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A Remote Sensing Nano-Satellite Time Control and Communication System

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Abstract: This project focuses on the development of a prototype Nano-satellite system designed for remote sensing applications using an ESP32 microcontroller. The system is capable of handling real-time control and communication tasks, simulating key functionalities of a small satellite platform. It integrates multiple sensors and actuators to monitor environmental conditions and maintain system stability. An accelerometer is used to detect orientation changes, enabling basic attitude control through the activation of two fans positioned on either side of the system. A DHT11 sensor measures temperature, while a gas sensor monitors atmospheric conditions for safety. Additionally, a light sensor is employed to detect ambient light intensity, allowing automatic control of a relay-connected bulb when illumination falls below a predefined threshold. This lighting system can also be manually controlled from a ground station interface. A servo motor is incorporated to facilitate controlled mechanical movement, simulating positioning mechanisms typically found in satellites. For communication, a LoRa module enables long-distance data transmission between the satellite prototype and a ground station. [1-3] An ESP32-based camera module captures images, which are transmitted to a computer for monitoring and analysis. The system is supported by a PC-based ground station that provides real-time visualization of sensor data and allows user interaction for control operations. This setup ensures continuous monitoring and effective management of the satellite's functions. Overall, the prototype demonstrates how cost-effective IoT components can be utilized to emulate Nano-satellite operations. It serves as a practical platform for research and learning in the fields of remote sensing, embedded systems, and space technology.

Keywords: Nano-satellite prototype, remote sensing, ESP32 microcontroller, real-time embedded systems, attitude control, LoRa communication, wireless telemetry, environmental monitoring, image transmission, MATLAB/Simulink simulation.

I. INTRODUCTION

In recent years, Nano-satellites have attracted considerable interest due to their affordability, compact form factor, and capability to perform a wide range of remote sensing and communication functions. These systems are increasingly utilized in applications such as environmental observation, disaster response, scientific research, and educational training. The adoption of IoT-enabled platforms like the ESP32 has further simplified the development of efficient and low-cost real-time embedded systems for such applications.[2-4]

This work presents the design and implementation of a remote sensing Nano-satellite prototype that emulates the core functionalities of an actual satellite. The system is built around an ESP32 microcontroller, which acts as the central unit for data collection, processing, and communication. It integrates multiple sensors, including an accelerometer for orientation detection, a DHT11 sensor for temperature measurement, a gas sensor for environmental monitoring, and a light sensor for detecting ambient illumination. An ESP32-based camera module is used for capturing images.

To simulate attitude control, two fans are controlled based on accelerometer inputs, while a servo motor enables directional movement and positioning. Long-range communication is achieved using LoRa modules, facilitating data exchange between the prototype and a ground station. Sensor readings and captured images are transmitted to a PC-based interface, where they can be visualized and controlled in real time. Additionally, a relay-controlled lighting system is incorporated, which automatically activates under low-light conditions, with an option for manual control through the ground station.[3-6]

The proposed system demonstrates how embedded technologies, sensor integration, and wireless communication can be effectively combined to replicate Nano-satellite operations in a compact and economical setup. This prototype provides a practical platform for research, academic exploration, and further development in the areas of remote sensing, real-time systems, and space technology simulation. Furthermore, the system is modeled and evaluated using MATLAB/Simulink to analyze its real-time performance and control behavior under different operating conditions. The simulation framework replicates onboard processing by organizing tasks such as sensor data acquisition, control decision-making, and communication into time-scheduled modules. This allows verification of system stability, response time, and data flow efficiency before physical implementation. By incorporating simulation alongside

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hardware development, the project ensures a more reliable and scalable design approach, enabling better understanding of real-time embedded system constraints in Nano-satellite applications.

II. LITERATURE REVIEW

1. **Performance Evaluation of LoRa for IoT Applications in Non-Terrestrial Networks via ns-3** (2025)

This paper evaluates the performance of LoRa technology for IoT applications in non-terrestrial networks, such as satellite communications. It discusses the feasibility of using LoRa for large-scale IoT connectivity through Low Earth Orbit (LEO) satellite gateways.

2. **LoRa-Based Low-Cost Nanosatellite for Emerging Communication Networks** (2023)

This study presents a CubeSat prototype employing LoRa technology to establish communication in remote areas. The CubeSat functions as a repeater, collecting data from mobile stations in inaccessible regions and transmitting it to a base station, facilitating emergency communications.

