

Implementation of CUBESAT for Environmental Monitoring

Mrs. Jabeena Banu¹, Mrs. Lubna Afza², Mrs. Nishaat Fatima³,

Mrs Tahsina Kauser⁴, Ms. Amna Zaiba Khan⁵

^{1,2,3,4}Asst. Professor, Dept. of ECE, KNS Institute of Technology, Bengaluru

⁵UG Student, 7TH Semester, Dept. of CSE-DS, KNS Institute of Technology, Bengaluru

Abstract— Nowadays, environmental degradation and pollution are rising at an alarming rate, posing serious health and ecological risks. Real-time monitoring of environmental parameters has become essential for ensuring public safety, early hazard detection, and supporting sustainable development. With increasing demand for portable and intelligent monitoring systems, the integration of IoT-based solutions is proving to be highly effective. In this context, we propose an environmental monitoring system based on the ESP32 microcontroller that can be deployed in various environments including remote or mobile settings. The system integrates multiple sensors such as the BMP280 for atmospheric pressure and temperature, the MPU6050 for motion and tilt detection, the MQ2 gas sensor for smoke and gas leak detection, an LDR for measuring light intensity, and the NEO-6M GPS module for location tracking. Data collected from these sensors is processed and transmitted to a web interface using MQTT protocol, with local display via a 0.96- inch OLED screen. Power is managed using a rechargeable battery setup with a DC-DC converter and power control circuit, making the device energy-efficient and portable. This paper aims to provide an accurate, scalable, and cost-effective solution for environmental data collection and monitoring, suitable for smart city applications, disaster-prone zones, and mobile deployments.

Index Terms— ESP32, IoT, Environmental Monitoring, MQTT, BMP280, MPU6050, MQ2, GPS, OLED Display

I. INTRODUCTION

Monitoring the environment is essential for evaluating ecosystem vitality, identifying ecological risks, and supporting long-term sustainability. Conventional monitoring frameworks typically utilize stationary, ground-based sensors to track metrics like atmospheric pressure, air quality, humidity, and temperature.

Despite their utility, these traditional methods often struggle with limited geographic reach, lack of mobility, and difficulties in scaling or accessing data in real time. These hurdles are especially evident in specialized or confined contexts, such as mobile sensing units or CubeSat missions.

To overcome these barriers, merging Internet of Things (IoT) capabilities with environmental systems provides a powerful alternative. This integration enables continuous data collection, seamless transmission, and instant visualization, bypassing the physical and geographical limitations of older hardware.

In recent years, CubeSats have gained increasing prominence in Earth observation, space research, and environmental monitoring. These miniature satellites, typically ranging from 1U (10×10×10 cm) to 3U in size, provide an affordable, compact, and scalable solution for deploying various sensing instruments into low Earth orbit (LEO). CubeSats can perform high-resolution measurements of atmospheric parameters, pollution, radiation, and even water quality, providing valuable data to scientists, policymakers, and environmentalists. Despite the inherent size and weight limitations of CubeSats, they have proven to be effective platforms for environmental monitoring by leveraging lightweight, low-cost sensors and efficient communication protocols. However, the success of CubeSat-based monitoring systems depends not only on the selection of suitable sensors but also on the integration of effective data processing and transmission systems that can operate in real-time and handle diverse environmental data.

This paper introduces implementation of a CubeSat-based Environmental Monitoring System (CES) that

integrates state-of-the-art IoT technologies to provide continuous environmental monitoring through real-time data acquisition, transmission, and visualization. The system is built around the ESP32 microcontroller, which acts as the central processing unit (CPU) and communication hub, handling the acquisition and processing of data from various sensors, and enabling wireless communication over Wi-Fi. The ESP32's ability to support both Wi-Fi and Bluetooth protocols, along with its low power consumption and high computational capabilities, makes it an ideal choice for space-constrained and power-limited applications such as CubeSats.

