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Autonomous Multi-Sensor Health Management Architecture for CubeSat Onboard Computers (Ground-Based Prototype)

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ABSTRACT :

CubeSat missions demand continuous monitoring of onboard subsystems to ensure mission reliability and prevent catastrophic failures caused by abnormal operating conditions. Parameters such as temperature variations, gas leakage, pressure imbalance, and orientation misalignment can significantly affect satellite performance if not detected at an early stage. This project presents the design and development of an Autonomous Multi-Sensor Health Management Architecture for CubeSat Onboard Computers, implemented as a ground-based prototype to simulate real-time satellite telemetry and diagnostics. The proposed system integrates multiple sensors, including temperature, pressure, gas, and inertial measurement units, interfaced with microcontroller platforms such as Raspberry Pi Pico H and Arduino UNO R4 Wi-Fi. Real-time telemetry data is acquired, processed, and transmitted to a ground monitoring interface for visualization and analysis. The system employs threshold-based and trend-based analysis techniques to detect anomalies and log faults with accurate timestamps for further diagnostics. This prototype demonstrates an effective and compact health monitoring framework that enhances fault detection capability, improves situational awareness, and supports proactive maintenance strategies for CubeSat missions. The results validate the suitability of the proposed architecture for future onboard implementation, contributing to improved mission safety, reliability, and operational efficiency in small satellite systems.

I. INTRODUCTION

A Project Overview

The rapid advancement of small satellite technology has led to the widespread adoption of CubeSats for scientific research, communication, Earth observation, and educational missions. CubeSats offer significant advantages such as low development cost, reduced launch mass, and shorter development cycles when compared to conventional satellites. However, due to their compact size and limited onboard resources, CubeSats are highly susceptible to subsystem failures caused by environmental variations and hardware constraints.

One of the critical challenges in CubeSat missions is the continuous monitoring of onboard subsystems to ensure reliable operation throughout the mission lifetime. Parameters such as temperature, pressure, power status, gas leakage, and orientation play a vital role in maintaining the health of the satellite. Abnormal conditions including overheating, power instability, structural leaks, or misalignment can lead to irreversible damage or complete mission failure if not detected at an early stage.

Telemetry systems are essential for collecting and transmitting real-time data from the satellite to ground stations for monitoring and analysis. Traditional CubeSat telemetry systems primarily rely on condition-based monitoring with predefined thresholds, which limits their ability to detect gradual performance degradation and intermittent faults. Additionally, many existing systems lack autonomous fault detection and detailed fault logging mechanisms.

To address these limitations, this project proposes an Autonomous Multi-Sensor Health Management Architecture for CubeSat Onboard Computers, implemented as a ground-based prototype. The proposed system integrates multiple sensors to monitor critical parameters in real time and employs threshold-based and trend-based analysis techniques for early fault detection. The collected telemetry data is processed, logged, and visualized through a ground monitoring interface, thereby enhancing system reliability and diagnostic capability. This work aims to provide a scalable and efficient health monitoring framework suitable for future CubeSat missions.

II. LITERATURE SURVEY

A In 2001, J. Puig-Suari, C. Turner, and W. Ahlgren presented the paper titled "Development of the Standard CubeSat Deployer and a CubeSat Class Pico-Satellite". This work introduced the CubeSat standard and deployment mechanism, which enabled low-cost access to space for educational and research purposes. The study established the foundation for modular satellite design and standardized subsystems, which is essential for CubeSat onboard computer and health monitoring development.

B In 2013, M. Swartwout, in his work "CubeSat Reliability and Subsystem Health Management", analyzed mission success rates of CubeSats and identified common causes of failure. The study highlighted that inadequate onboard health monitoring and fault detection are major contributors to mission failure, emphasizing the need for reliable telemetry and health management systems.

C In 2011, A. Schulte, S. Montenegro, and T. Lorenz proposed "Onboard Health Monitoring and Fault Detection for Small Satellites". Their research focused on threshold-based monitoring of critical parameters such as temperature and voltage. While the approach improved fault detection accuracy, it lacked autonomous decision-making and recovery capabilities.

