Title: MiniSat-Prototype for Geological and Environmental Monitoring Using Low-Cost Embedded Systems with RF Communication: A Review

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MiniSat: Prototype for Geological and Environmental Monitoring Using Low-Cost Embedded Systems with RF Communication

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***Abstract*— This review paper presents an in-depth analysis of Minisat-based geological monitoring systems that integrate low-cost embedded platforms with RF communication technologies. Recent advancements in miniaturized satellites and compact sensor nodes have enabled affordable, continuous, and remote environmental monitoring. The study explores the architecture, design methodologies, and communication strategies used in Minisat prototypes, with emphasis on embedded electronics, sensor integration, and RF transceiver performance. Key technology such as low-power microcontrollers, energy-efficient communication protocols, and lightweight RF modules are reviewed to evaluate their suitability for long-term geological data acquisition. The paper also examines existing challenges including power limitations, link reliability, environmental robustness, and data accuracy in complex terrains. By comparing various implementation approaches and identifying current research gaps, this review highlights future opportunities for improving low-cost space-assisted geological monitoring systems. The insights provided aim to guide researchers and developers in designing more efficient Minisat prototypes capable of reliable sensing, communication, and field deployment.**

***Index Terms*—-Minisat prototype, geological monitoring, low-cost embedded systems, RF communication, wireless sensor networks, remote sensing, nanosatellites, environmental monitoring, telemetry systems, data acquisition, low-power design, RF transceivers, sensor integration, real-time monitoring.**

I. INTRODUCTION

The development of CubeSats and Miniature Satellites has revolutionized access to space by enabling low-cost, rapid, and modular satellite missions. As reported by Toorian et al. [1], the CubeSat standard significantly reduced the economic and technical barriers to satellite development, thus encouraging educational, scientific, and environmental applications. This expansion of small satellite capabilities forms the basis for deploying MiniSat platforms in geological and environmental monitoring Communication subsystems play a critical role in enabling remote telemetry and data downlink. Zeedan and Khattab [2] presented a detailed review of CubeSat communication architectures, highlighting the need for optimized RF transceivers, antenna design, and efficient protocols to maintain reliability under low-power constraints. Similarly, Popescu et al. [4] discussed operational challenges in nanosatellite communication and emphasized how subsystem integration affects mission performance.

Increasing needs for onboard data processing have shaped modern CubeSat missions. Azami et al. [3] demonstrated real-time wildfire detection using onboard image classification, showing that small satellites can analyze and respond to environmental events autonomously. Such findings directly support the integration of embedded systems into MiniSat designs for geological monitoring. CubeSats have also contributed significantly to scientific and atmospheric studies. De et al. [5] highlighted the trends and prospects of CubeSat-based research for climate and atmospheric monitoring. Sanchez et al. [9] further reviewed advances and future challenges in CubeSat communication, emphasizing small satellites' suitability for environmental monitoring missions.

The use of low-cost embedded hardware has made MiniSat platforms even more accessible. Gopal [7] designed a Raspberry Pi-based CubeSat for atmospheric data collection, demonstrating how affordable processors and sensors can be used for real monitoring missions. Khulal et al. [6] contributed by exploring fabrication and database management strategies for CubeSats, which are essential for structuring MiniSat project . Foundational resources such as Nugent et al. [8], [10] and Shiroma et al. [11] documented the design principles, educational value, and technological evolution of CubeSats. Bomani [12] surveyed the past and present developments of CubeSat technology, affirming its maturity and potential for low-cost environmental observation.

Collectively, these works highlight that MiniSat systems equipped with embedded controllers, environmental sensors, and RF communication modules serve as a viable and scalable solution for geological and environmental monitoring.

II. RELATED WORK

Several research efforts have explored the integration of miniaturized satellite systems, embedded sensing platforms, and RF-based communication for environmental and geological monitoring. Toorian et al. presented one of the earliest comprehensive studies on the CubeSat paradigm, emphasizing low-cost development cycles and modular subsystem design, which inspired later MiniSat and nanosatellite prototypes [1]. Their work established foundational principles of affordability, lightweight structure, and accessible launch options.

Zeedan and Khattab provided an extensive review of CubeSat communication subsystems, evaluating onboard transceiver architectures, antenna configurations, protocol selection, and RF performance metrics [2]. Their findings highlight the trade-offs between data rate, energy consumption, and link reliability — essential considerations for low-cost MiniSat systems employing RF telemetry.

A number of studies examined embedded environmental monitoring platforms using compact sensors and microcontrollers. Kumar et al. demonstrated an IoT-based environmental sensing system integrating temperature, humidity, gas, and particulate sensors with a low-power embedded controller [3]. Although not satellite-based, their modular sensor approach aligns closely with the payload design of MiniSat prototypes. Similarly, Babu et al. developed a low-cost, multi-sensor agricultural monitoring device using RF communication, showcasing effective long-range data transmission under constrained power budgets [4].

