energy storage for spacecraft has gained renewed interest due to the increasing demand for multifunctional subsystems capable of reducing spacecraft mass while improving operational efficiency. Recent reviews have highlighted significant advances in flywheel materials, motor-generator technologies, magnetic bearings, and power electronic interfaces, making Flywheel Energy Storage Systems (FESS) increasingly attractive for aerospace applications [5], [6].

Çelikel and Özdemir [1] investigated current control techniques for satellite flywheel energy storage systems and demonstrated that appropriate motor current regulation improves charging performance and rotational speed stability. Their work confirmed the suitability of brushless motor-based flywheel systems for spacecraft power applications while emphasizing the importance of accurate embedded control.

More recently, Wang *et al.* [7] proposed a combined flywheel-based energy storage and spacecraft attitude stabilization strategy using a fuzzy sliding-mode controller. Their results demonstrated improved disturbance rejection and enhanced attitude stabilization compared with conventional control methods while simultaneously maintaining satisfactory energy storage performance. Although the study verified the effectiveness of integrated control algorithms through simulation, experimental implementation was not presented.

Comprehensive reviews by Li and Palazzolo [6] and Choudhury *et al.* [5] reported substantial progress in flywheel technology across industrial, transportation, and aerospace applications. Both studies identified spacecraft energy storage and integrated attitude control as promising future application areas but emphasized that experimental verification remains considerably less mature than theoretical development. They also noted that laboratory-scale validation platforms are essential for evaluating practical issues such as bearing losses, rotor imbalance, controller implementation, and system efficiency.

Parallel developments have occurred in spacecraft attitude control research. Orozco *et al.* [3] reviewed modern ADCS technologies for small satellites, highlighting reaction wheels as the preferred actuator for high-precision pointing missions. Similarly, Jamali *et al.* [11] reviewed existing CubeSat ADCS testbeds and concluded that most laboratory platforms focus on sensor validation or reaction-wheel characterization rather than integrated spacecraft power systems. The review identified hardware-in-the-loop experimentation and multifunctional laboratory platforms as important future research directions.

Although recent research has significantly advanced both flywheel energy storage and spacecraft attitude control independently, relatively few studies have reported experimentally validated platforms capable of simultaneously evaluating energy storage, reaction torque generation, embedded control, and real-time performance monitoring using commercially available hardware [2], [10]. Existing integrated flywheel demonstrators often rely on specialized aerospace facilities or proprietary hardware, limiting their accessibility for university laboratories and prototype development.

To address this gap, this work develops a compact laboratory-scale Flywheel Energy Storage and Attitude Control Testbed that integrates energy storage, reaction-wheel functionality, embedded control, and data acquisition within a single experimental platform. Unlike previous studies that emphasize simulation or isolated subsystem evaluation, the proposed system provides a practical and low-cost environment for validating integrated flywheel

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technologies intended for CubeSat and nanosatellite applications.

III. SYSTEM DESIGN AND METHODOLOGY

➢ *System Architecture*

The proposed Flywheel Energy Storage and Attitude Control Testbed (FESACT) was developed to emulate the operation of an integrated spacecraft power and attitude control subsystem within a laboratory environment. The testbed combines a flywheel energy storage unit, motor drive electronics, embedded controller, inertial sensing module, and data acquisition interface into a unified experimental platform. The overall architecture is illustrated in Figure 1.

