# *Design and Implementation of a 3U CubeSat for Advanced Earth Observation and AI-Driven Analysis*

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## ABSTRACT

*Abstract— This paper presents the design and development of a 3U CubeSat specifically engineered for Earth observation applications. The CubeSat is equipped with imaging capabilities that facilitate the capture and transmission of high-resolution images to a ground station for AI-driven analysis. Leveraging cutting-edge technologies in data processing and wireless communication, this CubeSat offers a cost-effective and easily manufactural alternative to traditional large satellites. The design features an integrated system comprising subsystems for power, communication, control, and payload management. By capturing multi-temporal images, the satellite enables onboard AI-based change detection. Its compact design and modular architecture facilitate low-cost deployment in space. This mission underscores the potential of CubeSat in enhancing environmental monitoring and disaster management through advanced technological integration.*

Keywords: CubeSat, Earth observation, image processing, AI-based analysis, Change detection, Environmental monitoring.

## I. INTRODUCTION

The advancement of satellite technology has significantly transformed Earth observation capabilities, enabling enhanced monitoring of environmental changes and disaster management. CubeSats, a class of miniaturized satellites, have emerged as a crucial tool in this domain due to their cost-effectiveness, compact size, and rapid deployment capabilities [1]. These small satellites, typically measuring 10x10x30 cm for a 3U configuration, offer a viable alternative to traditional large satellites, making space access more accessible for research and commercial purposes [2].

Satellite subsystems are categorized into two main components: hardware and software. The hardware encompasses the design and manufacturing of the various subsystem boards, while the software facilitates communication between these boards and the ground station. Additionally, a crucial third component—testing—integrates hardware and software to ensure the system functions as intended. The satellite subsystems are structured in five distinct layers. The first layer, power, is responsible for generating, storing, and distributing electrical power throughout the satellite. The second layer focuses on communication, enabling data exchange between the satellite and the ground station. The third layer, the On-Board Computer (OBC), acts as the satellite's central processing unit, controlling and monitoring all subsystems, processing data, executing commands, and coordinating operations among different components. The fourth layer, the Attitude Determination and Control System (ADCS), manages the satellite's orientation in space. Finally, the fifth layer contains the payload, which includes mission-specific instruments or sensors, such as cameras for Earth observation that fulfill the satellite's primary function [3].

Recent developments in artificial intelligence (AI) and machine learning have further augmented the functionality of CubeSats. By integrating AI algorithms for onboard data analysis, CubeSats can perform real-time change detection and data interpretation, significantly reducing the need for extensive ground processing (Kumar et al., 2022). This capability is particularly valuable in applications such as environmental monitoring, where timely data can inform decision-making processes during natural disasters or ecological changes [4].

This paper presents the design and development of a 3U CubeSat specifically tailored for Earth observation. The CubeSat captures multi-temporal images that are transmitted to a ground station for analysis. The integration of advanced subsystems—including power, communication, control, and payload ensures a fully functional platform capable of supporting various observation missions. By demonstrating the efficacy of CubeSats in this context, we aim to highlight their potential role in future environmental monitoring initiatives.

In particular, this research contributes the following points:

1)The comprehensive design framework for a 3U CubeSat tailored for Earth observation is developed.

2)The integration of key subsystems is described, including power, communication, control, and payload, ensuring functionality and efficiency.

3)The onboard AI for real-time change detection and data analysis is applied to enhance the CubeSat's operational capabilities.

4)The cost-effective approach to satellite design is demonstrated, which facilitates rapid deployment and accessibility for various missions.

5)The CubeSat's potential in supporting environmental monitoring and disaster management through advanced technologies is explored.

The rest of the paper is structured as follows: section II provides examples of the related research. Section III introduces the details of the proposed system. Section IV details the Simulation and Hardware Validation and the conclusion is presented in section V.

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## II. RELATED WORK

In recent years, numerous studies have focused on the design, development, and simulation frameworks for CubeSats, each providing significant insights into several aspects of CubeSat missions.