II. RELATED WORK

The paper titled "UVS in Monitoring of Environmental Factors" by V. Sprincean, A. Paladi, T. Bulimaga, and F. Paladi, presented at the 2020 IEEE 7th International Workshop on Metrology for Aerospace (Metro Aerospace), explores the utilization of Unmanned Vehicle Systems (UVS) in environmental monitoring. The authors discuss the integration of various sensors and measurement systems within UVS platforms to effectively monitor environmental parameters. By leveraging advancements in sensor technology and data processing algorithms, the paper highlights how UVS can provide real-time monitoring and assessment of environmental factors, contributing to more informed decision-making in environmental management

[1] The paper titled "Environmental monitoring using compact satellite systems like CanSats" has gained increasing attention in recent years due to their low cost, simplicity, and potential for real-time data collection in hard-to-reach or dangerous areas. Their system uses low-power microcontrollers and wireless transmission modules to relay environmental data in real-time. This work builds on earlier research that emphasized sensor integration, communication reliability, and deployment techniques. For instance, earlier studies such as the one presented in the 2021 International Conference on Electrical, Electronics, and Information Communication Technology (ICEEICT) emphasized the modularity and reusability of CanSat platforms in educational environments, especially for weather and pollution monitoring. These systems typically incorporate atmospheric sensors, GPS modules, and telemetry systems to track data

during descent or while airborne using balloons or UAVs.

[2] The paper titled "Design of Trash Can Sized Satellite for Air Quality Monitoring at an Altitude of 300m Above Ground Level" by M. Sinha et al., presented at the 2023 International Conference on Circuit Power and Computing Technologies (ICCPCT), explores the development of a compact satellite system aimed at monitoring air quality parameters at low altitudes. The study focuses on integrating various sensors within a trash can-sized satellite to measure pollutants and atmospheric conditions, facilitating real-time environmental monitoring. This research contributes to the growing field of small satellite applications in environmental monitoring, emphasizing the potential of low-cost, deployable systems for localized data collection. By operating at an altitude of approximately 300 meters, the satellite can provide high-resolution data pertinent to urban air quality assessments.

[3] This study "Development of an ESP-32 Microcontroller Based Weather Reporting Device" presents the development of a weather reporting device utilizing the ESP32 microcontroller. The system integrates various sensors, including the BMP280 for atmospheric pressure and temperature measurements, to collect environmental data. The collected data is processed and transmitted to a cloud-based platform for analysis and visualization. The device aims to provide an efficient and cost-effective solution for continuous air quality monitoring, with potential applications in smart cities and industrial environments.

III. BLOCK DIAGRAM

Technical Overview: Compact IoT Environmental Monitor

The proposed system is a highly integrated, Internet of Things (IoT)-enabled device engineered for the autonomous acquisition and transmission of environmental data.

Structural Design and Portability

The hardware is housed in a precision-engineered 8 cm³ cubic enclosure. This ultra-compact form factor was specifically chosen to balance structural durability with extreme portability. Its standardized dimensions

facilitate versatile deployment across various platforms, including:

- Mobile integration: Attachment to drones (UAVs) or integration into backpacks for personal exposure monitoring.
- Static deployment: Discrete installation in urban "Smart City" grids or rugged remote field sites.

System Architecture (Block Diagram Components)

The system's internal architecture is designed around a central processing unit that interfaces with a specialized sensor suite. The primary functional blocks include:

- Core Processing Unit: A low-power microcontroller (such as the ESP32) to manage data flow and power consumption.
- Sensor Array:
 - * Atmospheric Sensors: To measure ambient temperature, humidity, and barometric pressure.
 - Air Quality Modules: For detecting particulate matter (PM_{2.5} / PM₁₀) and volatile organic compounds (VOCs).
 - Positioning Module: Integrated GPS for geospatial tagging of collected data.
- Communication Layer: A wireless telemetry module (Wi-Fi, LoRa, or GSM) for real-time cloud data transmission.
- Power Management: A rechargeable lithium-polymer battery system with integrated voltage regulation.

