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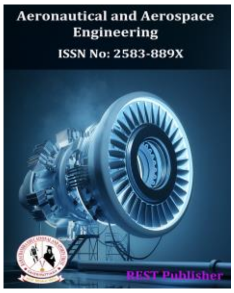

Cube sat: A Modular Cube sat for Low-Earth Orbit Experiments

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Abstract: *This paper presents the design and development of a modular Cube Sat platform for educational and research applications in low-Earth orbit. The proposed 1U Cube Sat (10cm × 10cm × 10cm) incorporates innovative design features enhancing modularity, power efficiency, and payload adaptability while maintaining standard deployment compatibility. Our methodology encompasses comprehensive structural design, subsystem integration, and prototype development validated through finite element analysis, thermal simulations, and functional testing. Results demonstrate successful integration of command and data handling (C&DH), power distribution, and payload interface systems with a final prototype mass of 1.12 kg, leaving sufficient margin for educational payloads. The platform supports various applications including Earth observation, atmospheric measurements, and technology demonstrations, making space- based experimentation accessible to educational institutions. This research contributes to democratizing space access for academic purposes while addressing key challenges in small satellite development.*

Keywords: *Cube Sat, Satellite Prototype, Space Systems, Subsystem Integration, Educational Model, Satellite Structure, Low-Earth Orbit, Systems Design.*

1. INTRODUCTION

Cube Sats have revolutionized access to space by providing a standardized, low-cost platform for orbital experiments and technology demonstration. These miniaturized satellites follow a modular design based on cubic units (U), where 1U represents a 10cm × 10cm × 10cm cube typically weighing up to 1.33 kg9. Originally developed to facilitate academic participation in space activities, Cube Sats have evolved into valuable platforms for scientific research, Earth observation, and commercial applications6. The primary advantage of Cube Sats lies in their standardized structure, which ensures compatibility with deployment systems across significantly reduces development time and costs, enabling universities, research institutions, and emerging space companies to participate in space missions that were traditionally dominated by large space agencies7. Despite their compact size, modern Cube Sats can perform sophisticated functions ranging from communication and remote sensing to interplanetary exploration8. The development of Cube Sats aims to make space more accessible to universities, research institutions, and emerging space industries. Their relatively simple design and reduced development time make them ideal for rapid technology testing, student training, and carrying out small-scale scientific missions. Despite their compact size, Cube Sats are capable of performing various functions such as Earth observation, communication, remote sensing, and space environment monitoring10. One of the main attractions of Cube Sat development is its cost-effectiveness. The standardized structure, compatibility with multiple launch vehicles, and the ability to be launched as secondary payloads significantly lower launch and development expenses. This opens up opportunities for small organizations, startups, and developing countries to participate in space activities, which were previously limited to large space agencies due to high costs4. This paper presents the design, development, and testing of a modular 1U Cube Sat platform specifically tailored for educational experiments in low-Earth orbit (LEO). Our approach emphasizes modularity, allowing for easy reconfiguration to accommodate various experimental payloads while addressing the fundamental challenges of power management, thermal control, and miniaturization inherent to small satellite development.

Problem Statement

The primary challenge in Cube Sat development lies in balancing size, weight, power, and functionality while ensuring reliability in the harsh space environment. Due to their small form factor, Cube Sats have limited space for payloads, power systems, and communication hardware, making it difficult to integrate high- performance instruments10. Thermal management, radiation protection, and power efficiency are critical issues, as Cube Sats often rely on small solar panels and batteries for energy.

Educational Cube Sat missions face additional challenges related to:

1. Budget constraints: Educational institutions often operate under limited funding, necessitating cost-effective design solutions and reliance on commercial off-the-shelf (COTS) components.
2. Technical expertise: Student teams may have varying levels of expertise, requiring simplified subsystem designs and clear documentation.
3. Development timeline: Academic projects must align with educational calendars, limiting development cycles.
4. Launch opportunities: Educational Cube Sats typically rely on rideshare opportunities, resulting in limited control over deployment parameters and orbit selection.

Limited propulsion options make it challenging to control Cube Sat orbits, leading to shorter mission lifespans and potential space debris concerns. Another significant challenge is the dependency on rideshare launches, where Cube Sats are secondary payloads, restricting their deployment schedule and orbit selection8.

