CubeSat Systems and Fundamental Orbital Mechanics

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Internship Project Report – Phase 01

Abstract

This report presents a foundational study of CubeSat systems with a specific focus on the 1U CubeSat configuration and the basic principles of orbital mechanics governing its operation. CubeSats have emerged as a revolutionary platform in space technology, enabling cost-effective and rapid development of small satellites for research, communication, and Earth observation applications.

The report begins with an introduction to CubeSat technology, followed by its evolution from academic projects to globally recognized space missions. The structural design and modular architecture of a 1U CubeSat are discussed to provide insight into its compact and standardized form.

Further, the core subsystems of a CubeSat are explained, including the Electrical Power System (EPS), On-Board Computer (OBC), and Communication System. These subsystems are essential for satellite functionality, ensuring power management, data processing, and communication with ground stations.

The second part of the report focuses on fundamental orbital mechanics, which determines how CubeSats operate in space. Concepts such as Low Earth Orbit (LEO), orbital motion, Kepler's laws, orbital parameters, orbital velocity, and Sun-synchronous orbits are explained in a simplified and intuitive manner.

Finally, the report highlights the applications, advantages, and limitations of CubeSats, emphasizing their role in modern space missions. The objective of this report is to build a clear and structured understanding of CubeSat systems and the essential physics behind their operation in space.

> **Key Objective**
>
> The primary goal of this report is to develop a clear conceptual understanding of CubeSat systems and the basic orbital mechanics that govern their operation, rather than focusing on overly complex mathematical formulations.

Contents

1 Introduction to CubeSat

CubeSats are a class of nanosatellites that follow a standardized design approach, making them compact, cost-effective, and easier to develop compared to traditional satellites. The concept of CubeSats was introduced to simplify access to space for educational institutions and small-scale research organizations.

A standard CubeSat unit, referred to as "1U," has dimensions of 10 cm $\times$ 10 cm $\times$ 10 cm and typically weighs less than 1.33 kg. Multiple units can be combined (such as 2U, 3U, or 6U) to increase functionality while maintaining the same modular design philosophy.

The primary advantage of CubeSats lies in their simplicity and standardization. By using predefined dimensions and interfaces, developers can focus more on payload design and mission objectives rather than structural complexities. This has significantly reduced development time and cost, enabling rapid prototyping and deployment.

CubeSats are widely used in various applications such as Earth observation, communication, scientific research, and technology demonstration. They are often launched as secondary payloads alongside larger satellites, making them an economical option for space missions.
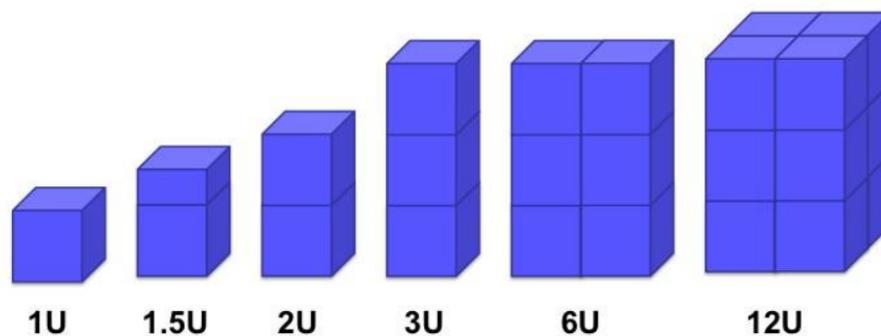

Figure 1: Basic Structure and Modular Design of a CubeSat

> **Key Concept**
>
> A CubeSat is not just a small satellite—it is a standardized platform that enables faster development, lower cost, and increased accessibility to space missions.

The growing popularity of CubeSats has transformed the space industry by allowing universities, startups, and even small organizations to participate in space exploration.

2 Evolution of CubeSat

The CubeSat concept was developed in 1999 by Professor Jordi Puig-Suari and Professor Bob Twiggs with the aim of providing a practical platform for students to design, build, and launch satellites. Initially, CubeSats were primarily used for educational purposes, allowing students to gain hands-on experience in satellite development.