The work in [5], focused on the integration of an Offner imaging hyperspectrometer within a 3U CubeSat for hyperspectral remote sensing applications, specifically targeting Earth observation. The authors present a novel design that employs radially fastened primary elements to enhance the optical performance and stability of the hyperspectrometer while maintaining the compact form factor essential for CubeSat missions. The study demonstrates the successful deployment of the hyperspectrometer in a CubeSat environment, highlighting its capability to capture high-resolution spectral data across various wavelengths. The results indicate that this approach not only improves data quality but also expands the potential for Earth observation applications, including environmental monitoring and resource management. This work contributes to the ongoing efforts to enhance CubeSat functionality through advanced imaging technologies, further establishing the viability of small satellites in complex remote sensing missions.

The authors of [6] introduced the design of a CubeSat imaging payload specifically aimed at monitoring environmental changes in Greenland. The authors detail the development of a compact imaging system capable of capturing high-resolution images to assess glacial dynamics, vegetation changes, and other ecological factors affecting the region. By leveraging advanced imaging technologies, the CubeSat is positioned to provide timely and accurate data essential for understanding the effects of climate change in the Arctic. The study emphasizes the importance of this payload in facilitating continuous observation and data collection, which can aid researchers and policymakers in making informed decisions regarding environmental management. Overall, this work underscores the potential of CubeSat missions to contribute significantly to Earth observation, particularly in remote and challenging environments like Greenland.

The research in [7] presented the critical design aspects of the FACSAT-2 CubeSat mission, which is specifically focused on the observation and analysis of the Colombian territory. The authors detail the design of a 3U CubeSat, emphasizing its compact form factor while incorporating advanced imaging sensors and a robust data processing system. The mission's objectives include monitoring land use, deforestation, and agricultural practices, thereby contributing valuable data for environmental management and policy-making in Colombia. The CubeSat is designed to capture high-resolution images and perform real-time analysis of the collected data. The study highlights the importance of the FACSAT-2 mission in enhancing the country's Earth observation capabilities and fostering sustainable development initiatives. Overall, this work illustrates the potential of 3U CubeSats to serve as effective tools for regional monitoring and assessment, addressing critical environmental challenges in Colombia.

The study in [8] developed a Hardware-in-the-Loop (HIL) simulation framework designed to support the co-testing of software and hardware for CubeSats. The primary objective of the framework is to streamline the software development process by simulating real mission conditions. The authors demonstrate that this framework significantly reduces the dependency on physical hardware, thereby lowering development costs and increasing flexibility during the testing phase.

In [9], the authors introduced a case study on the application of the NOS3 simulation suite during the development and testing of the STF-1 CubeSat. NOS3 enables comprehensive simulation of software and hardware components, facilitating early-stage testing and improving team training efficiency. The findings indicate that NOS3 played a crucial role in the success of the STF-1 mission by reducing reliance on physical flight hardware.

While the previous works contribute significantly to the field of CubeSat technology, they each have limitations that should be addressed. The research in [5] focus solely on hyperspectral remote sensing with an Offner imaging hyperspectrometer, which lacks the integrated AI-driven analysis capabilities. Similarly, the study presented in [6] emphasizes imaging payloads for environmental monitoring in Greenland but do not incorporate onboard processing, restricting their ability to respond dynamically to environmental changes. The authors of [7] highlight the design of the FACSAT-2 CubeSat for observing the Colombian territory, yet their approach is tailored to specific land use applications, limiting versatility in addressing a wider range of environmental challenges. Furthermore, while the works in [8] and [9] provide valuable insights into simulation frameworks and operational systems, they do not fully leverage the latest advancements in data communication and processing technologies.