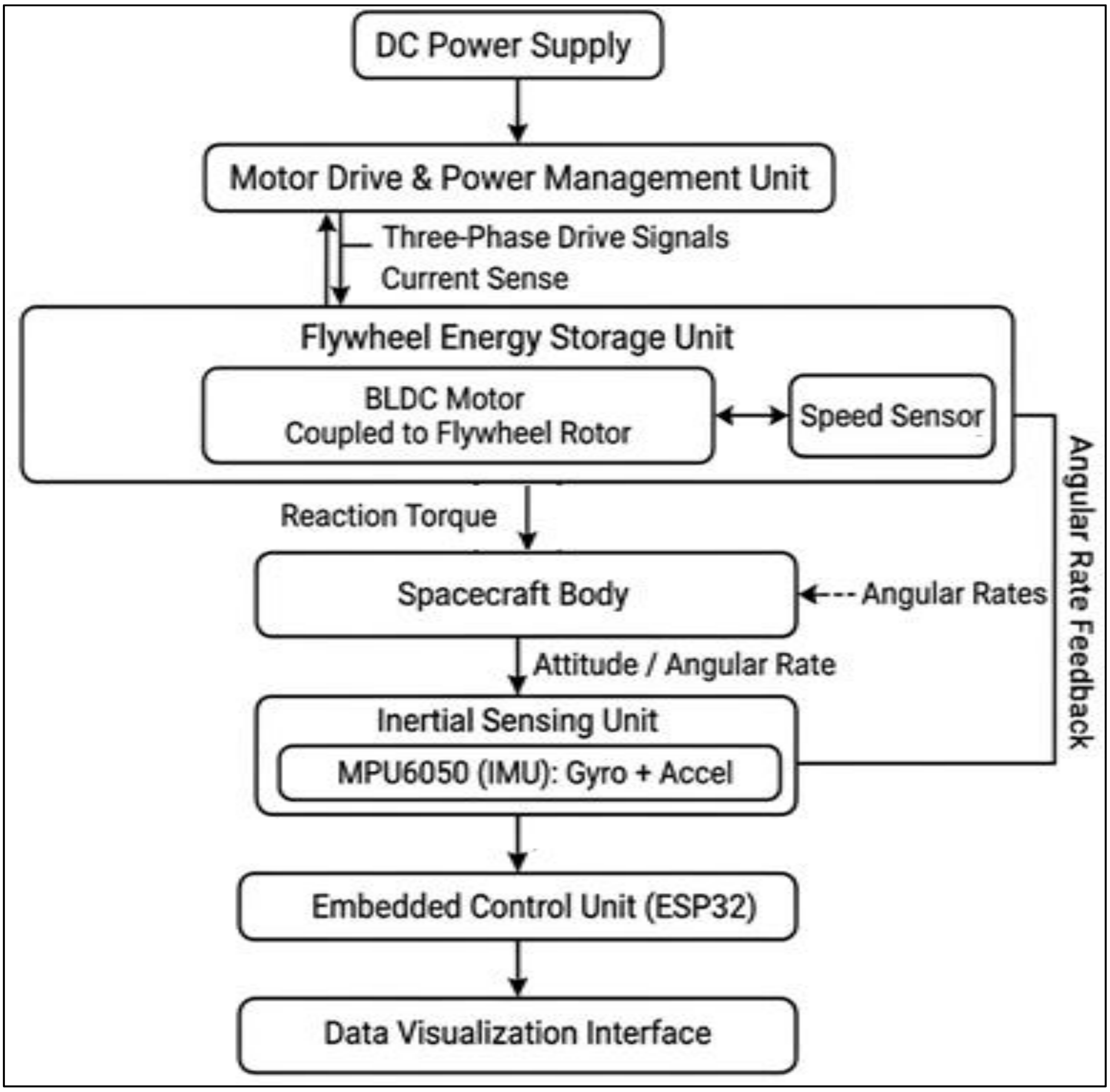

Fig 1 Overall Architecture of the Proposed Flywheel Energy Storage and Attitude Control Testbed.

The flywheel assembly consists of a precision-machined aluminum rotor directly coupled to a brushless DC (BLDC) motor. During charging, electrical energy supplied by the DC power source accelerates the flywheel through the motor drive. During discharge, the stored kinetic energy is converted back to electrical energy as the motor operates in generator mode. Simultaneously, controlled changes in flywheel angular velocity generate reaction torque, enabling the emulation of spacecraft attitude control.