3. **Design and Implementation of an Onboard Computer and Payload for Nano Satellite (CubeSat)** (2022)

The research focuses on designing an onboard computer for CubeSat Nano satellites, integrating sensors like temperature, gyroscope, and cameras. The onboard computer manages data from satellite subsystems and communicates with the ground station.

4. **Design and Implementation of ESP32-Based IoT Devices** (2021)

This paper discusses educational tools and technologies that simplify the design, implementation, and testing of IoT applications using ESP32 microcontrollers. It highlights various projects developed by students, demonstrating the versatility of ESP32 in IoT applications.

5. **Design of a Low-Cost Nanosatellite for Atmospheric Monitoring** (2021)

The study details the design of a low-cost Nanosatellite aimed at atmospheric monitoring. It utilizes the ESP32S microcontroller, known for its dual-core processor and ample memory, to handle sensor data and communication tasks efficiently.

III. EXISTING SYSTEM

In many existing implementations, satellite prototypes and remote sensing systems are often either expensive or limited in their overall capabilities. Most of these systems are designed to perform a single specific function, such as measuring temperature, detecting light intensity, or capturing images, rather than supporting a combination of operations. Additionally, real-time interaction with a ground station is frequently absent or minimal, which restricts effective monitoring and control. Communication capabilities in such setups are usually confined to short distances, reducing their practical usability in real-world scenarios.[6-9]

Another major limitation is the inability of these systems to manage multiple tasks simultaneously, as they are typically not designed for integrated or parallel processing. The reliance on complex and costly hardware further increases the barrier for development and experimentation. As a result, these systems do not provide the flexibility required for expanding functionalities or adapting to different application needs. This lack of versatility makes it difficult to replicate the behavior of actual satellite systems in a simplified and accessible manner.[8-11]

Furthermore, the limited accessibility and scalability of existing solutions pose challenges for students, researchers, and small organizations who aim to gain practical knowledge in this field. Without a unified platform that combines sensing, control, and communication features, it becomes difficult to conduct comprehensive experiments or simulate real-time satellite operations. These constraints highlight the need for a more affordable, flexible, and integrated system that can support multiple functionalities while enabling real-time monitoring and long-range communication.[12-14]

IV. PROPOSED SYSTEM

The proposed system is a low-cost nano-satellite prototype using an ESP32 microcontroller that overcomes the limitations of existing systems. It integrates multiple sensors (accelerometer, light sensor, DHT11 temperature sensor, gas sensor) to monitor the environment and orientation. Actuators such as fans, a servo motor, and a relay-controlled bulb respond automatically based on sensor data. An ESP32 camera captures images and sends them to a PC for real-time monitoring, while LoRa communication enables long-range data transfer. The system allows real-time control and observation from a PC, simulating multiple satellite functions at once.[15-17] This setup provides a practical, educational, and cost-effective platform for learning about remote sensing, attitude control, and embedded system design. Figure 1 shows the proposed transmitter section and figure 2 shows the receiver section of the project. In addition, the modular structure of the system allows for easy expansion and customization based on specific application requirements. New sensors, communication modules, or control algorithms can be incorporated without significantly altering the existing framework. This flexibility enhances the system's usability for advanced research, enabling users to experiment with different configurations and improve performance. Overall, the proposed solution offers a scalable and practical approach for developing and testing Nano-satellite technologies in an educational and research-oriented environment. Figure 3 shows the software simulation using MATLAB.[18]

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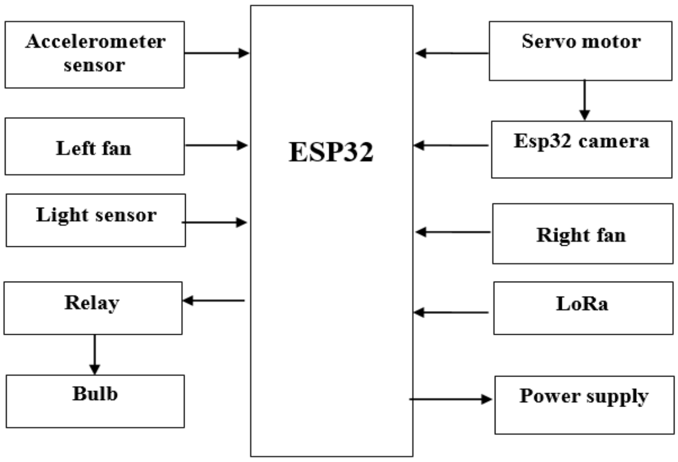