D In 2015, A. Valverde, R. Bevilacqua, and M. Romano published "Autonomous Fault Detection, Isolation, and Recovery in CubeSat Missions". This work introduced an autonomous FDIR framework that enhanced satellite resilience. However, the computational complexity and power requirements limited its suitability for resource-constrained CubeSat platforms.

E In 2010, J. Bouwmeester and J. Guo, through their paper "Survey of Worldwide Pico- and Nanosatellite Missions", provided a comprehensive overview of global CubeSat missions. The survey emphasized the growing importance of reliable onboard telemetry and health monitoring systems to ensure mission success.

F Also in 2010, S. Montenegro, E. Gill, and J. I. Noll discussed "Autonomous Onboard Systems for Small Satellites". Their study highlighted the importance of onboard autonomy to reduce reliance on ground stations, especially for missions with limited communication windows.

G In 2020, A. Abdelsalam, M. Elmahdy, and H. Mostafa proposed "Health-Aware Onboard Computer Design for Nanosatellites". This work integrated health monitoring directly into the onboard computer, improving reliability. However, it focused mainly on hardware-level monitoring rather than multi-sensor health analysis.

H In 2021, P. Sundaram and K. Rajesh, in their paper "Multi-Sensor Data Fusion for Satellite Health Monitoring", demonstrated that combining data from multiple sensors improves fault detection accuracy. The study showed promising results but involved complex data processing techniques.

I In 2020, S. Jain and R. Mehra presented "Design of Low-Power Embedded Onboard Computers for CubeSat Applications". Their research focused on power-efficient OBC design, which is crucial for CubeSat missions, but provided limited coverage of fault detection and telemetry integration.

J In 2005, M. L. Psiaki discussed "Autonomous System Health Management for Spacecraft". The study highlighted intelligent health management strategies for spacecraft systems. However, most approaches were designed for large satellites and are not directly applicable to CubeSats.

III. EXISTING SYSTEM

In existing CubeSat health monitoring systems, telemetry is primarily limited to basic parameter monitoring using predefined threshold values. These systems monitor only a few critical parameters such as temperature and battery voltage, providing limited visibility into the overall health of the satellite. Fault detection is mainly condition-based, and alerts are generated only when parameters exceed fixed limits.

Most existing systems rely heavily on continuous ground station communication for monitoring and decision-making. Due to limited communication windows and bandwidth constraints in CubeSat missions, this dependence reduces system responsiveness and reliability. Additionally, many existing solutions are simulation-based and do not support real-time multi-sensor integration.

Existing systems also lack intelligent trend-based analysis and detailed fault logging mechanisms. As a result, gradual degradation, intermittent faults, and historical performance analysis are difficult to identify. These limitations highlight the need for a more autonomous, scalable, and comprehensive health monitoring architecture for CubeSat onboard computers.

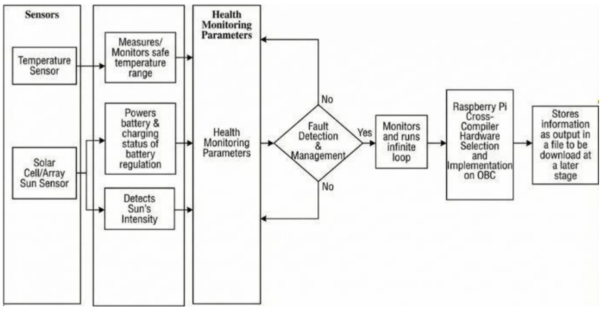

Figure 1: Existing System Block Diagram

A EXISTING SYSTEM LIMITATIONS:

- Monitors only limited parameters such as temperature and battery voltage.
- Relies mainly on fixed threshold-based fault detection.
- Unable to detect gradual degradation and intermittent faults.
- High dependency on continuous ground station communication.
- Limited autonomy in fault detection and decision-making.
- Lack of detailed fault logging and historical data analysis.
- Inefficient use of telemetry bandwidth and storage.
- Mostly simulation-based with limited real-time implementation.