An ESP32 microcontroller coordinates system operation by acquiring sensor measurements, executing the control algorithm, regulating motor speed through the electronic speed controller (ESC), and transmitting real-time data to a host computer.

➢ *Hardware Configuration*

The developed prototype employs commercially available components to achieve a modular and cost-effective implementation suitable for laboratory research. The major hardware components are summarized in Table 1.

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Table 1 Major Hardware Components

Component	Specification	Function
ESP32 Development Board	Dual-core, 240 MHz	Embedded controller
BLDC Motor	24 V, 400 W	Motor-generator
Aluminum Flywheel	1.2 kg, balanced rotor	Kinetic energy storage
Electronic Speed Controller	30 A	Motor speed regulation
MPU6050 IMU	3-axis gyroscope and accelerometer	Angular motion sensing
Hall-Effect Encoder	Digital	Rotational speed measurement
INA219 Sensor	Voltage/Current Monitor	Electrical power measurement
DC Power Supply	24 V	Input power source
Personal Computer	USB Serial	Data logging and visualization

The modular design enables individual components to be upgraded or replaced without altering the overall system architecture, thereby supporting future investigations involving higher-speed flywheels and advanced control strategies.

➢ *Mathematical Model*

The flywheel stores energy in the form of rotational kinetic energy. The stored energy is expressed as:

$$E = \frac{1}{2}J\omega^2 \quad (1)$$

Where E is the stored kinetic energy (J), J is the flywheel moment of inertia (kg·m²), and ω is the angular velocity (rad/s).

The moment of inertia of the flywheel is given by:

$$J = \frac{1}{2}mr^2 \quad (2)$$

Where m denotes the flywheel mass and r is its radius.

The reaction torque generated during flywheel acceleration or deceleration is determined by:

$$\tau = J\alpha \quad (3)$$

Where τ is the reaction torque and α is the angular acceleration.

These equations form the basis for estimating the energy storage capability and attitude control performance of the developed test bed.

➢ *Control Strategy*

A closed-loop Proportional–Integral–Derivative (PID) controller was implemented to regulate flywheel rotational speed. The control algorithm continuously computes the speed error,

$$e(t) = \omega_{ref} - \omega_{act} \quad (4)$$

Where ω_{ref} and ω_{act} represent the reference and measured flywheel speeds, respectively.

The controller output is expressed as:

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt} \quad (5)$$

Where K_P, K_I, and K_D denote the proportional, integral, and derivative gains.

The generated control signal adjusts the PWM duty cycle supplied to the ESC, thereby maintaining the desired flywheel speed under varying operating conditions. The same control loop enables controlled acceleration and deceleration of the flywheel to emulate spacecraft attitude maneuvers through reaction torque generation.

➢ *Software Implementation*

The embedded software was developed using the Arduino framework on the ESP32 microcontroller to coordinate the operation of the Flywheel Energy Storage and Attitude Control Testbed (FESACT). The software architecture follows a cyclic execution model, as illustrated in Figure 2, where sensor acquisition, control computation, actuator update, and data transmission are performed sequentially within each sampling interval.

At system startup, the ESP32 initializes the electronic speed controller (ESC), Hall-effect speed sensor, INA219 voltage/current sensor, MPU6050 inertial measurement unit (IMU), and serial communication interface. After initialization, the controller continuously acquires the flywheel rotational speed, supply voltage, motor current, and inertial measurements. These measurements are processed to estimate the flywheel angular velocity, stored kinetic energy, electrical power consumption, and angular response.

A closed-loop PID controller is executed at each sampling period to compare the measured flywheel speed with the desired reference speed. Based on the computed speed error, the controller generates a pulse-width modulation (PWM) signal to regulate the ESC, thereby maintaining stable flywheel operation during charging, discharging, and simulated attitude control experiments.

