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INTEGRATION OF SMART SENSOR NETWORKS AND VISION-BASED ANALYSIS FOR REALTIME CONSTRUCTION QUALITY MANAGEMENT

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***Abstract*— Construction sites are inherently hazardous and demand continuous monitoring to ensure both worker safety and structural integrity. Traditional manual inspections and wired sensor systems fall short in providing real-time, comprehensive coverage. This paper presents the design, implementation, and field validation of a low-cost, wireless Structural Health Monitoring (SHM) system integrating Internet of Things (IoT), drone technology, and Artificial Intelligence (AI). The proposed framework utilizes an ESP32 microcontroller paired with MPU6050 Inertial Measurement Units (IMUs), DHT22 temperature sensors, and capacitive moisture sensors. Data is securely streamed via MQTT to the Thinger.io cloud platform. Configured threshold breaches automatically trigger drone deployment (DJI Matrice 300 RTK) for targeted visual inspection, where a fine-tuned VGG16 Convolutional Neural Network achieves 99.2% accuracy in identifying concrete cracks. Field deployment results over 20 days demonstrate 99.8% data transmission reliability and early anomaly detection capabilities, offering significant improvements in safety response and an estimated 50-80% cost reduction over traditional methods.**

***Index Terms*— Structural Health Monitoring (SHM), IoT, ESP32, MPU6050, Drone Inspection, VGG16, Thinger.io.**

I. INTRODUCTION

Construction sites rank among the most hazardous workplaces globally, accounting for approximately 17% of all occupational fatalities despite comprising only 7% of the workforce. Beyond the immediate risk of fatal accidents, structural deficiencies such as cracks, excessive vibration, moisture ingress, and differential settlement pose persistent threats to both worker safety and the long-term durability of constructed assets. Traditional structural health monitoring (SHM) approaches—relying on periodic manual inspections or rigid wired strain gauge installations—are fundamentally inadequate for the continuous, multi-parameter monitoring required on active, large-scale outdoor construction sites.

This research addresses these deficiencies by developing an integrated monitoring system combining a low-cost IoT sensor network and drone-based aerial surveillance. Built around the ESP32 microcontroller and MPU6050 IMUs, the IoT network continuously measures vibration acceleration, ambient temperature, and concrete moisture. Transmitting via MQTT over TLS to the Thinger.io cloud platform, the system enables real-time visualization and automated rule-based alerting. Crucially, when structural anomalies are detected, the system automatically dispatches a drone for visual inspection, utilizing a VGG16-based Convolutional Neural Network (CNN) to detect surface cracking.

II. SYSTEM ARCHITECTURE

The integrated SHM framework consists of three primary subsystems: IoT sensor networks, cloud telemetry, and AI-enabled drone visual inspection.

A. IoT Sensor Hardware

The core of the IoT node is the ESP32 microcontroller, selected for its dual-core 240 MHz architecture, integrated Wi-Fi capabilities, and low-power operation. Structural vibration is measured using the MPU6050 six-axis MEMS IMU, configured for a ±2g range yielding high resolution (0.61 mg/LSB). Readings are converted into m/s² units for compliance with ISO 2631-1. Ambient temperature is captured via the DHT22 sensor, while concrete moisture is monitored using a capacitive moisture probe, which calculates the dielectric constant variations of the material.

Fig. 1. ESP32 Microcontroller Node Architecture.

B. Cloud Telemetry and Thinger.io

Data is transmitted using the MQTT protocol over TLS to ensure encryption and security. Thinger.io serves as the cloud backend, providing device management, time-series data storage, and a real-time visualization dashboard. A critical component is the Thinger.io rule engine, which evaluates incoming JSON payloads against predefined threshold limits (e.g., vibration > 2.80 m/s², temperature > 42°C, moisture > 18%).