This paper presents a significant advancement in the design and development of a 3U CubeSat specifically engineered for Earth observation applications. This CubeSat integrates broad imaging capabilities with AI-driven analysis for real-time change detection, enabling dynamic environmental monitoring. Its versatile architecture facilitates the analysis of various environmental phenomena, providing agile responses to a wide range of challenges, including disaster management. The design emphasizes a compact and cost-effective approach that supports practical applications of advanced technologies, allowing for high-resolution image capture and transmission to ground stations. By leveraging onboard AI for multi-temporal image analysis, our CubeSat underscores its potential as a multifunctional tool for enhancing environmental monitoring efforts, contributing meaningfully to the evolving landscape of CubeSat technology. Unlike the previous works, our CubeSat features a modular architecture and emphasizes cost-effectiveness, facilitating efficient transmission of high-resolution images for comprehensive analysis and making it a more robust solution for modern Earth observation needs.

## III. PROPOSED ALGORITHM

This paper proposes the development of a compact, modular, and cost-effective CubeSat platform designed for general-purpose Earth observation with enhanced capabilities driven by artificial intelligence (AI). The system integrates space technology with modern embedded systems and machine learning to facilitate flexible mission profiles, particularly in change detection across satellite images. The project encompasses the design and integration of two major segments:

1) Space Segment: A 3U CubeSat capable of capturing and transmitting high-resolution images and sensor data.
2) Ground Segment: Responsible for control, data reception, telemetry monitoring, and AI-based processing of satellite imagery.
3) A key innovation is the strategic offloading of computational tasks specifically AI inference onto the ground station, conserving power and resources onboard the satellite.

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### *A. System Overview and Architecture*

The proposed architecture divides responsibilities between the CubeSat and the ground station to achieve operational efficiency. The CubeSat is launched into a low Earth orbit (LEO), performing periodic Earth imaging. During passes within the ground station's line-of-sight, bidirectional communication is established using the NRF24L01 wireless module, with ESP32 microcontrollers managing protocol and data encoding/decoding. The modular nature of the system supports flexibility in mission objectives, allowing for updates or replacements of the AI model on the ground without modifying the satellite hardware. This scalability makes it adaptable to various remote sensing goals, such as vegetation monitoring, urban expansion tracking, or disaster assessment.

### *B. Units*

The main tasks of the ground station include sending commands, receiving telemetry, and payload data. The ground station features an ESP32 module paired with the NRF24L01 transceiver, facilitating long-range, low-power communication with the CubeSat during its orbital passes. Key functions include:

1) Mission command transmissions from a ground station to a CubeSat: It primarily involve commands to:
   - Initiate image capture at specific timestamps.
   - Transmit all or specific stored images.
   - Erase stored images.
   - Reset storage memory.
   - Send historical or real-time telemetry data.
2) Data Reception: A CubeSat ground station's data reception capabilities include
   - Live telemetry from onboard sensors.
   - Images stored onboard the satellite.
3) Control and Monitoring Interface:

   A custom GUI is developed using LabVIEW for real-time telemetry visualization and command logging.
4) AI Inference System:

   It processes received images using a deep learning model for change detection, supporting reconfigurability for different applications.
5) Orbital Pass Prediction:

   It utilizes the Satellite Tool Kit (STK) to simulate and predict CubeSat visibility windows and access times.

### *C. CubeSat Subsystem Design*

The CubeSat comprises five major subsystems, each engineered for minimal power consumption and compatibility:

**1) Structure Subsystem**

The mechanical structure adheres to the 3U CubeSat standard (10×10×30 cm), designed using SolidWorks and analyzed via ANSYS simulations for structural integrity. Constructed from Aluminum 6061, it offers lightweight, machinability, and thermal resistance.

**2) Power Subsystem**

This subsystem ensures regulated energy supply to all CubeSat modules. It includes fixed-position solar panels on four sides as the primary energy source. Rechargeable lithium batteries for eclipse operations as the secondary source. Buck and boost converters providing three voltage rails: 12V, 5V, and 3.3V. Monitoring by voltage sensors on each output line and tracking overall power consumption through a centralized current sensor to allow for real-time tracking and control of the power distribution, ensuring that each component receives the correct voltage and current. Finally, Safety mechanisms include a remove before flight (RBF) switch, a kill switch for critical systems, and a separation switch for non-essential modules.