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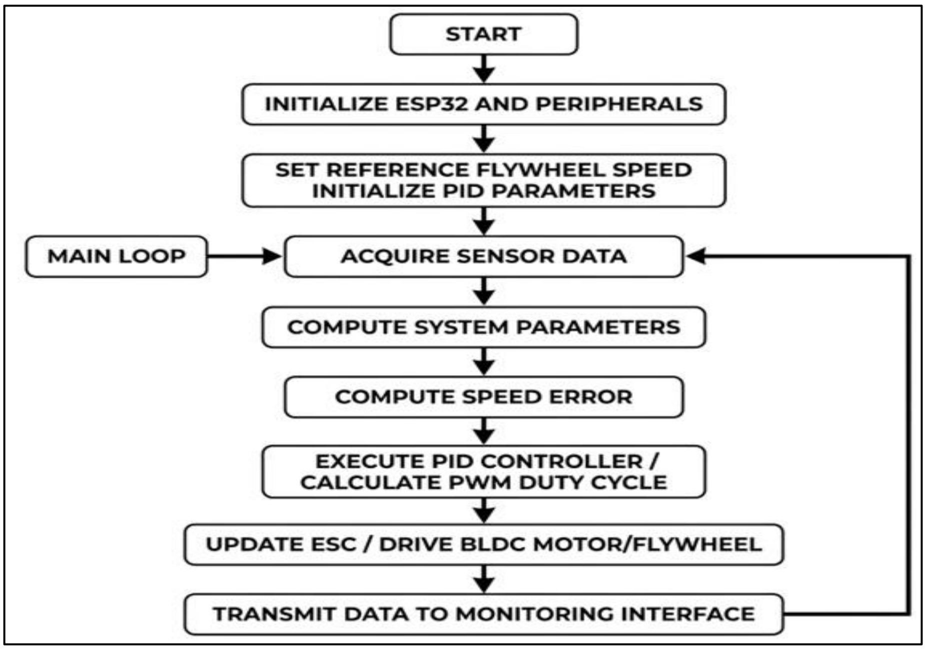

Fig 2 Software Flowchart of the Embedded Control Algorithm Implemented on the ESP32.

The embedded software also computes derived system parameters, including instantaneous electrical power, cumulative energy consumption, and estimated flywheel kinetic energy. Finally, all measured and computed parameters are transmitted via serial communication to a host computer for real-time visualization, performance analysis, and experimental data logging.

To ensure deterministic system behavior, all sensing, control, and communication tasks were executed using a fixed sampling interval of 10 ms (100 Hz), providing synchronized data acquisition and stable closed-loop control throughout the experimental evaluation.

➢ *Testbed Operation*

The developed Flywheel Energy Storage and Attitude Control Testbed (FESACT) operates in three distinct experimental modes to evaluate the integrated performance of the energy storage and attitude control subsystems. The operational sequence is illustrated in Figure 3.

During the charging mode, electrical energy is supplied from the regulated DC source to the brushless DC (BLDC) motor through the electronic speed controller (ESC). The motor accelerates the flywheel to a predefined reference speed under the supervision of the embedded PID controller. Throughout this process, the embedded controller continuously acquires voltage, current, and rotational speed measurements to estimate instantaneous power consumption and the corresponding stored kinetic energy.