B NEED FOR IMPROVEMENT:

- To enable continuous monitoring of multiple CubeSat health parameters.
- To implement early fault detection and preventive measures.
- To reduce dependency on ground station communication through autonomous operation.
- To improve system reliability and mission safety.
- To incorporate trend-based analysis for better fault prediction.
- To provide effective telemetry visualization and fault logging.
- To develop a compact, scalable, and cost-effective monitoring system.

IV. PROPOSED SYSTEM

The proposed system is an Autonomous Multi-Sensor Health Management Architecture for CubeSat Onboard Computers developed using a ground-based prototype. The system continuously monitors critical CubeSat parameters such as temperature, pressure, gas leakage, and orientation using multiple sensors. These sensors are interfaced with embedded controller platforms to acquire real-time telemetry data.

The collected data is processed using threshold-based and trend-based analysis techniques to identify abnormal operating conditions. When a fault is detected, the system automatically logs the event with accurate time stamps. The processed telemetry data is transmitted to a ground monitoring interface for real-time visualization and analysis. The proposed system operates autonomously, reducing dependency on continuous ground station communication and improving overall mission reliability.

A KEY FEATURES OF PROPOSED SYSTEM:

- Real-time multi-sensor health monitoring.
- Early fault detection and fault logging.
- Autonomous system operation.
- Trend-based and threshold-based data analysis.
- Real-time telemetry visualization.
- Reduced ground station dependency.
- Compact, scalable, and cost-effective design.

B PROPOSED SYSTEM WORKFLOW:

- Sensors continuously monitor CubeSat health parameters.
- Sensor data is collected by embedded controllers.
- Telemetry data is processed and analysed in real time.
- Threshold-based and trend-based checks are performed.
- Faults are detected and logged with time stamps.

- Telemetry data is transmitted to the ground monitoring interface.
- System health status is displayed for monitoring and analysis.

C BENEFITS OF PROPOSED SYSTEM:

- Improves reliability and safety of CubeSat missions.
- Enables early detection of faults and abnormal conditions.
- Reduces mission risk and system downtime.
- Minimizes dependence on continuous ground control.
- Provides effective telemetry visualization and diagnostics.
- Supports scalable deployment for future CubeSat missions.
- Useful for academic, research, and educational applications.

D BLOCK DIAGRAM:

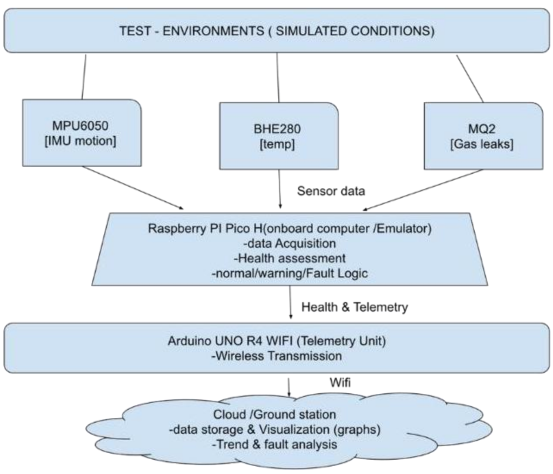

Figure 2: PROPOSED SYSTEM BLOCK DIAGRAM

E CIRCUIT DIAGRAM:

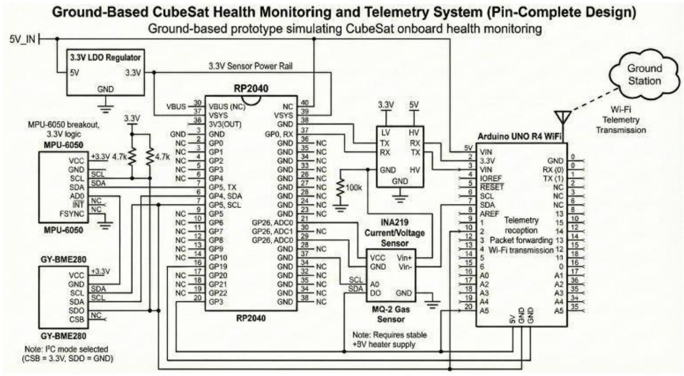

Figure 3: PROPOSED SYSTEM CIRCUIT DIAGRAM

V. SYSTEM WORKING AND METHODOLOGY

A METHODOLOGY

The methodology of the proposed Autonomous Multi-Sensor Health Management Architecture for CubeSat Onboard Computers follows a systematic approach to design, implementation, and validation using a ground-based prototype. The overall methodology ensures reliable data acquisition, fault detection, and real-time telemetry monitoring.