**3) Communication Subsystem**

This subsystem enables both internal and external data transfer. Internally, wired connections link the On-Board Computer (OBC), payload system, and sensors. Externally, an NRF24L01 module facilitates data transmission to the ground station, supporting scheduled or event-triggered communications.

**4) Payload Subsystem**

The payload comprises a compact imaging system with an ESP32-CAM microcontroller for image capture and an SD card module for local image storage. Upon receiving a “capture” command, the ESP32-CAM captures and stores the image, optimizing both timing and power usage by decoupling image acquisition from transmission.

**5) Attitude Determination and Control System (ADCS)**

This subsystem maintains the CubeSat’s orientation, ensuring optimal solar panel alignment and camera positioning. It includes three motors aligned to orthogonal axes, driven by two motor drivers. In addition, an MPU6050 IMU sensor for pitch, roll, and yaw measurements, allowing real-time adjustments based on orientation feedback

### *D. Authors and Affiliations*

Given the limited internal space of the CubeSat, the electronic layout was optimized through custom PCB designs using Easy EDA, featuring:

1) Seven custom PCBs for separating functionalities.
2) Vertical stacking with 80-pin through-connectors.
3) A compact layout ensuring reliable connections and resistance to vibration during launch and operation.

### *E. Authors and Affiliations*

The AI model for image change detection provides intelligent processing capabilities, utilizing deep learning for accurate change identification rather than traditional hardcoded methods. The model is trained on the LEVIR-CD dataset. The LEVIR-CD dataset is used to train models for change detection in satellite imagery. It provides pairs of pre-event (Image A) and post-event (Image B) satellite images, along with a binary mask. This mask acts as a ground truth, indicating which regions within the images have undergone a change. The LEVIR-CD dataset is preprocessed by resizing images and masks to 256x256 pixels, normalizing pixel values, and then concatenating image pairs into a six-channel tensor input for model training. This preparation ensures the data is in a consistent format for deep learning models, specifically for change detection tasks.

The U-Net model is a powerful architecture for image segmentation, particularly in tasks like identifying changed areas. It consists of an encoder path that systematically extracts features from input images, progressively downsampling to capture essential information at various scales. This is followed by a bottleneck layer, where high-level semantic information is synthesized, allowing the model to understand the broader context of the image. The decoder path then reconstructs the pixel-wise segmentation, upsampling the features to generate a detailed output. Importantly, skip connections are integrated throughout the architecture to preserve spatial details lost during downsampling, enabling the model to maintain fine-grained information in the final output. Ultimately, the model produces a binary mask that effectively identifies areas of change, facilitating applications in fields such as remote sensing and medical imaging. Figure 1 illustrates the U-Net architecture overview.

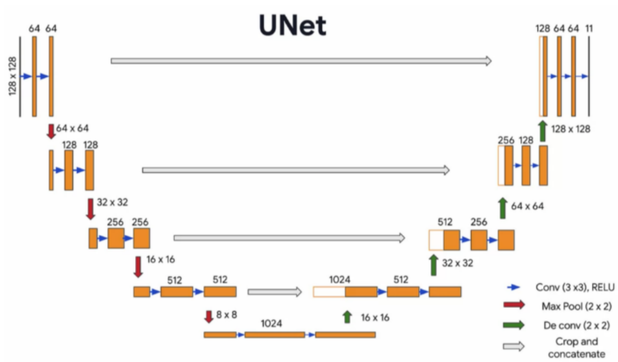


Figure 1. U-Net architecture overview.

The proposed system employs a U-Net architecture optimized using Binary Cross Entropy (BCE) loss, which quantifies pixel-level classification errors, and Dice Loss, which emphasizes the overlap between predicted and actual regions. Performance evaluation metrics include Binary Accuracy and the Dice Coefficient, providing a comprehensive assessment of the model's effectiveness.

The training process utilizes a standard gradient descent-based optimizer with a fixed learning rate. Several callbacks are implemented to enhance the training procedure: model checkpoint saves the best-performing model, early stopping terminates training when no improvement is observed, and reduce LR on plateau adjusts the learning rate when validation performance stagnates.