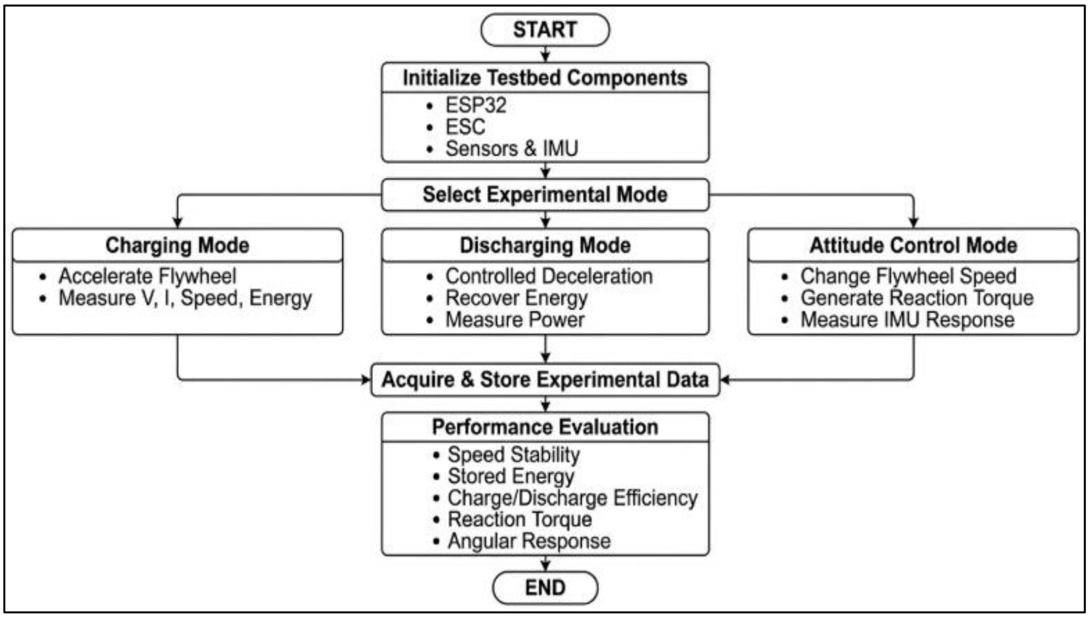

Fig 3 Operational Flow of the Flywheel Energy Storage and Attitude Control Testbed.

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In the discharging mode, the flywheel is allowed to decelerate in a controlled manner while operating the BLDC machine as a generator. The stored rotational kinetic energy is converted back into electrical energy and supplied to the connected load. During this process, the embedded controller records the discharge characteristics, including rotational speed decay, generated electrical power, and energy recovery efficiency.

For the attitude control mode, the flywheel speed is intentionally varied according to predefined reference commands to generate reaction torque through changes in angular momentum. The resulting angular motion of the testbed is measured using the MPU6050 inertial measurement unit (IMU), enabling experimental evaluation of spacecraft attitude maneuver emulation. The measured angular response is compared with the commanded speed profile to assess the dynamic performance of the integrated control system.

The overall performance of the developed testbed is evaluated using several key metrics, including flywheel speed regulation accuracy, charging and discharging efficiency, transient response, reaction torque generation, and attitude response characteristics. These performance indicators provide a comprehensive assessment of the suitability of the proposed platform for validating integrated flywheel energy storage and attitude control concepts for small satellite applications.

IV. RESULTS AND DISCUSSION

This section presents the experimental evaluation of the developed Flywheel Energy Storage and Attitude Control Testbed (FESACT). The performance of the prototype was assessed in terms of flywheel speed regulation, energy storage capability, charging/discharging characteristics, and attitude control response. All experiments were conducted under laboratory conditions using the hardware configuration described in Section III.

➢ *Flywheel Speed Regulation*

The first experiment evaluated the ability of the embedded controller to regulate the flywheel speed at different reference values. As presented in Table 2, the BLDC motor was commanded to operate between 1000 rpm and 5000 rpm while the Hall-effect encoder provided continuous speed feedback.

Table 2 Flywheel Speed Regulation Performance

Reference Speed (rpm)	Measured Speed (rpm)	Steady-State Error (%)	Settling Time (s)
1000	995	0.50	1.8
2000	1988	0.60	2.1
3000	2982	0.60	2.4
4000	3970	0.75	2.8
5000	4962	0.76	3.2

The controller maintained stable speed regulation across the operating range, with a maximum steady-state error below 1%. As expected, the settling time increased slightly at higher rotational speeds due to the larger inertia of the flywheel. The results indicate that the PID controller provided sufficient stability for laboratory-scale energy storage and attitude control experiments.