The first successful launch of CubeSats took place in 2003, marking the beginning of a new era in small satellite technology. Over time, advancements in electronics, miniaturization, and communication systems enabled CubeSats to perform increasingly complex tasks.

In the early stages, CubeSats were limited in capability due to constraints in power, processing, and communication. However, with the development of efficient solar panels, compact onboard computers, and reliable communication modules, modern CubeSats can now support advanced missions including Earth imaging, climate monitoring, and inter-satellite communication.
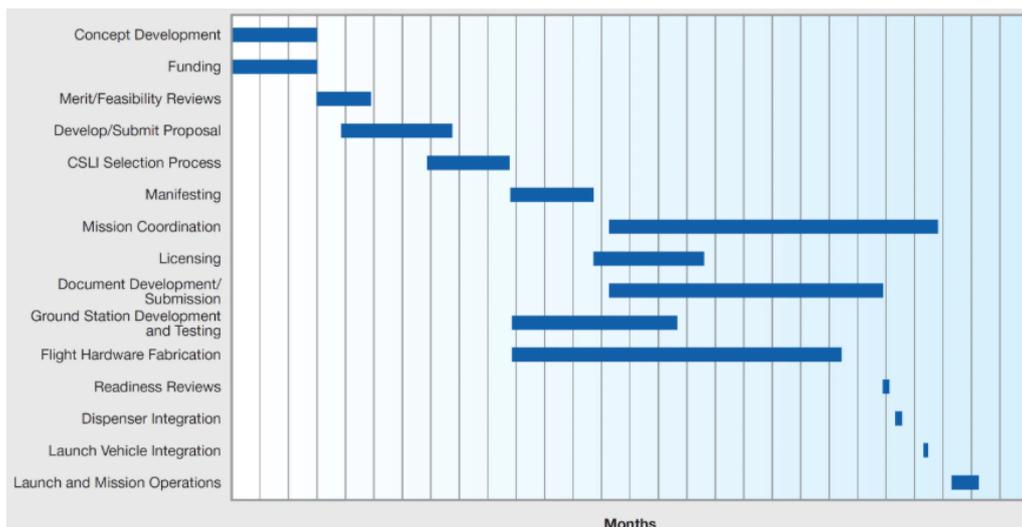

Figure 2: An example timeline of a CubeSat project.Source: NASA

> **Important Insight**
>
> CubeSats have evolved from simple student projects into powerful tools used by space agencies, research institutions, and private companies for real-world missions.

Today, CubeSats are being deployed by major space organizations and companies for a wide range of applications. Their role in space missions continues to expand due to their flexibility, scalability, and cost-effectiveness. They are also being considered for deep-space missions, which highlights their growing importance in the future of space exploration.

The evolution of CubeSats reflects a broader trend in space technology toward miniaturization and increased accessibility, making space research more inclusive and innovation-driven.

3   What is a 1U CubeSat

A 1U CubeSat is the most basic and fundamental unit of the CubeSat standard. The term "1U" refers to a single unit with fixed dimensions of 10 cm × 10 cm × 10 cm and a mass typically not exceeding 1.33 kg. This compact size makes it suitable for low-cost missions and educational purposes.

The 1U CubeSat serves as a building block for larger CubeSat configurations such as 2U, 3U, and 6U, where multiple units are combined to increase payload capacity and functionality. Despite its small size, a 1U CubeSat is capable of performing essential satellite operations such as data collection, communication, and basic onboard processing.

One of the key advantages of the 1U CubeSat is its compatibility with standardized deployment systems. This ensures that it can be safely launched into space along with other satellites without requiring custom integration.
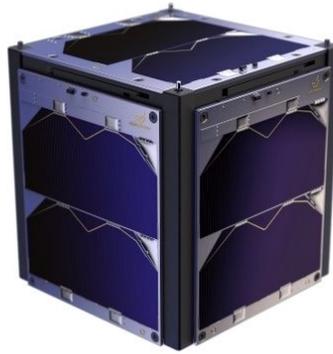

Figure 3: Typical 1U CubeSat

> **Key Point**
>
> A 1U CubeSat is the smallest standard satellite unit that combines simplicity, modularity, and functionality, making it ideal for learning and initial space missions.