C. Automated Drone Deployment

Upon threshold violation, the rule engine initiates an HTTP POST command via the DJI Ground Station Pro API. This autonomous command dispatches a DJI Matrice 300 RTK drone to the exact GPS coordinates of the flagged sensor. The drone captures high-resolution imagery of the structural zone, which is subsequently transmitted for edge-processing.

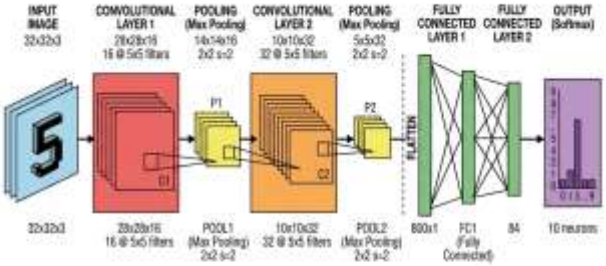


Fig. 2. Integrated System Architecture Data Flow.

III. HARDWARE AND FIRMWARE IMPLEMENTATION

The firmware, developed in C++ using the Arduino IDE, establishes a strictly non-blocking architecture ensuring simultaneous data acquisition, processing, and communication. The firmware handles dual I2C buses (Wire and Wire1) to accommodate four MPU6050 sensors simultaneously, bypassing I2C address conflicts.

The main operational loop utilizes the millis() function for precise timing of sensor reads (every 10ms), OLED display updates (every 200ms), and Wi-Fi watchdog checks. Vibration signals undergo Exponential Moving Average (EMA) filtering to remove DC offsets and isolate dynamic acceleration. The system incorporates bidirectional control logic through Thinger.io, allowing dynamic adjustments of the vibration threshold slider which are written directly to the ESP32's Non-Volatile Storage (NVS). In the event of a critical threshold breach, the ESP32 triggers fallback notification mechanisms, pushing alerts to ntfy.sh and dispatching Twilio SMS messages containing localized sensor telemetry.

IV. FIELD DEPLOYMENT AND EXPERIMENTAL RESULTS

The integrated framework was deployed for a 20-day monitoring campaign on a four-story reinforced concrete frame under construction. Four identical IoT nodes (North, South, East, West) were securely anchored to the structural columns. A total of 1,200 scheduled readings were recorded.

A. Telemetry Reliability and Thinger.io Dashboards

The system achieved a 99.8% data transmission success rate with a mean MQTT latency of 185 ms over a 4G LTE connection. The data was visualized in real-time using Thinger.io dashboards.

Fig. 3. Thinger.io Dashboard - Vibration Trend Analysis.

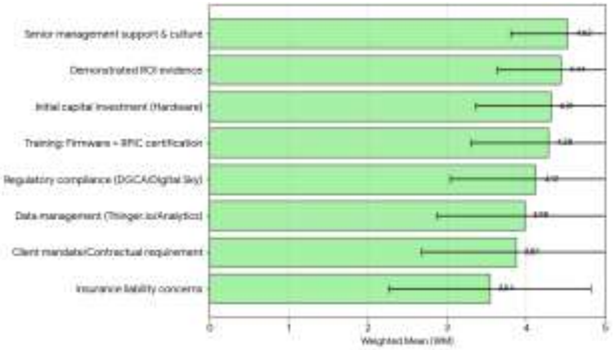


Fig. 4. Sensor Data Analysis Charts.

B. Vibration and Environmental Trends

Vibration readings across the nodes established baseline normative behaviors, with the North node experiencing the highest mean vibration (1.87 m/s²) due to prevailing wind dynamic loading. Linear regression analysis identified a statistically significant positive vibration trend (+0.0048 m/s² per day), signifying cumulative stress unseen by manual inspection. Temperature readings highlighted expected diurnal cycling (28°C to 42°C), inversely correlating with capacitive moisture readings (8.2% to 17.8%). Multiple linear regression confirmed that vibration variance was dominated by mechanical loading rather than thermal expansion.