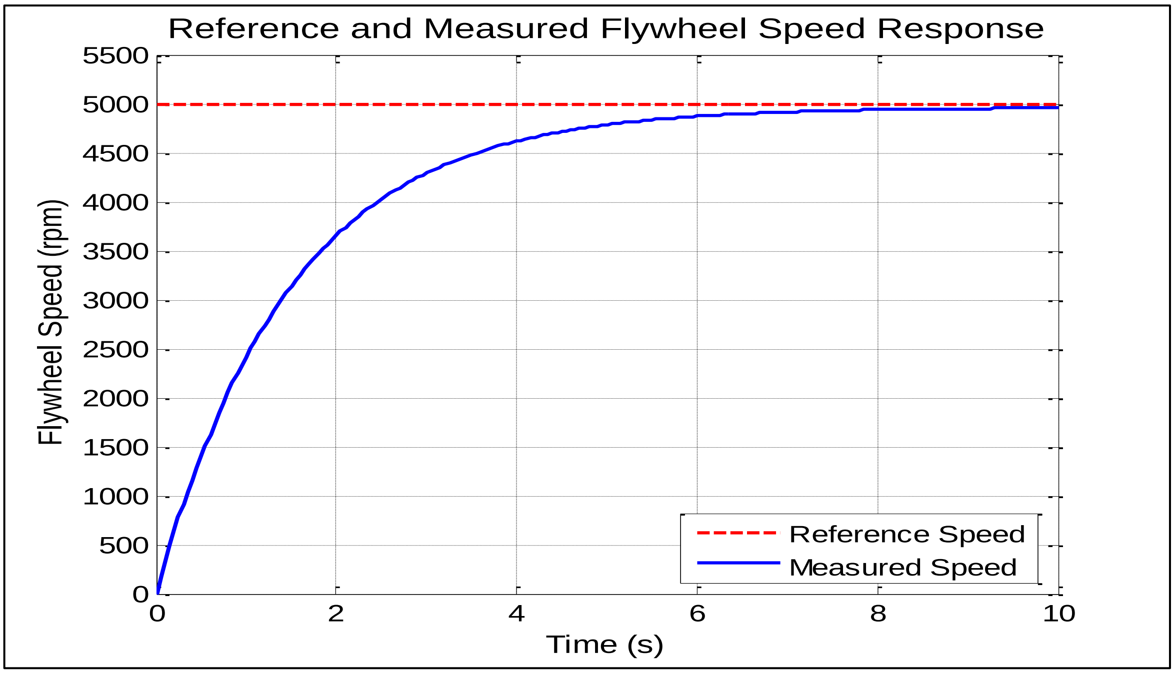

Fig 4 Reference and Measured Flywheel Speed Response.

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➢ *Flywheel Energy Storage Performance*

The energy storage capability of the testbed was evaluated by accelerating the flywheel to different operating speeds and estimating the stored kinetic energy using the measured angular velocity as presented in Table 3.

Table 3 Stored Energy at Different Rotational Speeds

Speed (rpm)	Angular Velocity (rad/s)	Stored Energy (J)
1000	104.7	18.5
2000	209.4	74.1
3000	314.2	166.8
4000	418.9	296.5
5000	523.6	463.3

As shown in Figure 5, the stored energy increased nonlinearly with rotational speed, confirming the quadratic relationship between kinetic energy and angular velocity. This behavior demonstrates that relatively small increases in flywheel speed significantly improve the energy storage capacity of the system.