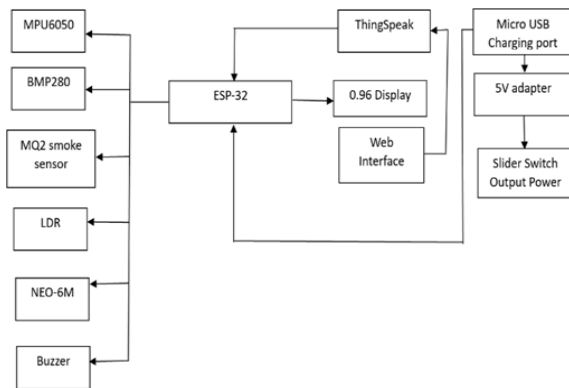


Fig 1: Block diagram of proposed model.

A. Hardware Components

1. BMP280: High-Precision Atmospheric Sensor

The BMP280 serves as the system's primary diagnostic tool for ambient environmental conditions. Engineered by Bosch, this digital sensor is specifically

designed for mobile applications where low power consumption and high accuracy are paramount.

2. MPU6050: Inertial Measurement Unit (IMU)

The MPU6050 is a sophisticated 6-axis motion tracking device that integrates a 3-axis gyroscope with a 3-axis accelerometer.

Dynamic Tracking: It provides the system with "spatial awareness," allowing it to detect physical orientation, vibration levels, and gravitational shifts.

Mission Stability: In mobile or aerial deployments (such as CanSats or drones), this sensor is vital for telemetry, ensuring the device remains stable and providing data on the unit's pitch, roll, and yaw during flight or descent.

3. MQ2: Combustible Gas and Smoke Detector

The MQ2 is a versatile metal-oxide semiconductor sensor designed to identify a broad spectrum of atmospheric hazards.

Detection Capabilities: It is highly sensitive to LPG, Propane, Methane, Hydrogen, and Smoke, making it an essential component for fire detection or industrial leak monitoring.

Signal Processing: Operating primarily through an analog output, the sensor allows the system to trigger early warning alerts when gas concentrations exceed safe thresholds, enhancing the safety of urban or industrial monitoring sites.

4. LDR: Photoresistor for Luminosity Tracking

The LDR (Light Dependent Resistor) provides a cost-effective method for quantifying ambient light levels.

Environmental Analysis: By measuring changes in resistance relative to light intensity, the system can track solar cycles or artificial lighting conditions.

Applications: This data is particularly valuable in precision agriculture for monitoring crop light exposure and in smart building automation to optimize energy efficiency by adjusting internal systems based on natural light availability.

5. NEO-6M: Geospatial Positioning Module

The NEO-6M GPS engine acts as the system's primary source of spatio-temporal data.

Precision Localization: It provides high-accuracy coordinates, including latitude, longitude, and altitude, by communicating with global satellite constellations.

Data Correlation: This module is critical for "mapping" environmental data; without it, sensor

readings lack the geographic context necessary for creating pollution heat maps or tracking the flight path of a mobile monitoring unit.

Audible Alert System: Active Piezo Buzzer

The buzzer functions as the primary localized notification interface, providing an immediate acoustic response to environmental triggers. Managed directly by the ESP32 microcontroller, it translates digital logic into a high-frequency warning signal to ensure user safety and system awareness.

Logic-Based Triggering Mechanism

The buzzer is programmed to activate when specific sensor thresholds are exceeded, serving as a fail-safe for the following conditions:

- **Atmospheric Hazards:** Responds to the MQ2 sensor when concentrations of combustible gases or smoke reach dangerous levels.
- **Structural/Inertial Events:** Alerts operators to sudden impacts, tilting, or unauthorized movement detected by the MPU6050 6-axis IMU.
- **Climatic Extremes:** Triggers during rapid pressure drops or temperature spikes identified by the BMP280, which may indicate incoming weather fronts or equipment overheating.