Due to its limited volume, careful design and efficient utilization of space are essential in a 1U CubeSat. Engineers must optimize the placement of components to ensure proper functioning of all subsystems within the confined structure.

4   Structure of CubeSat

The structure of a CubeSat is designed to be compact, modular, and robust enough to withstand the harsh conditions of launch and space environments. It typically consists of an aluminum frame that provides mechanical support and maintains the standardized dimensions.

The internal structure is organized in layers or stacks, where different subsystems such as power, communication, and processing units are arranged efficiently. Each subsystem is usually mounted on printed circuit boards (PCBs) that are stacked within the frame.

Externally, the CubeSat is equipped with solar panels mounted on its surfaces to generate electrical power. Some designs may include deployable solar panels to increase power generation capacity. Antennas are also integrated or deployed after launch to enable communication with ground stations.
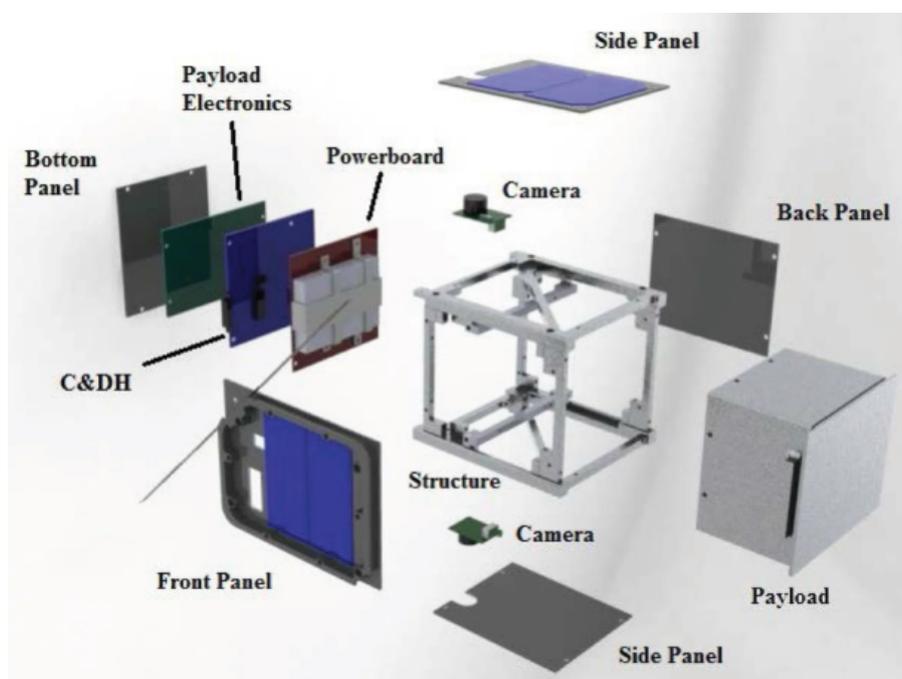

Figure 4: The basic modules that comprise a typical CubeSat. Source: NASA

> **Design Insight**
>
> The structural design of a CubeSat is not just about holding components—it ensures efficient space utilization, mechanical stability during launch, and proper functioning of all onboard systems.

The structure must also comply with CubeSat design specifications to ensure compatibility with deployment systems. This includes constraints on dimensions, mass, and external features such as rails and surface finishes.

Proper thermal management is another important aspect of CubeSat structure design. Since space has extreme temperature variations, the structure helps in dissipating heat and protecting sensitive components.

Overall, the CubeSat structure plays a crucial role in integrating all subsystems into a compact and functional unit capable of operating reliably in space.

5 CubeSat Subsystems

A CubeSat is composed of several essential subsystems that work together to ensure proper functionality in space. Each subsystem performs a specific role, and their integration determines the overall performance of the satellite.

The three primary subsystems considered in this report are:

- Electrical Power System (EPS)

- On-Board Computer (OBC)

- Communication System

5.1 Electrical Power System (EPS)

The Electrical Power System (EPS) is responsible for generating, storing, and distributing electrical energy to all other subsystems of the CubeSat. Without a reliable power system, the satellite cannot function.