Upon completion of training, the model is deployed at the ground station. It processes incoming image pairs from the CubeSat, performing inference to identify and highlight changed regions. This ground-based processing allows for the use of various models tailored for specific applications, including flood detection, urban development tracking, and agricultural monitoring. This modularity offers significant flexibility, enabling the integration of new datasets and models without necessitating modifications to the space hardware

## *IV*. SIMULATION AND HARDWARE VALIDATION OF A 3U CUBESAT DESIGN FOR EARTH OBSERVATION APPLICATIONS

This section details the simulation and analysis outcomes achieved through a suite of software tools, validating the design and functionality of our CubeSat. The simulation process is structured into four key components: mechanical design, orbital analysis, onboard system implementation, and telemetry visualization.

### *A. Mechanical Design using SolidWorks*

The CubeSat's structural design was modeled in SolidWorks to adhere to standard mechanical constraints for CubeSats. Configured as a 3U CubeSat, it measures 100 mm × 100 mm × 340.5 mm. The internal layout was optimized for efficient mass distribution, thermal management, and modular subsystem integration. The structural frame is crafted from Aluminum 6061-T6, chosen for its high strength-to-weight ratio and corrosion resistance essential traits for space-grade components. SolidWorks simulations indicate that the frame weighs under 400 grams, while the total CubeSat mass remains below 4 kilograms, ensuring compliance with the 3U CubeSat standard and compatibility with conventional deployer systems.

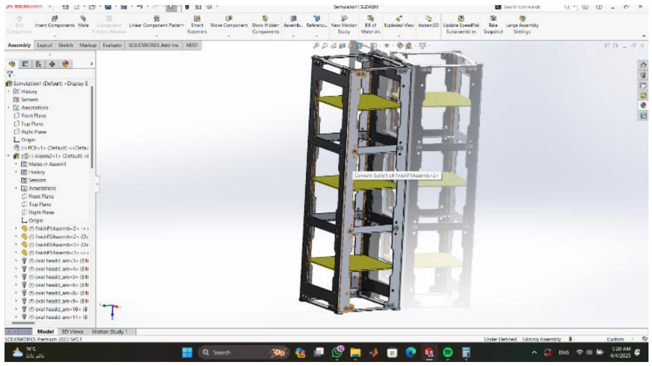

Figure 2. The 3D model of the CubeSat structure designed in SolidWorks.

### *B. Orbital Analysis Using STK*

Headings, or heads, are organizational devices that guide the reader through your paper. Text heads organize the topics on a relational, hierarchical basis. For example, the paper title is the primary text head because all subsequent material relates and elaborates on this one topic. If there are two or more sub-topics, the next level head should be used and, conversely, if there are not at least two sub-topics, then no subheads should be introduced. Styles named “Heading 1”, “Heading 2”, “Heading 3”, and “Heading 4” are prescribed.

There are three heading styles in this template, Heading 1, a centered, bold, all-caps heading, and Heading 2, a lettered, running list that is bold and italicized, and Heading 3, a slightly smaller, text in bold title case Orbital simulations were conducted using the Systems Tool Kit (STK) to assess the satellite’s trajectory and ground station accessibility. A Low Earth Orbit (LEO) configuration was selected, with an altitude of approximately 500 km and an inclination suitable for sun-synchronous operation. Key results from the STK analysis include:

- Number of ground station passes per day: 4–6
- Average duration of each pass: 6–9 minutes
- Total daily communication window: ~40 minutes

These findings support the feasibility of frequent data downlink opportunities to the Egyptian Space Agency (EGSA).