B. Software Description

Arduino IDE (Integrated Development Environment)

The Arduino IDE serves as the primary software gateway for developing embedded projects. It features a streamlined interface that includes a specialized code editor, a status message area, and a debugging console. Beyond simple text entry, the environment provides a pre-configured toolbar for compiling and deploying code. It acts as the bridge between the computer and hardware, allowing developers to flash firmware onto boards like the Arduino or ESP32 and monitor real-time data via the Serial Monitor.

2. The C Programming Language

In the world of hardware, C remains the gold standard for its exceptional balance of performance and low-level control. Its ability to interface directly with memory and hardware registers makes it the engine behind most modern embedded systems. For this project, C provides the framework to manage the ESP32 microcontroller's complex operations. Its efficiency is critical for:

- **Hardware Interfacing:** Direct management of sensor inputs and display outputs.
- **Data Processing:** Handling computational tasks with minimal latency.
- **Connectivity:** Orchestrating seamless communication with IoT cloud platforms like Thing Speak.
- **Optimization:** Ensuring the system operates reliably within the limited memory and power constraints of an IoT environment.

IV. METHODOLOGY

System Architecture and Functional Integration

The proposed solution utilizes an ESP32 microcontroller as the central hub for an integrated multi-sensor safety and environmental monitoring array. The system interfaces with a diverse suite of modules, including:

- **MPU6050:** For motion and orientation tracking.
- **BMP280:** For atmospheric pressure and temperature readings.
- **MQ2:** For detecting combustible gas and smoke levels.
- **LDR:** For measuring ambient light intensity.
- **NEO-6M:** For precise GPS geographic positioning.

The ESP32 processes real-time telemetry from these inputs, outputting live data to an onboard 0.96-inch OLED display. For remote monitoring, the device hosts a local web server accessible via Wi-Fi and pushes data to the Thing Speak IoT platform for long-term cloud storage and graphical analysis. Safety protocols are automated; for instance, the detection of hazardous smoke triggers an integrated acoustic buzzer for immediate local alerts. The unit is powered by a 5V micro-USB adapter, controlled by a physical slider switch for power management.

A. Physical Design and Enclosure

The hardware is housed in a streamlined, $8 \times 8 \times 8$ cm cubic enclosure designed for portability and resilience in various environments. To ensure a balance between weight and structural integrity, the casing is 3D-printed using PLA (Polylactic Acid) filament.

The interior is strategically compartmentalized to organize the microcontroller, sensors, and wiring while allowing for easy maintenance or future hardware upgrades. Key design features include:

- **Strategic Ventilation:** Precisely placed vents allow for natural airflow, ensuring that the MQ2 and BMP280 sensors receive accurate ambient readings.
- **Integrated Form Factor:** All components including the display, power modules, and sensors are fully embedded within the cube to provide a professional, field-ready finish.
- **Weather Resistance:** The compact build is optimized for both indoor deployment and shielded outdoor applications.

B. System Architecture

The backbone of this project is a central ESP32 microcontroller, which orchestrates data acquisition, real-time processing, peripheral management, and wireless data transmission. Each sensor is integrated via either digital (I2C/SPI) or analog interfaces, with the firmware configured to poll these inputs at precise intervals.

Local visualization is handled by an internal OLED display, while long-distance data transmission utilizes the MQTT protocol for high-efficiency communication. The architectural design is entirely self-contained; from power regulation to sensor fusion, every operation occurs within the 8cm³ enclosure, requiring no external modules or tethered peripherals.

C. Power Management Strategy

To ensure both stability and versatility, the system is powered via a 5V Micro-USB interface. This port connects to a standard adapter, supplying regulated power to the ESP32 and its sensor array. A hardware slider switch is integrated into the circuit to provide manual power control, allowing users to toggle the system off to conserve energy during downtime. This power configuration supports both stationary deployment and portable use-cases, ensuring a consistent voltage floor for sensitive sensor readings.