In a typical 1U CubeSat, electrical power is generated using solar panels mounted on the outer surfaces. These panels convert solar energy into electrical energy when exposed to sunlight. Since the satellite experiences periods of darkness while orbiting the Earth, rechargeable batteries are used to store energy for continuous operation.

The EPS also includes power regulation circuits that ensure a stable voltage supply to sensitive components. It distributes power efficiently to different subsystems based on their requirements.
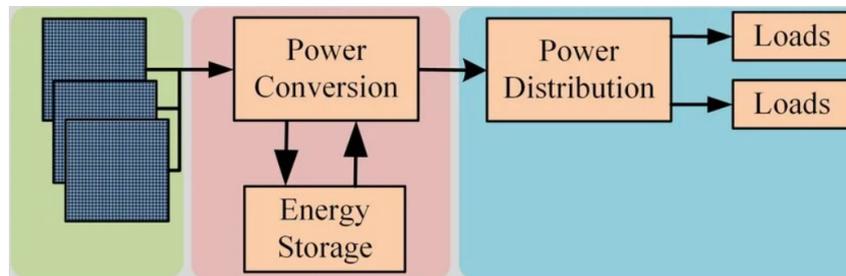

Figure 5: Basic Architecture of CubeSat Electrical Power System

> **Key Function**
>
> The EPS ensures uninterrupted operation of the CubeSat by managing power generation, storage, and regulated distribution across all subsystems.

Efficient power management is critical in CubeSats due to their limited surface area and battery capacity. Engineers must carefully balance power consumption and generation to avoid system failure.

5.2 On-Board Computer (OBC)

The On-Board Computer (OBC) acts as the central processing unit of the CubeSat. It controls and coordinates the operation of all subsystems, making it one of the most critical components.

The OBC is responsible for executing commands, processing sensor data, managing memory, and handling communication tasks. It operates based on pre-programmed instructions and can also receive commands from ground stations.

In addition, the OBC performs fault detection and recovery operations. If any subsystem malfunctions, the OBC can attempt corrective actions to restore normal operation.

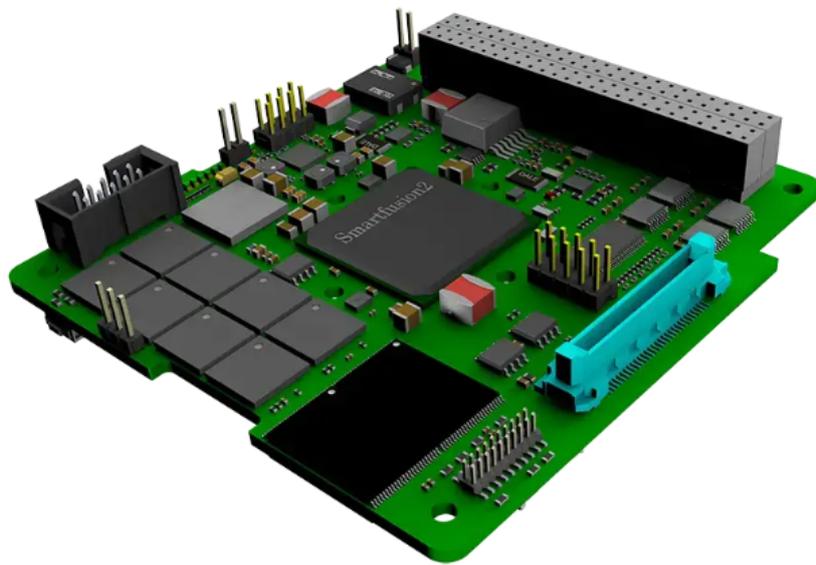Figure 6: On-Board Computer in CubeSat

> **Key Function**
>
> The OBC acts as the brain of the CubeSat, controlling all operations and ensuring coordination between different subsystems.

Due to limited computational resources, CubeSat OBCs are designed to be efficient and reliable rather than highly powerful. They must also withstand radiation effects in space, which can impact electronic performance.