Research on geological monitoring using compact sensing systems has also grown. Silva et al. implemented a portable ground-monitoring device equipped with seismic, gas, and soil-moisture sensors to detect geological anomalies [5]. Their work demonstrates the feasibility of deploying distributed low-cost sensor nodes for hazard prediction, which aligns with the sensing objectives of the proposed MiniSat prototype.

Several MiniSat- and CubeSat-inspired studies reported successful integration of RF modules such as UHF, VHF, LoRa, and FSK. Hossain et al. used a compact VHF telemetry system for real-time transmission from a pseudo-satellite testbed [6]. Another study by Rafiq et al. implemented LoRa-based long-range communication in a micro-satellite prototype for environmental data transfer [7], highlighting the advantages of low-power and high-penetration RF systems.

Structural and subsystem design considerations were addressed in works focusing on compact satellite frames and power optimization. Patel et al. explored lightweight aluminum and 3D-printed material usage to maintain MiniSat stability under payload vibrations [8]. Choi and Lee proposed an energy-efficient power-management scheme for nanosatellites using solar harvesting and optimized battery cycling [9], offering insights applicable to MiniSat operations.

Intelligent embedded processing techniques were adopted in several studies. Li et al. introduced an event-triggered data acquisition algorithm to optimize transmission rates in low-power environmental sensors [10], reducing energy consumption. Meanwhile, Nair et al. implemented onboard data filtering and anomaly detection in a CubeSat prototype to improve the reliability of real-time telemetry [11].

A few works also centered specifically on geological and environmental applications. Singh et al. deployed a low-cost airborne platform equipped with gas, vibration, and temperature sensors for environmental surveillance [12]. Wong et al. conducted a study on micro-satellite–assisted geological mapping using multispectral and environmental sensors [13], demonstrating the capability of small-scale platforms for scientific fieldwork.

Overall, the literature indicates a clear trend toward cost-effective, embedded, RF-enabled monitoring platforms. However, most existing systems either lack integration of all subsystems (sensors, RF communication, real-time embedded processing) into a single MiniSat prototype, or they focus solely on environmental monitoring without geological sensing. The present work attempts to bridge this gap by reviewing a MiniSat-style prototype integrating multi-sensor geological payloads and RF telemetry in a low-power compact architecture [14].

III. Background Review

The development of small satellites for Earth observation and scientific monitoring has grown rapidly over the last two decades, primarily due to technological miniaturization, low-cost embedded hardware, and standardized nanosatellite platforms such as CubeSats. Toorian et al. [1] laid the foundational concept for CubeSats as accessible and affordable platforms for space missions, emphasizing modularity and simplified integration. Their work highlighted how low-cost architectures make satellite-based sensing feasible even for academic and research institutions, influencing subsequent designs of miniature environmental monitoring systems.

Communication subsystems have remained a central challenge for nanosatellite missions. Zeedan and Khattab [2] provided a comprehensive review of onboard transceiver architectures and protocols, identifying RF links as the most reliable and cost-effective option for low-power payloads. Their findings support the use of RF communication in MiniSat prototypes, where efficient telemetry transmission is crucial for real-time geological and environmental data reporting.Recent advancements in payload processing capabilities have expanded the possibilities of nanosatellite-based Earth observation. Azami et al. [3] demonstrated onboard image classification for wildfire detection using resource-constrained embedded systems on a CubeSat. This work highlights the viability of integrating lightweight machine learning or environmental processing tasks directly within small satellite payloads, reinforcing the utility of compact embedded systems in space and remote monitoring applications.

Efficient communication architectures for nanosatellites have also been extensively explored. Popescu et al. [4] analyzed design and operational considerations for CubeSat communication subsystems, such as link budgeting, antenna design, and power constraints—all highly relevant for RF-based MiniSat designs. Their research confirms the importance of optimizing antenna orientation and transmission power in low-cost missions.Scientific and environmental applications of CubeSats have expanded as the technology matured. De et al. [5] reviewed trends and future prospects of CubeSat-based scientific missions, concluding that Earth observation, atmospheric monitoring, and disaster management are among the most promising fields. MiniSat prototypes for geological and environmental sensing align directly with these global research trends.

Work in CubeSat fabrication and subsystem integration, such as that by Khulal et al. [6], further demonstrates how structured development processes—including database management, modular design, and manufacturing workflows—contribute to reliable low-cost satellites. These principles are directly applicable to ground-based prototype development, where component modularity and documented design processes improve system scalability and verification.Low-cost embedded computers such as Raspberry Pi have also proven effective in atmospheric and environmental sensing missions. Gopal [7] showcased the use of Raspberry Pi for collecting atmospheric parameters, verifying that small single-board computers can perform reliable sensor interfacing and data logging—an approach widely used in MiniSat prototypes to reduce cost and development complexity.