Figure 1 shows the proposed transmitter section of the Nano-satellite

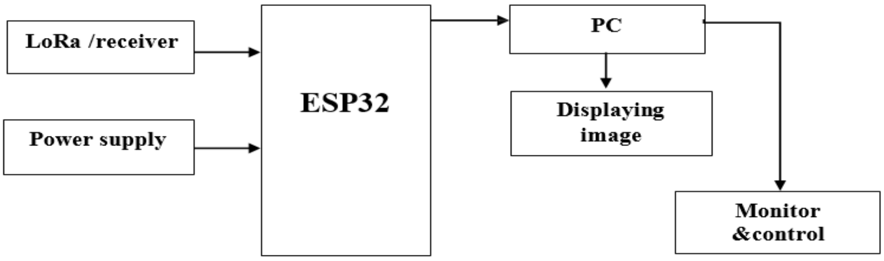

Figure 2 shows the proposed receiver section of the Nano-satellite

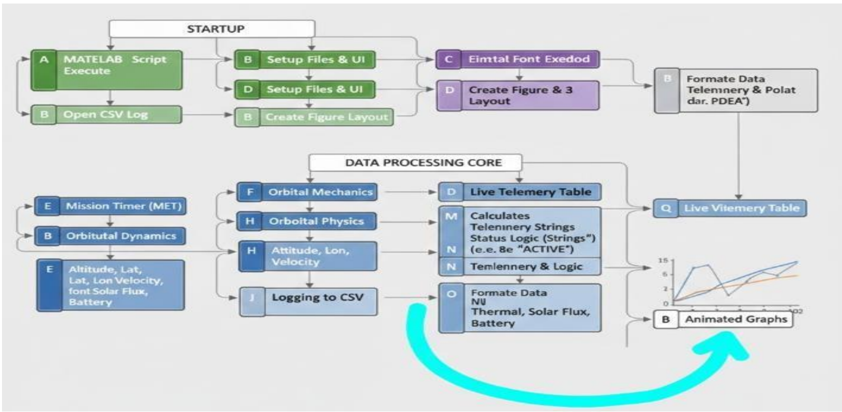

Figure 3 shows the software simulation using MATLAB

V. PROBLEM STATEMENT

Satellites are essential for applications such as remote sensing, environmental monitoring, communication, and scientific exploration. However, the design, development, and operation of real satellite systems involve high costs, complex technologies, and specialized infrastructure. Due to these challenges, direct access to satellite-based experimentation is often not feasible for students, researchers, and small-scale organizations, limiting opportunities for practical learning and innovation in this domain.

There is therefore a growing need for a compact and cost-effective Nano-satellite prototype that can replicate the core functionalities of an actual satellite system. Such a prototype should be capable of performing remote sensing operations using cameras and environmental sensors, including temperature, gas, and light monitoring. In addition, it should demonstrate basic attitude control mechanisms through the use of actuators such as fans and servo motors, which respond dynamically to orientation data.

Another important requirement is the ability to establish real-time communication between the satellite prototype and a ground station. This includes transmitting sensor readings and captured images efficiently over long distances, as well

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as enabling automated responses based on environmental conditions. For example, the system should be able to perform actions such as activating a light source when the surrounding illumination falls below a predefined level, thereby demonstrating intelligent control behavior.

To address these challenges, this project proposes an ESP32-based embedded system integrated with multiple sensors, actuators, a camera module, and LoRa communication technology. The system provides a hands-on platform that allows users to monitor and control operations through a PC interface in real time. Furthermore, with the support of MATLAB-based simulation, it becomes possible to analyze system behavior and study satellite-like operations without requiring actual space deployment, making it highly suitable for educational and research purposes.