Despite these challenges, Cube Sat technology has rapidly evolved, with advancements in miniaturized electronics, AI-driven automation, and propulsion systems improving mission capabilities. New materials and thermal control techniques enhance durability, while deployable solar panels and efficient batteries extend operational life5.

Our research addresses these challenges by developing a modular Cube Sat platform that:

1. Maximizes payload volume through efficient subsystem integration
2. Incorporates sustainable power management strategies
3. Employs passive thermal control techniques
4. Simplifies assembly and integration procedures
5. Provides standardized interfaces for educational payloads

2. METHODOLOGY

A. Design Approach and Workflow

The development process followed a systematic workflow encompassing conceptual design, detailed engineering, manufacturing, assembly, and testing phases. A modular approach was adopted to facilitate interchangeability of subsystems and enable adaptation to various educational missions. [INSERT FIGURE 1: Project workflow diagram showing the sequential development phases from conceptual design through testing. Include design review gates between major phases.] The design emphasized accessibility for educational purposes while maintaining compliance with Cube Sat Design Specifications (CDS) to ensure compatibility with standard deployment mechanisms. Computer-aided design (CAD) tools were utilized to create detailed 3D models, enabling virtual integration and spatial optimization before physical prototyping.

B. Materials Selection

Material selection balanced structural requirements, thermal properties, radiation resistance, weight limitations, and manufacturing considerations. For the primary structure, aluminum 6061-T6 was selected due to its favorable strength-to-weight ratio, thermal conductivity, machinability, and flight heritage7. For non-structural components and prototyping, advanced polymers including PLA, ABS, ASA, and PEEK were evaluated based on their mechanical properties and thermal stability.

C. Structural Design

The Cube Sat structure consists of a modular frame with integrated mounting features for subsystems and payloads. The design incorporates:

1. External dimensions of 100 × 100 × 100 mm in accordance with Cube Sat specifications
2. Deployment rails with appropriate materials and tolerances for compatibility with standard deplorers
3. Removable panels for access during integration and testing
4. Internal mounting structure with standardized grid pattern for modular component attachment
5. Separation springs for deployment from P-POD or equivalent deployment mechanisms

D. Subsystem Development

1) Power System

The power system features:

- Body-mounted solar panels on multiple faces to ensure power generation regardless of orientation
- Maximum power point tracking (MPPT) for optimized energy harvest
- Lithium-ion battery storage with capacity sized for eclipse operations

- Power distribution unit with voltage regulation and protection circuitry
- Low-power modes for extended mission duration

2) Command and Data Handling (C&DH) The C&DH system employs:
A microcontroller-based architecture with real-time operating system (RTOS)

- Flash memory for program and data storage
- Watchdog functionality for system reliability
- I2C, SPI, and UART interfaces for subsystem integration
- Customizable software framework for educational payload control

3) Payload Interface
The standardized payload interface provides:

- Mechanical mounting provisions with standardized fastener patterns
- Data interfaces compatible with common sensors and instruments
- Thermal interfaces for heat management

E. Analysis Methods
Multiple analysis techniques were employed to validate the design:

1) Finite Element Analysis (FEA)
Structural analysis using FEA was performed to verify the integrity of the Cube Sat structure under expected mechanical loads during launch and deployment. The analysis evaluated:

- Stress distribution under static acceleration loads
- Modal frequencies to avoid resonance with launch vehicle frequencies
- Random vibration response to launch environments
- Structural margins against material yield and ultimate strengths

2) Thermal Analysis
Thermal modelling was conducted to predict temperature profiles during orbital operations, considering:

- Solar illumination in various orbital attitudes
- Earth albedo and infrared radiation
- Internal heat generationfrom electronics
- Radiative and conductive heat transfer mechanisms

3) Power Budget Analysis
A comprehensive power budget was developed to ensure mission viability, accounting for:

- Solar power generation in various orbital scenarios
- Power consumption of all subsystems in different operational modes
- Battery charging and discharging cycles
- Depth of discharge limitations for battery longevity

F. Prototype Development and Testing
The prototype development process involved:

1. Fabrication of structural components using precision machining and 3D printing
2. Electronic circuit board design and assembly
3. Software development and integration
4. Subsystem testing followed by integrated system testing

Testing procedures included:

1. Functional verification of all electronic subsystems
2. Power generationand distribution testing
3. Communication system validation
4. Software validation through simulated mission scenarios
5. Physical fit checks with deployment system simulators