5.3   Communication System

The Communication System enables data exchange between the CubeSat and ground stations on Earth. It is essential for transmitting collected data and receiving commands.

This subsystem typically includes transmitters, receivers, antennas, and modulation circuits. Communication is usually carried out using radio frequency (RF) signals in specific frequency bands such as UHF, VHF, or S-band.

The communication system operates in two modes:

- Uplink: Receiving commands from the ground station

- Downlink: Sending data from the CubeSat to Earth

> **Key Function**
>
> The communication system acts as the link between the CubeSat and Earth, enabling control, monitoring, and data transmission.

One of the challenges in CubeSat communication is maintaining a reliable link despite limited power and small antenna size. Efficient design and proper frequency selection are essential to ensure successful communication.

6 CubeSat Deployment Mechanism

CubeSats are typically launched as secondary payloads along with larger satellites. To ensure safe and standardized deployment into space, special deployment systems are used.

One of the most commonly used deployment mechanisms is the Poly-Picosatellite Orbital Deployer (P-POD). This device acts as a container that holds CubeSats securely during launch and releases them into orbit once the launch vehicle reaches the desired altitude.

The deployment process is carefully controlled using spring-based mechanisms that push the CubeSat out of the deployer at a specific velocity. This ensures that the satellite is safely separated from the launch vehicle and other payloads.
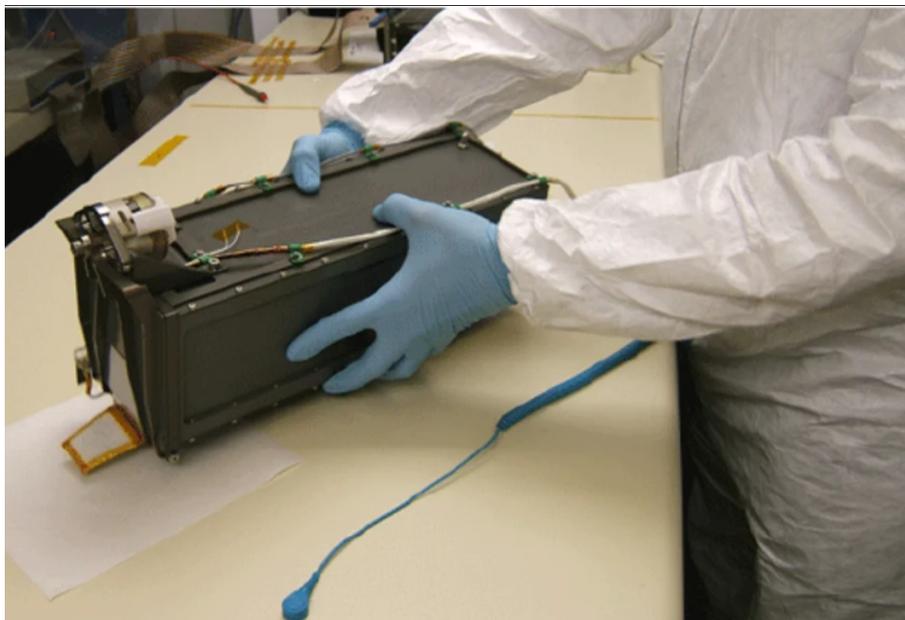

Figure 7: CubeSat Deployment Using P-POD

> **Key Point**
>
> Deployment systems ensure that CubeSats are released safely into orbit without collision or damage, following standardized procedures.

After deployment, the CubeSat begins its independent operation, including activation of subsystems, stabilization, and communication with ground stations.

7 Fundamentals of Orbital Mechanics

Orbital mechanics is the study of the motion of objects in space under the influence of gravitational forces. It explains how CubeSats move around the Earth and maintain their orbit.

Understanding these basic principles is essential for designing and operating any satellite mission.

7.1 Low Earth Orbit (LEO)

Low Earth Orbit (LEO) is the region of space located approximately 160 km to 2000 km above the Earth's surface. Most CubeSats operate in LEO due to its proximity to Earth and lower launch cost.

In LEO, satellites experience reduced communication delay and require less energy for launch compared to higher orbits.