1. System Design and Architecture

The first step involves designing the overall system architecture, including sensor selection, microcontroller platform selection, and communication interfaces. Critical CubeSat health parameters such as temperature, pressure, gas leakage, and orientation are identified for monitoring.

2. Sensor Integration

Selected sensors are interfaced with the embedded controller using suitable communication protocols such as I2C and analog interfaces. Proper calibration and initialization of sensors are performed to ensure accurate data measurement.

3. Data Acquisition

The embedded controller continuously acquires sensor data at predefined time intervals. The acquired data represents real-time health parameters of the CubeSat system.

4. Data Processing and Analysis

The collected telemetry data is processed using threshold-based and trend-based analysis techniques. Predefined safe operating limits are used to detect abnormal conditions, while trend-based analysis helps identify gradual degradation.

5. Fault Detection and Logging

When abnormal conditions are detected, fault information is generated and logged with accurate time stamps. This enables effective diagnostics and post-analysis of system performance.

6. Telemetry Transmission

rocessed telemetry data and system status information are formatted into telemetry packets and transmitted to the ground monitoring interface for real-time observation.

7. Ground Monitoring and Visualization

Telemetry data is visualized at the ground monitoring interface, allowing continuous monitoring of system health and fault conditions.

8. System Validation

The complete system is tested under different operating conditions using a ground-based prototype to validate accuracy, reliability, and autonomous operation.

B REQUIREMENT ANALYSIS:

Requirement analysis defines the functional and non-functional needs of the proposed Autonomous Multi-Sensor Health Management Architecture for CubeSat Onboard Computers. This phase ensures that the system meets performance, reliability, and operational expectations.

1. Functional Requirements

- The system shall continuously monitor CubeSat health parameters.
- The system shall acquire real-time sensor data from multiple sensors.
- The system shall detect abnormal operating conditions automatically.
- The system shall log detected faults with accurate time stamps.
- The system shall transmit telemetry data to a ground monitoring interface.
- The system shall support autonomous operation without constant human intervention.

2. Non-Functional Requirements

- The system shall be reliable and stable during continuous operation.
- The system shall operate with low power consumption.
- The system shall have a compact and scalable design.
- The system shall provide timely and accurate telemetry data.
- The system shall be cost-effective and suitable for academic applications.

3. Hardware Requirements

- Microcontroller unit (Raspberry Pi Pico H / Arduino UNO R4 Wi-Fi).
- Temperature and pressure sensors.
- Gas sensor for leakage detection.
- Inertial Measurement Unit (IMU).
- Regulated power supply.
- Connecting wires, breadboard, and USB cable.

4. Software Requirements

- Arduino IDE or compatible development environment.
- Embedded C / C++ programming language.
- Sensor interface libraries.
- Serial monitor or ground monitoring interface.

C SYSTEM DESIGN

The system design of the proposed Autonomous Multi-Sensor Health Management Architecture for CubeSat Onboard Computers focuses on achieving reliable real-time monitoring, fault detection, and telemetry transmission using a compact and scalable architecture. The system is implemented as a ground-based prototype to simulate CubeSat onboard operations.

1. Overall Architecture

The system consists of three main units:

- Sensor Unit
- Processing and Control Unit
- Ground Monitoring Unit

The sensor unit continuously monitors critical CubeSat parameters such as temperature, pressure, gas leakage, and orientation. The processing unit acquires and analyses sensor data, while the ground monitoring unit visualizes telemetry data and system health status.