VI. METHODOLOGY

Design and integration of a Nano-satellite prototype using an ESP32 microcontroller as the central processing unit, combined with multiple sensors, actuators, and communication modules. Initially, environmental and orientation data are collected from sensors such as the accelerometer, DHT11, gas sensor, and light sensor, which are continuously processed by the ESP32 to make real-time control decisions. Based on this data, actuators including fans, a servo motor, and a relay-controlled bulb are automatically operated to simulate attitude control and environmental response. Simultaneously, an ESP32 camera captures images, and both sensor data and visual information are transmitted to a ground station using LoRa communication for long-range connectivity. A PC-based interface is used for real-time monitoring and manual control, while MATLAB/Simulink is employed to model and analyze system behavior, ensuring efficient task scheduling and performance validation before implementation. Figure 3 shows the systematic methodology of design involved in the project.

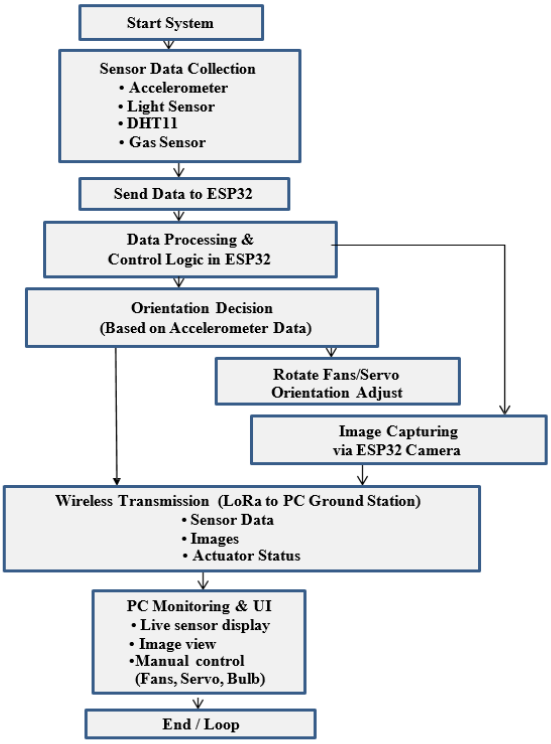

Figure 3 shows the systematic methodology of design involved in the project.

Arduino IDE and Embedded C

1. **Sensor Data Collection:**
- Sensors including accelerometer, light sensor, DHT11 (temperature), and gas sensor continuously monitor the environment and orientation.
- The sensors send real-time data to the ESP32 microcontroller for processing.

2. **Data Processing and Control:**
- ESP32 analyzes the sensor readings and decides the appropriate actions:
  - Fans rotate on the left or right based on accelerometer data to simulate orientation adjustment.
  - Servo motor rotates the prototype as needed for positioning.

3. **Image Capturing:**

The ESP32 camera captures images of the surroundings and the images are sent to the ESP32 and then transmitted to the PC via LoRa .

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4. **Wireless Communication:**
- LoRa modules provide long-range data transmission between the satellite prototype and the PC.
- Sensor data, images, and actuator status are transmitted in real time for monitoring.

5. **PC Monitoring and Control:**

The PC acts as a ground station, receiving data from the ESP32.Users can monitor sensor readings, view images, and control actuators like fans, servo, and bulb manually if needed.

6. **Software simulation**

Phase	Key Action	Goal
I. Initialization	Load Scripts & UI	Prepare the software environment.
II. Ingestion	Read CSV & Telemetry	Bring in raw sensor/simulation data.
III. Computation	Physics & Logic Processing	Turn raw data into orbital coordinates and status states.
IV. Rendering	Table & Graph Generation	Display data for real-time human intervention.

1. **Startup & Environment Initialization**

The process begins with the "STARTUP" block, which focuses on setting up the workspace and UI components.
- **Script Execution:** Initiates the primary logic (labeled as "MATELAB," likely a typo for MATLAB).
- **Resource Allocation:** Simultaneously loads CSV logs and configures setup files.
- **UI/UX Construction:** Generates the "Figure Layout" and sets up font styles and specific 3D layout environments to prepare the visual stage for the data.

2. **Data Ingestion & Pre-Processing**

Before the core processing begins, the raw data is formatted.
- **Data Formatting:** Telemetry data is converted into a readable format (e.g., PDEA).
- **Input Stream:** External data sources (Mission Timer, Orbital Dynamics, and sensor data like Altitude/Solar Flux) are fed into the core engine.