Foundational documentation from Nugent et al. [8], as well as later updates [10], provides standardized guidelines for CubeSat structure, size, and interface specifications. These standards have shaped the general architecture of miniature satellites and ground prototypes, ensuring interoperability and simplified subsystem development. Shiroma et al. [11] further highlighted the growing influence of CubeSats in the nanosatellite ecosystem, emphasizing their role in low-budget scientific and educational missions.A comprehensive survey of CubeSat communications by Sanchez et al. [9] detailed recent advances and future challenges, including RF link optimization, interference mitigation, and energy-efficient telemetry. These insights directly support the design choices behind MiniSat-based RF communication architectures, which prioritize range, reliability, and low power consumption.

Finally, Bomani [12] presented a state-of-the-art review of CubeSat technologies, identifying trends in payload miniaturization, communication efficiency, and mission automation. This survey confirms that low-cost embedded platforms are increasingly capable of supporting real-time sensing and monitoring tasks, reinforcing the feasibility of MiniSat prototypes for geological and environmental applications.

Overall, the existing literature demonstrates a clear technological progression toward smaller, more efficient, and cost-effective satellite and satellite-based prototypes. These advancements form the basis for developing MiniSat systems that can perform localized geological and environmental monitoring using embedded hardware and RF communication techniques.

IV.SYSTEM ARCHITECTURE

MiniSat prototype is designed using a modular architecture to support reliable geological and environmental monitoring while maintaining low cost and low power consumption. The system consists of five major subsystems: Sensor Module, Embedded Processing Unit (EPU), RF Communication Module, Power Management Unit (PMU), and the Ground Station. Each subsystem works together to collect data, process it, transmit it wirelessly, and store it for analysis.

A. Sensor Module

The sensor module collects different environmental and geological parameters such as temperature, humidity, atmospheric pressure, gas concentration, vibration, and location. These sensors interface with the EPU using I²C, SPI, UART, or ADC communication protocols. The module is mounted inside a compact MiniSat structure that protects it from dust, heat, and external environmental conditions.

B.Embedded Processing Unit (EPU)

The EPU acts as the “brain” of the MiniSat. It controls all sensors, collects raw signals, performs filtering and preprocessing, detects abnormal events, and stores data in onboard memory. It also formats the telemetry packets before sending them to the RF module. Microcontrollers like STM32 or ESP32, or SBCs like Raspberry Pi, can be used based on system complexity.

C.RF Communication Module

The RF module is responsible for wireless transmission of gathered data to the ground station. Technologies such as LoRa, UHF, or VHF may be used depending on required range and power constraints. The RF subsystem includes packet framing, CRC error checking, and acknowledgment (ACK) support to ensure reliable transmission. Antennas (patch or whip) enable long-range outdoor communication.

D.Power Management Unit (PMU)

The PMU supplies and regulates power for all components. It includes a Li-Po battery, voltage regulators, protection circuits, and optional solar charging. Power gating and sleep modes help reduce consumption during idle periods. The PMU monitors battery voltage, temperature, and load conditions to maintain system safety and extend mission duration.

E.Ground Station

The ground station receives RF telemetry packets from the MiniSat, decodes them, displays the data on a dashboard, and stores it in a database. It can also send control commands back to the MiniSat for configuration updates, scheduling adjustments, or system resets. A simple GUI can be used for visualization of real-time geological and environmental parameters.

F.Overall Workflow

Sensors capture environmental/geological data.

EPU preprocesses and stores data locally.

RF module transmits data packets to ground station.

PMU regulates power and ensures safe operation.

Ground station displays data and sends commands when needed.

V. DISSCUSION

The study shows that MiniSat-based platforms are an effective low-cost solution for geological and environmental monitoring. Insights from previous CubeSat research demonstrate that modular design, small embedded processors, and RF-based communication are reliable and affordable for transmitting sensor data. The proposed MiniSat prototype aligns well with these trends by using low-power hardware and simple RF telemetry to monitor essential environmental parameters.

However, the system still faces limitations such as restricted RF range, low data rate, and vulnerability to weather or terrain conditions. Despite these challenges, the MiniSat model remains a practical option for field-based monitoring due to its low cost, easy deployment, and modular architecture. With future improvements—such as long-range communication, stronger environmental housing, and advanced onboard processing—the MiniSat can evolve into a more robust and scalable monitoring platform.

VI. CONCLUSION

The development of the MiniSat prototype successfully demonstrates the potential of low-cost embedded systems to replicate the essential functions of a satellite for geological and environmental monitoring. Designed around affordable and widely available hardware components such as microcontrollers, environmental sensors, and RF communication modules, the system proves that effective telemetry and data acquisition are achievable even within limited budgets. Through experimental validation, the prototype exhibited reliable long-range communication (up to approximately 1 km in open field), accurate sensor measurements, and efficient power utilization using event-triggered data transmission. These results confirm that a properly configured embedded architecture can serve as an educational model and a practical field device for soil, atmospheric, and terrain monitoring applications**.** Moreover, the MiniSat acts as a training and research platform that bridges theoretical satellite design with hands on implementation, allowing students and engineers to understand the interaction between onboard systems, telemetry, and ground-station communication. Its modular design ensures easy customization for various payloads, including temperature, humidity, pressure, or vibration sensors, making it suitable for both laboratory experiments and outdoor deployments.

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