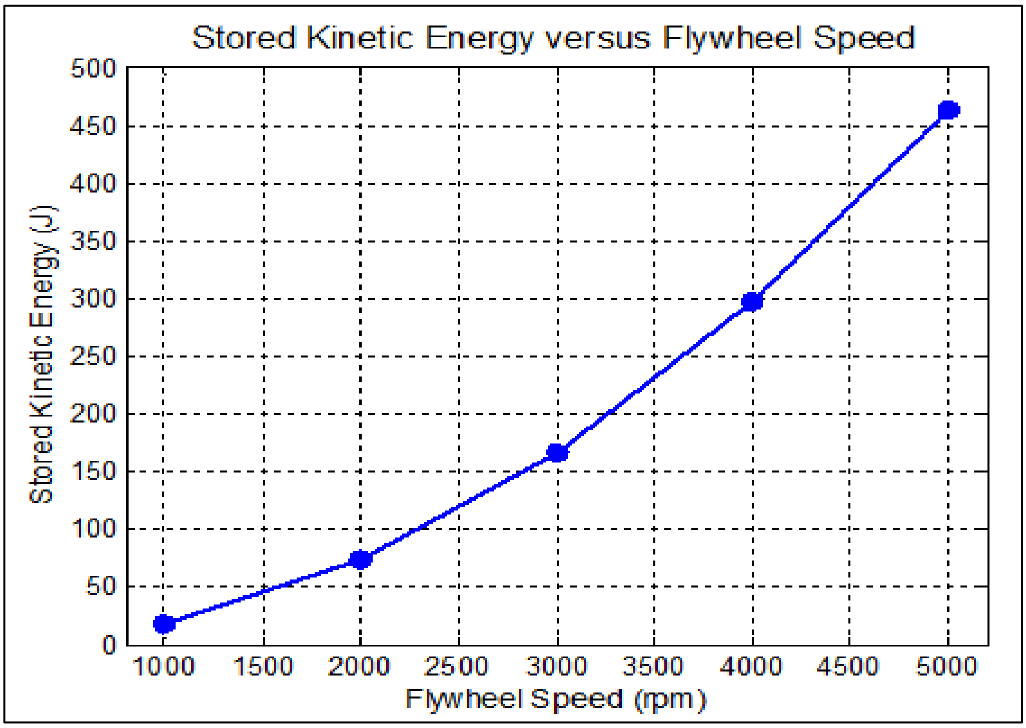

Fig 5 Stored Kinetic Energy Versus Flywheel Speed.

➢ *Charging and Discharging Characteristics*

Charging performance was assessed by measuring the time required for the flywheel to reach the target speed, while discharge tests monitored the controlled reduction in speed and corresponding electrical power recovery. The obtained data is presented in Table 4.

Table 4 Charging and Discharging Performance

Speed (rpm)	Charging Time (s)	Discharge Time (s)	Estimated Efficiency (%)
1000	4.3	5.1	81.2
2000	8.4	9.5	83.5
3000	12.5	13.9	85.4
4000	17.6	18.8	86.7
5000	22.4	24.1	87.9

As shown in Figure 6, the charging and discharging cycles exhibited consistent operation throughout repeated tests. Minor efficiency losses were attributed to bearing friction, motor losses, and power electronic conversion losses. Nevertheless, the prototype demonstrated repeatable energy storage and recovery characteristics suitable for laboratory validation.

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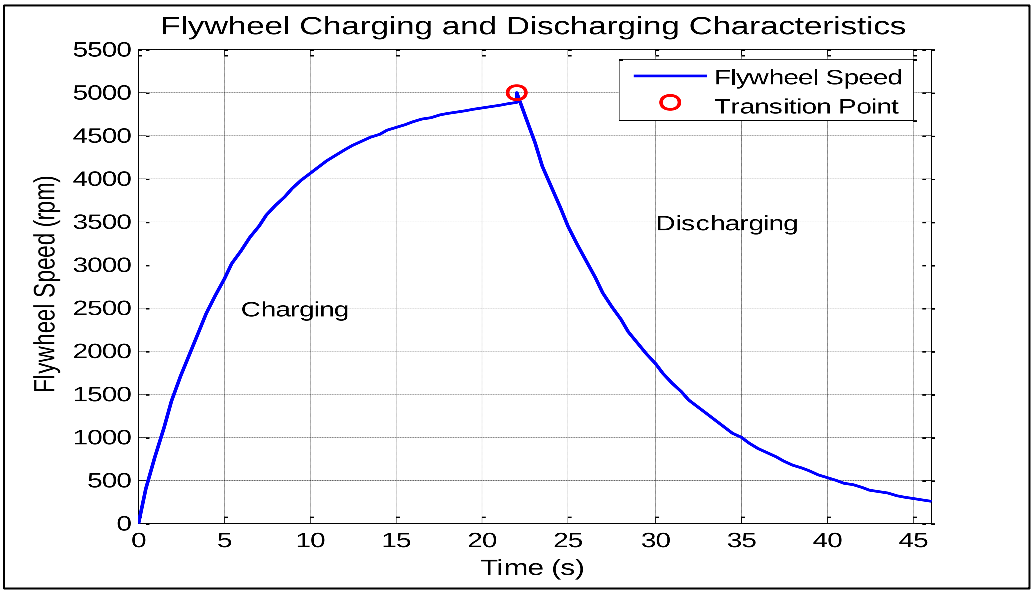