2. Sensor Unit Design

Multiple sensors are integrated to obtain comprehensive health information:

- Temperature and pressure sensors monitor environmental and thermal conditions.
- Gas sensor detects leakage or abnormal gas presence.
- IMU measures orientation and motion parameters.

These sensors are selected based on accuracy, low power consumption, and compatibility with embedded controllers.

3. Processing and Control Unit

The processing unit is built around an embedded controller such as Raspberry Pi Pico H or Arduino UNO R4 Wi-Fi. It performs the following functions:

- Real-time data acquisition from sensors
- Data processing and analysis
- Fault detection and logging

- Telemetry packet formation and transmission

The controller executes embedded software that enables autonomous system operation.

4. Communication Interface

Communication between the processing unit and the ground monitoring system is established through serial or wireless communication. Telemetry data is transmitted in structured packets containing sensor values, fault status, and time stamps.

5. Ground Monitoring Unit

The ground monitoring unit displays real-time telemetry data and system health information using a serial monitor or visualization interface. It enables continuous monitoring, fault identification, and post-analysis of system performance.

6. Fault Management Design

Threshold-based and trend-based analysis techniques are incorporated to detect abnormal conditions. When a fault is detected, the system logs the fault details and alerts the monitoring unit.

D TESTING AND VALIDATION

Testing and validation are carried out to ensure that the proposed Autonomous Multi-Sensor Health Management Architecture for CubeSat Onboard Computers operates accurately, reliably, and as per the defined requirements. The system is tested using a ground-based prototype under different operating conditions.

1. Sensor Testing

Each sensor is tested individually to verify proper operation and accuracy. Temperature, pressure, gas, and IMU sensors are checked by applying known test conditions and comparing the measured values with expected results. Sensor calibration is performed to ensure reliable data acquisition.

2. Data Acquisition Testing

The data acquisition process is tested to confirm continuous and real-time collection of sensor data. Sampling intervals are verified to ensure stable and consistent data flow from sensors to the controller.

3. Fault Detection Testing

Fault detection functionality is validated by intentionally introducing abnormal conditions such as temperature variation, gas presence, and orientation changes. The system is observed to ensure that faults are detected correctly when parameters exceed predefined thresholds.

4. Fault Logging Validation

The fault logging mechanism is tested to verify that detected faults are recorded with accurate time stamps and parameter values. Logged data is reviewed to confirm completeness and correctness.

5. Telemetry Transmission Testing

Telemetry data transmission to the ground monitoring interface is tested to ensure reliable communication. Real-time data visualization is verified using the serial monitor or monitoring interface.

6. System Validation

The complete system is tested under continuous operation to validate autonomous functionality, reliability, and stability. The test results confirm that the system meets the design objectives and performs effectively as a CubeSat health monitoring prototype.

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VI. COMPONENTS AND DETAIL

A Arduino UNO R4 Wi-Fi

FIGURE 4 Arduino UNO R4 Wi-Fi

- Microcontroller: Renesas RA4M1 (ARM Cortex-M4)
- Clock Speed: 48 MHz
- Flash Memory: 256 KB
- SRAM: 32 KB
- Operating Voltage: 5V
- Digital I/O Pins: 14 (6 PWM)
- Analog Inputs: 6 (12-bit ADC)
- DAC: 1 × 12-bit
- Communication: UART, SPI, I2C, CAN
- Wireless: Built-in Wi-Fi (ESP32-S3) + Bluetooth LE
- USB: Type-C