> **Key Insight**
>
> LEO is the most preferred orbit for CubeSats because it provides a balance between performance, cost, and mission efficiency.

7.2 Orbital Motion

A satellite remains in orbit due to the balance between gravitational force and its forward velocity. Gravity pulls the satellite toward the Earth, while its velocity keeps it moving forward, resulting in a curved path around the Earth.

This continuous free-fall motion creates a stable orbit.

7.3 Kepler's Laws of Planetary Motion

Kepler's laws describe the motion of objects in orbit:

- First Law: Satellites move in elliptical orbits with Earth at one focus.

- Second Law: A line joining the satellite and Earth sweeps equal areas in equal times.

- Third Law: The square of the orbital period is proportional to the cube of the orbit's radius.

> **Simplified Understanding**
>
> Kepler's laws help predict how a CubeSat moves in space without requiring complex calculations.

7.4 Orbital Parameters

Orbital parameters define the shape and position of an orbit. Important parameters include:

- Altitude: Height of the satellite above Earth

- Inclination: Angle of orbit relative to Earth's equator

- Eccentricity: Shape of the orbit (circular or elliptical)

- Orbital period: Time taken to complete one orbit

7.5 Orbital Velocity

Orbital velocity is the speed required for a satellite to remain in orbit. In LEO, this is typically around 7.8 km/s.

> **Key Point**
>
> If the velocity is too low, the satellite will fall back to Earth. If it is too high, it may escape Earth's gravitational field.

7.6 Sun-Synchronous Orbit

A Sun-synchronous orbit is a special type of orbit where the satellite passes over the same part of Earth at the same local solar time each day. This is useful for Earth observation missions.

CubeSats in Sun-synchronous orbit can capture images under consistent lighting conditions, which improves data accuracy.
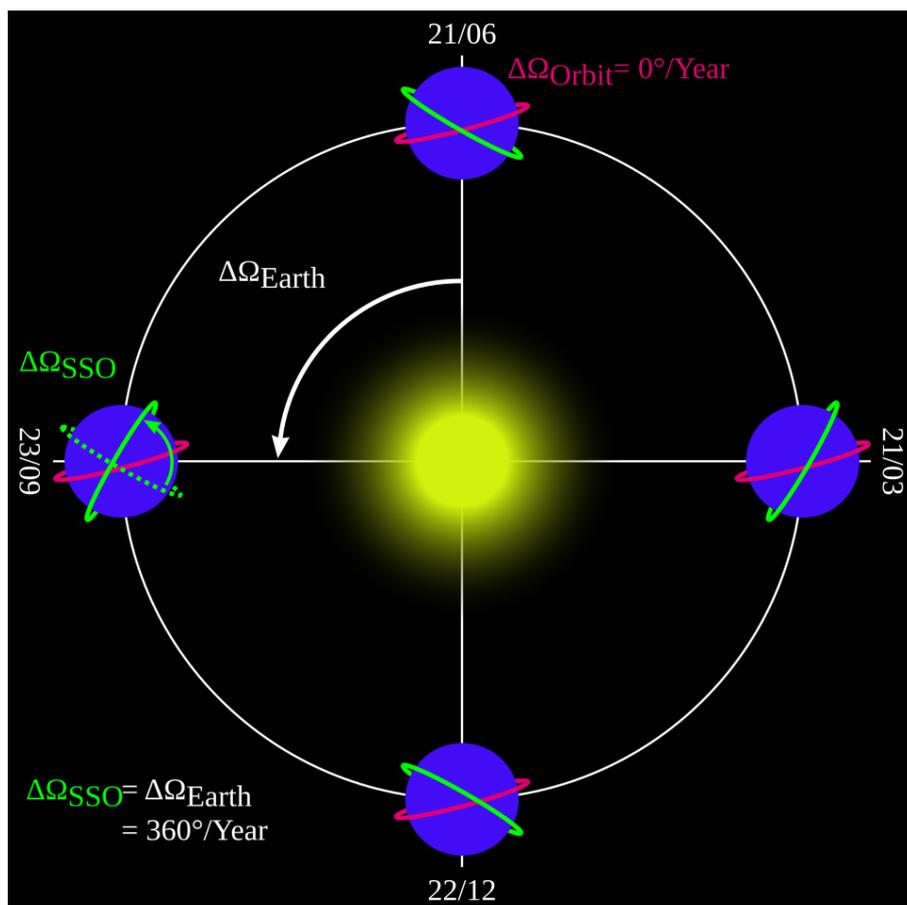
Figure 8: Illustration of Sun-Synchronous Orbit