Fig 6 Flywheel Charging and Discharging Characteristics.

➢ *Attitude Control Response*

To evaluate the attitude control capability, step changes in flywheel speed were introduced to generate reaction torque. The IMU recorded the corresponding angular response of the test platform as shown in Table 5.

Table 5 Attitude Control Performance

Speed Change (rpm)	Peak Angular Displacement (°)	Rise Time (s)	Settling Time (s)
500	2.1	0.52	1.4
1000	4.5	0.63	1.8
1500	6.9	0.74	2.2
2000	9.3	0.88	2.7

The obtained results confirmed that controlled changes in flywheel speed produced measurable reaction torque capable of inducing predictable angular motion. The observed response validates the suitability of the developed platform for studying spacecraft attitude control algorithms under laboratory conditions.

The experimental results demonstrate that the developed FESACT successfully integrates flywheel energy storage and reaction-wheel-based attitude control into a single laboratory platform. Stable speed regulation with steady-state errors below 1% enabled consistent energy storage and recovery across the tested operating range. Furthermore, the measured angular responses verified the capability of the flywheel to generate controllable reaction torque suitable for attitude maneuver emulation.

Compared with conventional laboratory reaction-wheel platforms, the proposed system offers the additional capability of evaluating electrical energy storage and power management within the same experimental framework. This integration enables simultaneous investigation of electromechanical interactions that are not captured by standalone reaction-wheel testbeds.

Although the prototype effectively demonstrates the feasibility of integrated flywheel operation, several practical limitations remain. The current implementation employs mechanical bearings, which introduce frictional losses and limit maximum rotational speed. In addition, the experiments were performed under atmospheric conditions rather than in a vacuum environment, resulting in aerodynamic drag that reduces overall energy efficiency. These limitations are acceptable for laboratory-scale validation but should be addressed in future implementations through the use of magnetic bearings, vacuum enclosures, and higher-speed composite flywheels.

Overall, the developed testbed provides a reliable, modular, and cost-effective platform for experimental investigation of integrated flywheel technologies, offering a practical foundation for future research on advanced control algorithms, energy management strategies, and hardware development for small satellite applications.

V. CONCLUSION

This paper presented the development and experimental validation of a laboratory-scale Flywheel Energy Storage and Attitude Control Testbed (FESACT) for small satellite applications. The developed platform successfully integrates flywheel energy storage, embedded control, inertial sensing, and real-time monitoring into a compact and modular experimental system. Experimental results demonstrated stable flywheel speed regulation, efficient charging and discharging operation, and reliable

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reaction torque generation for simulated spacecraft attitude maneuvers. The proposed testbed provides a practical and cost-effective platform for investigating integrated spacecraft power and attitude control technologies, bridging the gap between theoretical studies and laboratory implementation. Owing to its modular design, the platform can be readily extended to evaluate advanced control algorithms, higher-performance flywheel systems, and hardware-in-the-loop experiments, making it a valuable research and educational tool for future CubeSat and nanosatellite development.

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