D. Data Handling and Processing

The ESP32 firmware follows a structured "Read-Buffer-Broadcast" loop. As sensor data is collected, it is formatted and simultaneously routed through three primary channels:

- **Local Output:** Real-time updates are pushed to the integrated OLED screen for immediate onsite inspection.

- **Cloud Integration:** Data packets are published via Wi-Fi to ThingSpeak using MQTT topics for remote logging.
- **Contextual Synchronization:** Environmental readings are time-stamped and synchronized with GPS and motion data to provide a comprehensive situational snapshot. This processing loop is highly optimized to maintain low latency, ensuring that spike detections (like smoke or sudden motion) are handled with high priority.

E. Remote Web-Based Interface

The system includes a custom HTML5-based web dashboard, serving as a remote command center. This interface allows users to:

- **Monitor Telemetry:** View live streams of all environmental and safety parameters.
- **System Commands:** Remotely toggle sensor states or manage the display settings.
- **Geospatial Tracking:** Visualize the device's location through GPS tagging. The interaction between the dashboard and the ESP32 is facilitated by a bidirectional MQTT bridge, ensuring that commands from the user and updates from the device are exchanged securely and near-instantaneously.

V. FLOW CHART

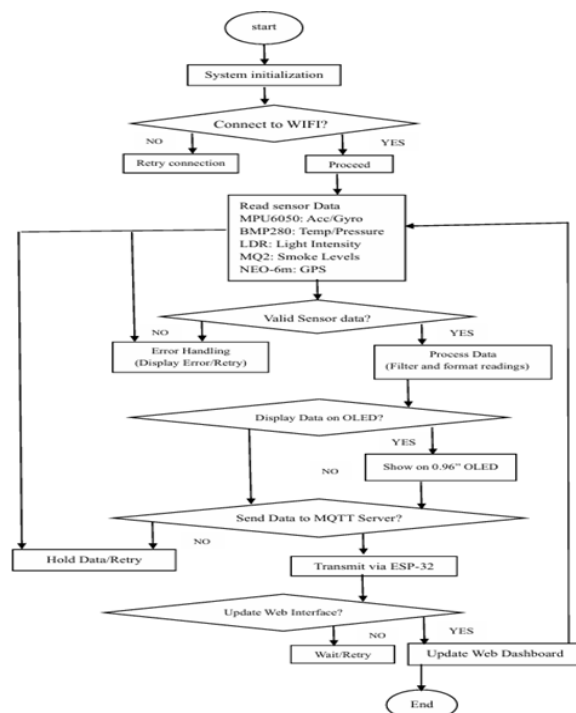




Fig 2: Output model of Environmental Monitoring system.

VI. IMPLEMENTATION

The ESP32 serves as the primary processing engine, performing real-time operations such as data filtering, normalization, and threshold validation. This "edge processing" capability allows the system to trigger immediate alerts based on preset environmental conditions without relying on external servers. For onsite interaction, a 0.96-inch OLED display provides an instantaneous readout of all critical parameters, offering a standalone monitoring solution that functions independently of network connectivity.

Cloud Connectivity via MQTT and Thing Speak

Beyond local feedback, the system leverages the MQTT (Message Queuing Telemetry Transport) protocol to broadcast sensor data over Wi-Fi. Chosen for its minimal overhead and high efficiency in low-bandwidth environments, MQTT is the ideal bridge for IoT hardware.

The data is published to the Thing Speak cloud platform, which acts as a centralized hub for:

- Live Visualizations: Transforming raw telemetry into dynamic, real-time graphs.
- Long-term Storage: Archiving historical data for trend analysis.
- Advanced Analytics: Utilizing MATLAB integration for sophisticated statistical modelling, predictive forecasting, and automated anomaly detection.