3. **Data Processing Core (The Analytical Engine)**

This is the "brain" of the operation where raw numbers become actionable information.
- **Physics Modeling:** Calculations for Orbital Mechanics and Orbital Physics are performed.
- **State Estimation:** The system determines the craft's Attitude, Longitude, and Velocity.
- **Logic Extraction:** The "Calculates Telemetry Strings" phase applies status logic (e.g., checking if a system is "ACTIVE") to translate raw numbers into status messages.
- **Persistence:** All processed data is simultaneously logged to a CSV for post-mission analysis.

4. **Visualization & Output Rendering**

The final phase focuses on the human-machine interface (HMI).
- **Live Telemetry Tables:** A real-time data grid (Live Vitemery/Telemetry Table) is populated for precise monitoring.
- **Visual Representation:** Data relating to Thermal, Solar Flux, and Battery status is channeled into Animated Graphs.
- **Dynamic Feedback:** The light blue arrow in your image indicates a specific feedback loop or direct data path from the core formatting block ("O") directly to the visual graph rendering ("B"), ensuring low-latency updates for the user.

VII. RESULTS

- The Nano-satellite prototype successfully integrates ESP32, sensors, actuators, camera, and LoRa communication.
- Real-time data collection and monitoring from accelerometer, light, temperature, and gas sensors is achieved.
- Fans and servo motor respond automatically to orientation data, simulating satellite attitude control.
- Images captured by the ESP32 camera are transmitted to the PC for observation. Figure 4 shows the control dashboard.

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- The system demonstrates wireless communication and remote control, proving the concept of a low-cost satellite prototype. Figure 5 and 6 show the model/ prototype and the software displaying the signal.