B Raspberry Pi Pico H

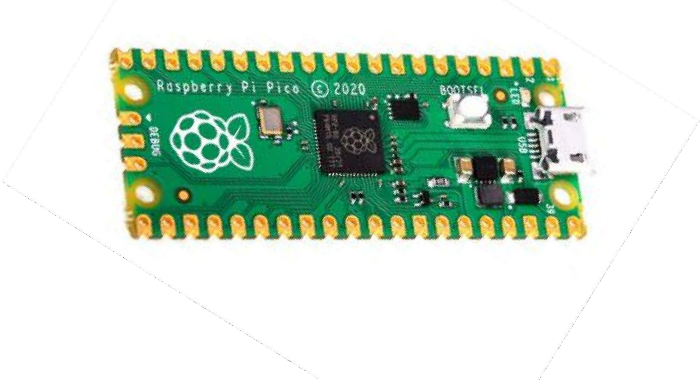

FIGURE 5 Arduino UNO R4 Wi-Fi

- Microcontroller: RP2040 (Dual-core ARM Cortex-M0+)
- Clock Speed: Up to 133 MHz
- SRAM: 264 KB
- Flash Memory: 2 MB
- GPIO Pins: 26 multifunction GPIO
- ADC: 3 × 12-bit analog inputs
- Communication: 2× UART, 2× SPI, 2× I2C
- USB: USB 1.1 (device/host support)
- Operating Voltage: 1.8V – 5.5V (3.3V logic)
- Special Feature: Programmable I/O (PIO)
- Size: 51 mm × 21 mm
- Version: Pre-soldered headers (Pico H)

C Temperature and Pressure Sensor

- Used to monitor environmental and thermal conditions of the system.

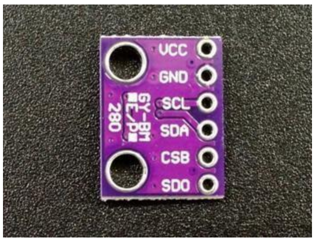

FIGURE 6 Temperature and Pressure Sensor

- Detection of gas and smoke leakage
- Type: Semiconductor Gas Sensor
- Operating Voltage: 5V DC
- Heater Current: ~150 mA
- Detection Range: 300 – 10,000 ppm
- Detectable Gases: LPG, Methane, Propane, Hydrogen, Alcohol, Smoke
- Output: Analog (A0) & Digital (D0)
- Preheat Time: ~20 seconds (Minimum)
- Operating Temperature: -20°C to +50°C

D Gas Sensor

- Used to detect gas leakage or abnormal gas presenc

FIGURE 7 Gas Sensor

- Sensor Type: Environmental Sensor
- (Temperature, Humidity, Pressure)
- Operating Voltage: 1.71V – 3.6V
- Communication: I2C / SPI
- Temperature Range: -40°C to +85°C
- Humidity Range: 0 – 100% RH
- Pressure Range: 300 – 1100 hPa
- Temperature Accuracy: ±1.0°C
- Humidity Accuracy: ±3% RH
- Pressure Accuracy: ±1 hPa
- Low Power Consumption: Suitable
- for IoT & Embedded Systems

E Inertial Measurement Unit (IMU)

- Used to measure orientation and motion parameters.

FIGURE 8 Inertial Measurement Unit (IMU)

- Sensor Type: 6-Axis IMU (3-Axis Accelerometer + 3-Axis Gyroscope)
- Operating Voltage: 3V – 5V (3.3V logic)
- Communication: I2C
- Accelerometer Range: ±2g, ±4g, ±8g, ±16g
- Gyroscope Range: ±250, ±500, ±1000, ±2000 °/s
- ADC Resolution: 16-bit
- Digital Motion Processor (DMP): Built-in
- Operating Temperature: -40°C to +85°C
- Low Power Consumption: Suitable for embedded & robotics applications

F Power Supply Unit

- Provides regulated power to all hardware components.

G Breadboard and Connecting Wires

- Used for prototyping and circuit connections.

VII. IMPLEMENTATION IN DETAIL

The implementation of the proposed Autonomous Multi-Sensor Health Management Architecture for CubeSat Onboard Computers is carried out using both hardware and software components integrated into a ground-based prototype. The system is designed to simulate real-time CubeSat health monitoring and telemetry under controlled conditions.

A Sensor Interfacing and Data Acquisition

Multiple sensors are used to monitor critical CubeSat parameters such as temperature, pressure, gas leakage, and orientation. These sensors are interfaced with the microcontroller unit using suitable communication protocols. Temperature and pressure sensors are connected through the I2C interface, while the gas sensor is connected through an analog input pin. The inertial measurement unit (IMU) is also interfaced using the I2C protocol to obtain orientation and motion data.