### *C. Figures and Tables*

The onboard system logic was implemented and tested using the Arduino IDE on an ESP32-S3 microcontroller, serving as the main controller for managing CubeSat subsystems. The software architecture dynamically initializes and monitors all components based on battery voltage levels, ensuring optimal power management and safe operation across various mission scenarios. At startup, the system activates all hardware interfaces, including sensors and communication modules. Based on the measured battery voltage, the CubeSat automatically enters one of three operational modes:

- Initial Mode (80% – 100% battery): All subsystems are fully powered.
- Safe Mode (60% – 80% battery): Critical systems remain active while non-

essential payloads are powered down to conserve energy.

- Sleep Mode (< 60% battery): The system enters a low-power state, maintaining only essential functions to monitor battery levels.

This intelligent mode-based control optimizes power efficiency and extends mission lifetime. The implementation was validated through serial output logs and simulated voltage inputs, confirming reliable mode transitions and safe power management.

### *D. Telemetry Visualization Using Labview*

For real-time telemetry monitoring, LabVIEW was employed to create a graphical interface visualizing sensor readings and control signals. The system captured data such as:

- Angular orientation (Pitch, Roll, Yaw)
- Battery voltage and current
- Control outputs (PWM signals to motors)

This live visualization facilitated debugging and tuning of the PID controller, demonstrating system responsiveness under varied test conditions. Figure 3 shows a sample LabVIEW dashboard during system operation.


Figure 3. labview result for ADCS subsystem

### *E. Telemetry Visualization Using Labview*

A series of simulations were conducted using various change detection algorithms to evaluate their accuracy and robustness across diverse scenarios. The results demonstrated strong performance in identifying spatial or temporal changes, with an overall accuracy exceeding Accuracy: 97%,Dice Score: 0.748,Custom Loss: 0.10 .The algorithm effectively responded to subtle variations while minimizing false positives. These outcomes highlight the system's ability to operate under noisy conditions and maintain stability across different test cases, suggesting its suitability for real-world applications such as ground monitoring and satellite image analysis.

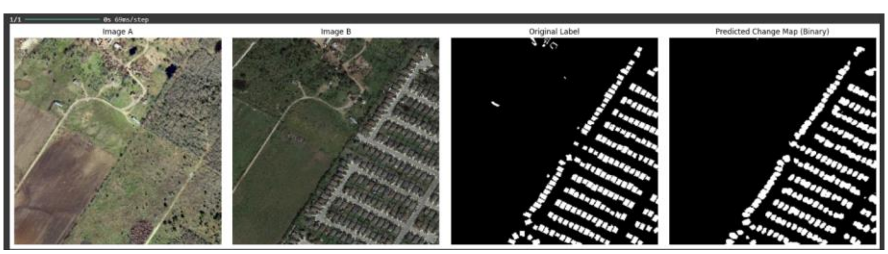


Figure 4. AI Results

### *F. Telemetry Visualization Using Labview*

The hardware of the educational CubeSat was implemented using three ESP32 microcontrollers, each assigned to a specific subsystem. The components were integrated onto custom-designed PCBs tailored to fit the dimensions of a 3U CubeSat structure. The system includes an image acquisition module (Payload) using an ESP32-CAM, a communication module utilizing an ESP32 with an NRF24L01 transceiver, and a Ground Station unit. These modules are interconnected using UART and SPI protocols. All subsystems were tested on the Ground Support Assembly (GSA). The final assembled hardware is shown in Figure 5.

Figure 5. Hardware Results

## V. CONCLUSION

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## ACKNOWLEDGMENT

This paper presented the design and development of a 3U CubeSat tailored for Earth observation applications, emphasizing its potential to revolutionize data collection and analysis in this field. Through a comprehensive simulation process encompassing mechanical design, orbital analysis, onboard system implementation, and telemetry visualization, we have validated the CubeSat's functionality and performance. The integration of advanced imaging capabilities and AI-driven analysis enables efficient monitoring of environmental changes, disaster management, and urban development tracking. The CubeSat's modular architecture and cost-effective design highlight its adaptability for future missions, allowing for the incorporation of new technologies and datasets without necessitating changes to space hardware. By leveraging cutting-edge techniques in data processing and wireless communication, this CubeSat serves as a viable alternative to traditional large satellites, democratizing access to space-based observation.

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