3. RESULTS AND DISCUSSION

A. Structural Performance

Finite element analysis confirmed the structural integrity of the Cube Sat design under anticipated launch conditions. The analysis revealed a minimum safety factor of 2.3 against yield strength under maximum expected acceleration loads of 8.5g. Modal analysis identified the lowest natural frequency at 127 Hz, which is above the critical frequency range specified by most launch vehicle providers. [INSERT TABLE I: Structural Analysis Results
Columns: Load Case, Maximum Stress (MPa), Yield Strength (Mpa), Safety Factor Include rows for various load cases including static acceleration, random vibration, and shock]

B. Thermal Performance

Thermal analysis demonstrated that all components remain within their operational temperature ranges throughout the simulated orbit. The passive thermal design, utilizing selective surface finishes and thermal coupling, maintained electronics between -10°C and +40°C during worst-case hot and cold scenarios. [INSERT FIGURE 6: Graph showing temperature profiles of key components over a simulated orbit period, indicating maximum and minimum temperatures.]

C. Power System Performance

The power system demonstrated reliable performance during testing, with solar panels generating an average of 2.2W during illuminated periods. The power distribution system maintained regulation within ±3% of nominal voltages under various load conditions, and the battery provided sufficient capacity for eclipse operations with a maximum depth of discharge of 20%. [INSERT TABLE II: Power System Performance Columns: Parameter, Design Value, Measured Value, Margin Include rows for solar power generation, battery capacity, voltage regulation, etc.]

D. Command and Data Handling

The C&DH system successfully executed all command sequences during testing and demonstrated reliable data management capabilities. The system handled data rates up to 1 Mbps without errors and maintained timing accuracy within 10ms over extended operation. The software architecture provided flexibility for educational payload control while ensuring core satellite functions.

E. Mass Budget

The final mass of the integrated Cube Sat prototype was 1.12 kg, providing a margin of 0.21 kg for additional payload mass within the 1.33 kg limit specified by the Cube Sat standard. The mass distribution among subsystems is shown in Figure 7. [INSERT FIGURE 7: Pie chart showing mass distribution among different subsystems including structure, power, C&DH, and available payload allocation.]

F. Educational Applications

The modular Cube Sat platform supports various educational applications, including:

1. Earth observation using miniature cameras and sensors
2. Atmospheric studiesusing simple spectrometers or particle detectors
3. Communication technology demonstrations
4. Microgravity experiments
5. Technology validation for student- developed components

The standardized interfaces and documentation enable students to focus on payload development without requiring expertise in all satellite subsystems, making space research more accessible in educational contexts

4. CONCLUSION

This paper presented the design and development of a modular Cube Sat platform optimized for educational applications in low- Earth orbit. The research successfully addressed key challenges in educational Cube Sat development through innovative approaches to structural design, power management, thermal control, and subsystem integration. The platform demonstrates the feasibility of developing cost-effective, reliable Cube Sats for educational purposes while maintaining compliance with industry standards for space systems. The modular architecture enables adaptation to various mission objectives without redesigning core subsystems, reducing development time and resources for educational institutions.

Key achievements include:

1. A validated structural design with sufficient margins for launch and orbital environments
2. An efficient power system capable of supporting various educational payloads
3. A flexible command and data handling architecture adaptable to different mission requirements
4. A thermal design that maintains all components within operational temperature ranges

5. A mass-efficient integration approach that maximizes available payload capacity

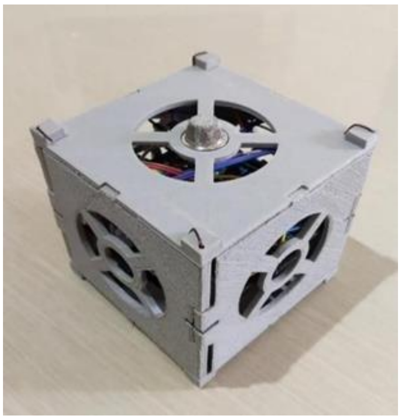

FIGURE. 1

Future work will focus on environmental testing under vacuum conditions, radiation tolerance evaluation, and development of standardized educational payload modules that can be integrated with the platform. Additionally, flight software will be further developed to incorporate autonomous operations and fault detection capabilities. This research contributes to democratizing access to space for educational institutions and provides a foundation for hands-on learning in spacecraft engineering. By lowering the barriers to Cube Sat development, this platform enables more students to gain practical experience in space systems engineering, inspiring the next generation of space professionals.

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