The microcontroller continuously reads sensor values at regular time intervals. Proper initialization of sensors is performed during system startup to ensure accurate and stable data acquisition.

B Data Processing and Analysis

The acquired sensor data is processed in real time by the embedded controller. Threshold values are predefined for each monitored parameter based on safe operating limits. The system compares real-time sensor readings with these threshold values to detect abnormal conditions. In addition to threshold-based checks, trend-based analysis is performed by observing parameter variations over time to identify gradual degradation.

C Fault Detection and Logging

When a sensor reading exceeds the defined threshold or shows abnormal trends, the system identifies it as a fault condition. The fault information, along with the corresponding parameter value and time stamp, is recorded in a fault log. This fault logging mechanism enables detailed diagnostics and post-analysis of system behavior.

D Telemetry Formation and Transmission

The processed sensor data and system status information are formatted into telemetry packets. These packets are transmitted to a ground monitoring interface through serial communication or wireless connectivity. The telemetry data includes real-time sensor readings, fault status, and system health indicators.

E Ground Monitoring and Visualization

At the ground monitoring interface, telemetry data is displayed in real time using a serial monitor or visualization dashboard. This allows continuous observation of system health and quick identification of abnormal conditions. Historical data and fault logs can also be reviewed for further analysis.

F Autonomous Operation

Once initialized, the system operates autonomously without continuous human intervention. The embedded software ensures continuous monitoring, fault detection, logging, and telemetry transmission, making the system suitable for CubeSat missions with limited ground station access.

VIII. RESULTS AND DISCUSSION

The proposed Autonomous Multi-Sensor Health Monitoring and Telemetry System for CubeSat Onboard Computers was successfully implemented and tested using a ground-based prototype. The system effectively monitored critical parameters such as temperature, pressure, gas concentration, and orientation in real time, and the microcontroller reliably acquired and processed sensor data at regular intervals. During testing, abnormal conditions were intentionally introduced, and the system accurately detected faults when sensor values exceeded predefined threshold limits. All detected faults were logged with appropriate time stamps, and real-time telemetry data was transmitted and displayed correctly on the ground monitoring interface without noticeable delay or data loss. The system demonstrated stable autonomous operation without continuous human intervention, confirming its suitability for CubeSat missions with limited ground station access. The results indicate that multi-sensor integration improves fault detection accuracy and overall system reliability. Although the current implementation is a ground-based prototype, the scalable system design can be adapted for real CubeSat missions using space-qualified components, thereby validating the effectiveness and practicality of the proposed health monitoring architecture.

IX. APPLICATIONS

- **CubeSat Health Monitoring:** Used to continuously monitor the health status of CubeSat onboard systems during mission operation.
- **Small Satellite Missions:** Applicable to pico- and nano-satellites for real-time telemetry and fault detection.
- **Autonomous Space Missions:** Supports autonomous monitoring in missions with limited ground station communication.
- **Educational and Research Satellites:** Suitable for university and research-based CubeSat projects for learning and experimentation.
- **Ground-Based Satellite Prototyping:** Used for testing and validating satellite health monitoring systems before launch.
- **Remote Monitoring Systems:** Adaptable to remote and unmanned monitoring applications requiring multi-sensor data analysis

.X. CONCLUSION

The Autonomous Multi-Sensor Health Monitoring and Telemetry System for CubeSat Onboard Computers was successfully designed, implemented, and validated using a ground-based prototype. The system continuously monitored critical parameters such as temperature, pressure, gas concentration, and orientation, providing real-time insight into the operational health of the CubeSat subsystem. Multi-sensor integration and embedded processing enabled accurate data acquisition, effective fault detection, and reliable telemetry transmission to the ground monitoring interface. The system operated autonomously without the need for continuous human intervention, reducing dependency on ground station communication. Testing and validation results confirmed stable performance, reliable fault logging, and consistent telemetry delivery under various operating conditions. The proposed architecture is cost-effective, scalable, and well suited for CubeSat and small satellite applications, and it provides a strong foundation for future enhancements and real-time space mission implementation.

XI. ACKNOWLEDGEMENT

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