Deployment for Space and Field Research

Designed with a strict $8 \times 8 \times 8$ cm cubic footprint, the system is engineered for environments where mass and volume are at a premium. Its compact, lightweight architecture makes it a viable candidate for CubeSat missions or specialized aerospace payloads.

The modular design ensures the system remains future-proof, allowing for the easy integration of new sensor modules tailored to specific mission requirements. Furthermore, the power-efficient firmware and hardware selection ensure long-term operational stability, even in resource-constrained field deployments or remote orbital applications.

Local Data Visualization and Edge Processing

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System Working section, rewritten to improve the professional tone while avoiding repetitive phrasing.

Operational Workflow

The system functions as an autonomous data acquisition and transmission hub, centered around the ESP32 microcontroller. Its operation follows a continuous cycle of sensing, processing, and broadcasting to ensure persistent environmental awareness.

1. Data Acquisition & Edge Processing

The ESP32 interfaces with a specialized sensor array including the MPU6050 for motion, BMP280 for atmospheric data, MQ2 for air quality, LDR for light levels, and NEO-6M for global positioning. The microcontroller polls these peripherals at defined intervals, capturing raw signals and converting them into standardized units. During this phase, the firmware performs "edge processing" to filter noise and format the data for multi-channel output.

2. Concurrent Data Distribution

Once processed, the information is dispatched through three parallel streams:

- **Local Visualization:** Critical telemetry is pushed to the integrated OLED screen, providing an immediate, "at-a-glance" status update for onsite users.
- **Cloud Telemetry:** Utilizing its onboard Wi-Fi stack, the ESP32 publishes data packets to an MQTT broker. This allows the system to maintain a low-bandwidth, persistent connection to remote monitoring platforms.
- **Web Hosting:** The device runs a lightweight asynchronous web server, hosting a mobile-responsive dashboard that allows users to interact with the live data via any browser on the local network.

3. Efficiency and Reliability

The entire operational logic is optimized for low-power consumption and high uptime. By leveraging the publish-subscribe model of MQTT and the efficient sleep modes of the ESP32, the system maintains a consistent monitoring presence without overtaxing power resources. This makes the architecture ideal for remote deployments, industrial

safety monitoring, or research payloads where reliability and wireless efficiency are paramount.

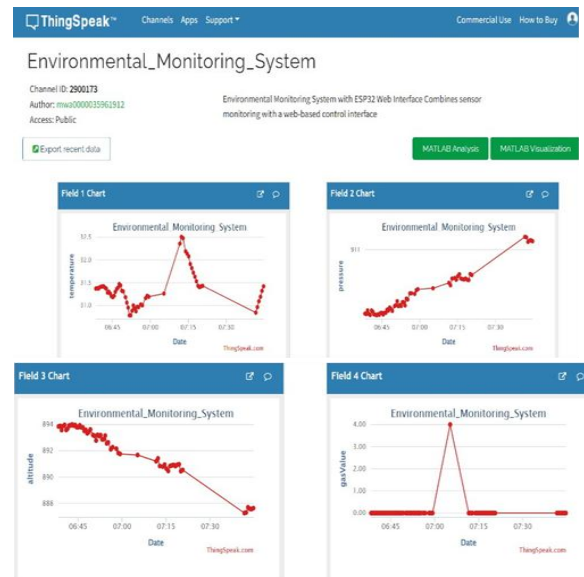
VII. RESULT AND FUTURE SCOPE

The environmental monitoring prototype underwent rigorous field testing to evaluate its data acquisition accuracy and transmission stability. The ESP32 demonstrated seamless integration with the full sensor suite, maintaining high-fidelity communication with the MPU6050, BMP280, MQ2, LDR, and NEO-6M modules. This allowed for the simultaneous capture of spatial orientation, atmospheric conditions, hazardous gas levels, ambient light, and precise geographic coordinates Data Visualization: The 0.96-inch OLED interface provided consistent, flicker-free updates of all telemetry, allowing for reliable onsite data verification without external hardware.