8 Applications of CubeSats

CubeSats have become an important part of modern space missions due to their versatility and cost-effectiveness. Despite their small size, they are capable of supporting a wide range of applications across different domains.

One of the primary applications of CubeSats is Earth observation. They are used to monitor environmental changes, track weather patterns, and study natural disasters such as floods and wildfires. Their ability to provide frequent data updates makes them highly valuable for real-time monitoring.

CubeSats are also widely used in communication systems. They can act as relay satellites, enabling data transmission between remote locations. This is particularly useful in areas where traditional communication infrastructure is limited.

In the field of scientific research, CubeSats are used to conduct experiments in microgravity and space environments. They provide a platform for testing new technologies and collecting data that would otherwise require expensive missions.

Educational institutions use CubeSats as a hands-on learning tool for students. By designing and building CubeSats, students gain practical experience in satellite systems, electronics, and space science.

> **Key Insight**
>
> CubeSats enable low-cost access to space, making them suitable for research, communication, education, and technology demonstration missions.

The flexibility and scalability of CubeSats allow them to be used in both individual missions and large constellations, expanding their range of applications significantly.

9 Advantages and Limitations of CubeSats

9.1 Advantages

CubeSats offer several advantages that make them attractive for modern space missions:

- **Low Cost:** CubeSats are significantly cheaper to design, build, and launch compared to traditional satellites.

- **Short Development Time:** Standardized design allows faster development and testing.

- **Compact Size:** Small dimensions make them easier to handle and integrate into launch systems.

- **Ease of Deployment:** Compatibility with standardized deployers simplifies launch procedures.

- **Educational Value:** Ideal for academic and research purposes.

> **Key Advantage**
>
> CubeSats reduce the barrier to entry for space missions, enabling innovation and participation from smaller organizations.

9.2 Limitations

Despite their advantages, CubeSats also face certain limitations:

- **Limited Power:** Small surface area restricts solar power generation.

- **Restricted Payload Capacity:** Limited space reduces the complexity of onboard instruments.

- **Short Lifespan:** Typically operate for a shorter duration compared to larger satellites.

- **Communication Constraints:** Limited antenna size affects signal strength and data rate.

> **Key Limitation**
>
> The small size of CubeSats, while beneficial, also imposes constraints on power, payload, and overall mission capability.

Understanding these advantages and limitations is essential for designing effective CubeSat missions.

10   Conclusion

This report provided a structured overview of CubeSat systems with a focus on the 1U CubeSat and the fundamental principles of orbital mechanics. The study began with an introduction to CubeSats and their evolution, highlighting their transition from educational tools to essential components of modern space missions.

The structural design and key subsystems, including the Electrical Power System (EPS), On-Board Computer (OBC), and Communication System, were discussed to explain how a CubeSat operates as an integrated system. Each subsystem plays a crucial role in ensuring the functionality and reliability of the satellite.

The report also covered the basics of orbital mechanics, including Low Earth Orbit (LEO), orbital motion, Kepler's laws, and orbital parameters. These concepts provide the foundation for understanding how CubeSats are placed and maintained in orbit.

Finally, the applications, advantages, and limitations of CubeSats were examined to present a balanced view of their capabilities. While CubeSats offer numerous benefits such as low cost and ease of development, they also face challenges related to power, payload, and lifespan.

Overall, CubeSats represent a significant advancement in space technology by making space exploration more accessible and innovation-driven. This foundational understanding will support further study and development of more advanced CubeSat systems in future phases of the project.

> **Final Remark**
>
> A strong understanding of CubeSat systems and orbital mechanics forms the basis for designing efficient and successful satellite missions.