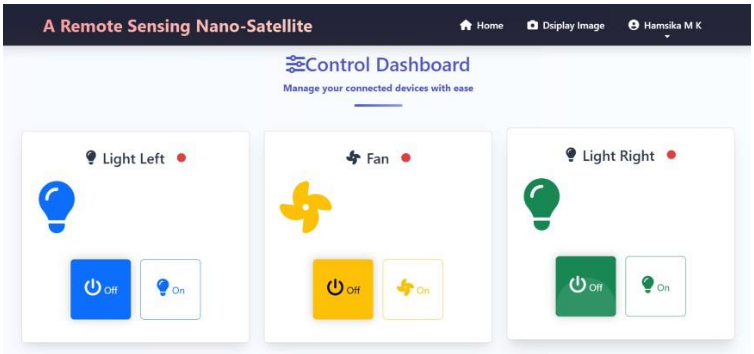

Figure 4 shows the control dashboard of the project

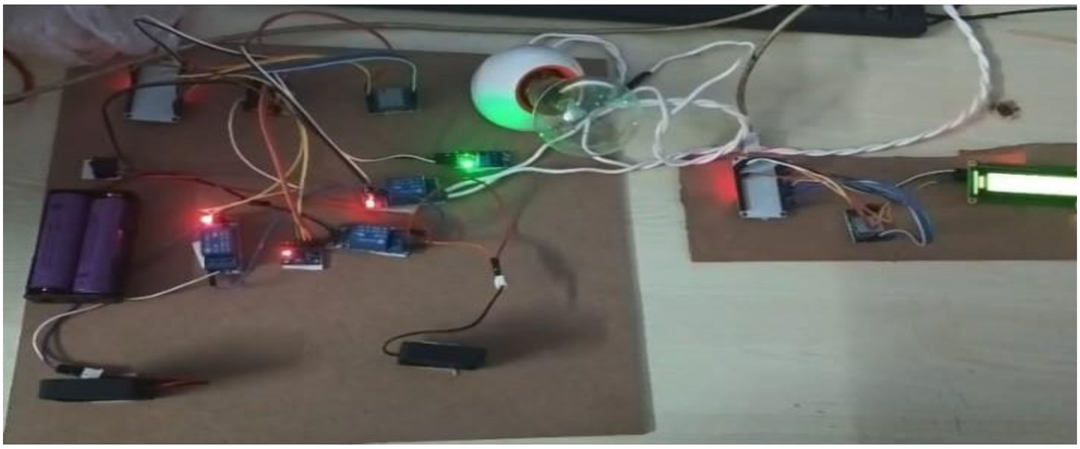

Figure 5 shows the model/ prototype developed

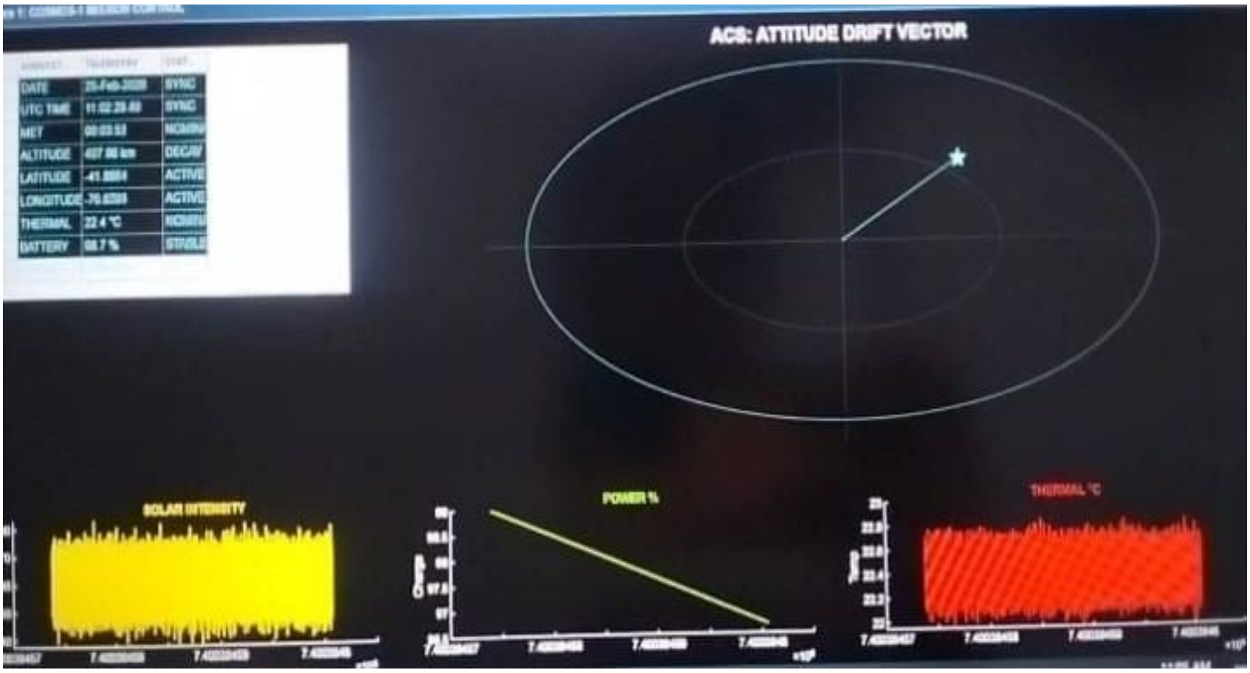

Figure 6 shows the simulation software displaying the signal

CONCLUSIONS

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The project successfully demonstrates the development of a functional and cost-effective Nano-satellite prototype that is well suited for educational and research applications. By integrating multiple sensors, actuators, and communication modules, the system effectively replicates essential satellite operations on a small scale. It provides a practical platform for gaining hands-on experience in embedded systems, IoT-based remote sensing, and real-time control, making complex satellite concepts more accessible. In addition, the prototype addresses many limitations associated with traditional satellite experimentation by offering an affordable, compact, and interactive solution.

Furthermore, the project presents a simulated implementation of a remote sensing Nano-satellite with real-time control and communication capabilities. Through the incorporation of task scheduling, environmental monitoring, and wireless image transmission, the system closely mimics the behavior of actual satellite operations. This combined hardware and simulation approach enhances understanding of system performance and reliability, making the model an effective tool for studying and experimenting with modern satellite technologies. Additionally, the system offers strong potential for future enhancements and scalability, allowing it to be extended with advanced features such as improved communication protocols, higher-resolution imaging, and intelligent data processing techniques. The modular design enables easy integration of new components and algorithms, making it adaptable for a wide range of applications beyond basic simulation, thereby supporting further research, innovation, and practical exploration in the field of nano-satellite systems.

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