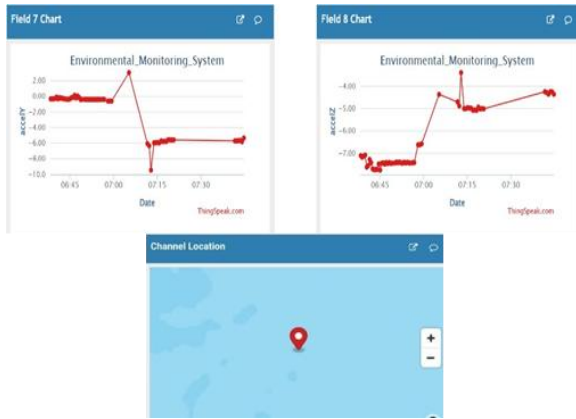
Transmission Latency: Cloud synchronization via the MQTT protocol was highly efficient, with data packets reaching the remote server with minimal millisecond-range latency.

- **Sensor Accuracy:** * The BMP280 maintained high precision, with temperature fluctuations remaining well within the predefined tolerance thresholds.
- The MQ2 sensor showed high sensitivity, successfully triggering alerts upon detecting shifts in smoke and gas concentrations.

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VIII. FUTURE SCOPE

1. Data Persistence and Redundancy

While the current system relies on cloud-based logging, integrating an onboard SD card module would provide a critical layer of data redundancy. This ensures continuous "black box" recording during network outages, allowing for local data retrieval and synchronization once connectivity is restored.

2. Energy Autonomy

To support long-term deployment in off-grid or remote locations, the integration of a solar energy harvesting unit is recommended. Combined with a high-capacity lithium-polymer (LiPo) battery management system,

this would enable the device to operate indefinitely on renewable power, significantly reducing maintenance requirements.

3. Advanced Analytics and Intelligence

The next iteration of the firmware could incorporate Edge Machine Learning (TinyML). By running lightweight algorithms directly on the ESP32, the system could perform:

Real-time Anomaly Detection: Identifying irregular environmental patterns (e.g., gas leaks or structural shifts) more accurately than simple thresholding.

Predictive Modeling: Forecasting environmental trends based on historical local data.

4. Extended Communication and Miniaturization

To move beyond the limitations of Wi-Fi, future versions will explore long-range telemetry options:

LoRaWAN & Satellite Links: For communication in deep-field or orbital environments. Form Factor Optimization: Further miniaturizing the PCB and component layout to meet the stringent "1U" volume and mass constraints of CubeSat missions

IX. CONCLUSION

The developed environmental monitoring system demonstrates the successful integration of a multi-modal sensor suite comprising the MPU6050, BMP280, MQ2, LDR, and NEO-6M GPS governed by a high-performance ESP32 microcontroller. This architecture effectively bridges the gap between local data visualization and remote cloud analytics.

Core Accomplishments

- Dual-Channel Monitoring: The system provides immediate situational awareness via an onboard 0.96-inch OLED display while maintaining a persistent data uplink to an MQTT server for global accessibility.
- User Interactivity: A dedicated Wi-Fi-enabled web dashboard allows for seamless, real-time interaction with environmental telemetry, offering a user-centric approach to data management.
- Hardware Efficiency: With a physical interface featuring a dedicated power slider and a USB charging port, the device prioritizes portability and ease of maintenance in the field.
- Performance Validation: Experimental results confirm the system's robustness, achieving high-

fidelity data capture and transmission with negligible latency under real-world conditions.

Final Assessment

The design represents a compact, energy-efficient, and highly scalable solution for modern IoT challenges. Its modular nature and standardized "cube" form factor make it an ideal candidate for specialized applications, ranging from terrestrial remote sensing to 1U CubeSat atmospheric studies.

Moving forward, the platform is positioned for significant upgrades, including the adoption of onboard SD logging for data redundancy, solar harvesting for energy independence, and Edge AI/Machine Learning for intelligent, predictive environmental analysis.

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