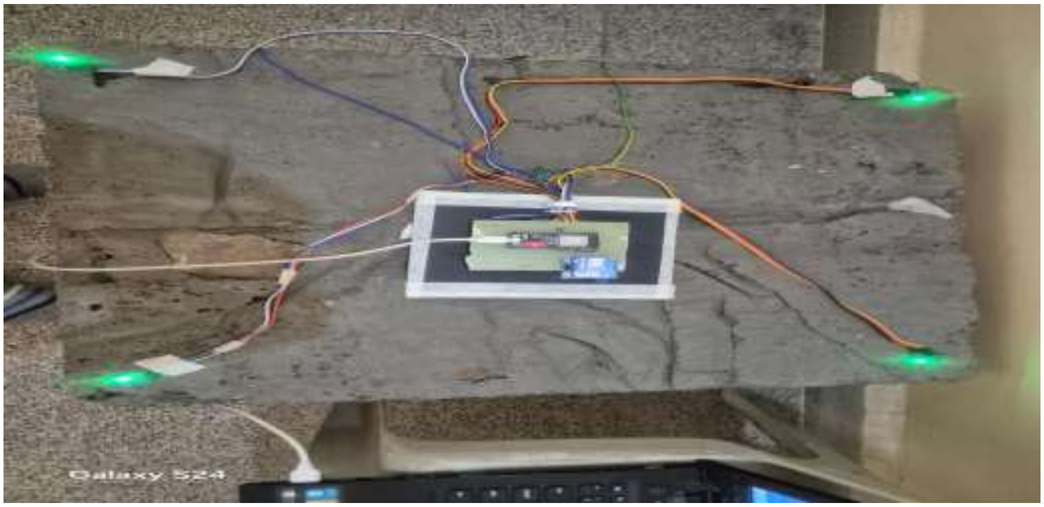


Fig. 5. Placement of Node

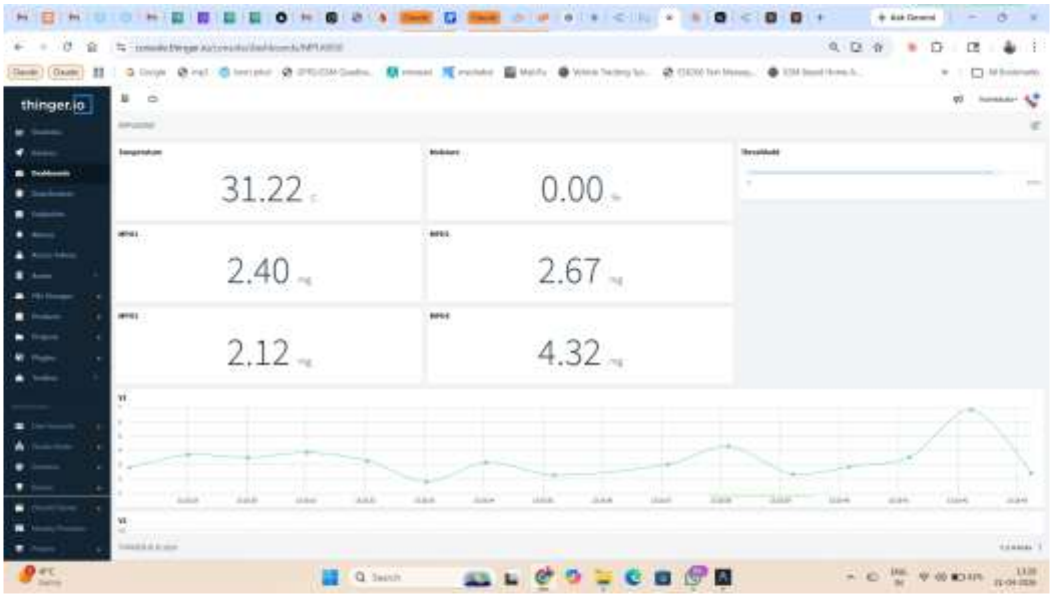


Fig. 6. Vibration Descriptive Statistics by Node.

Fig. 7.Real Time Monitoring .

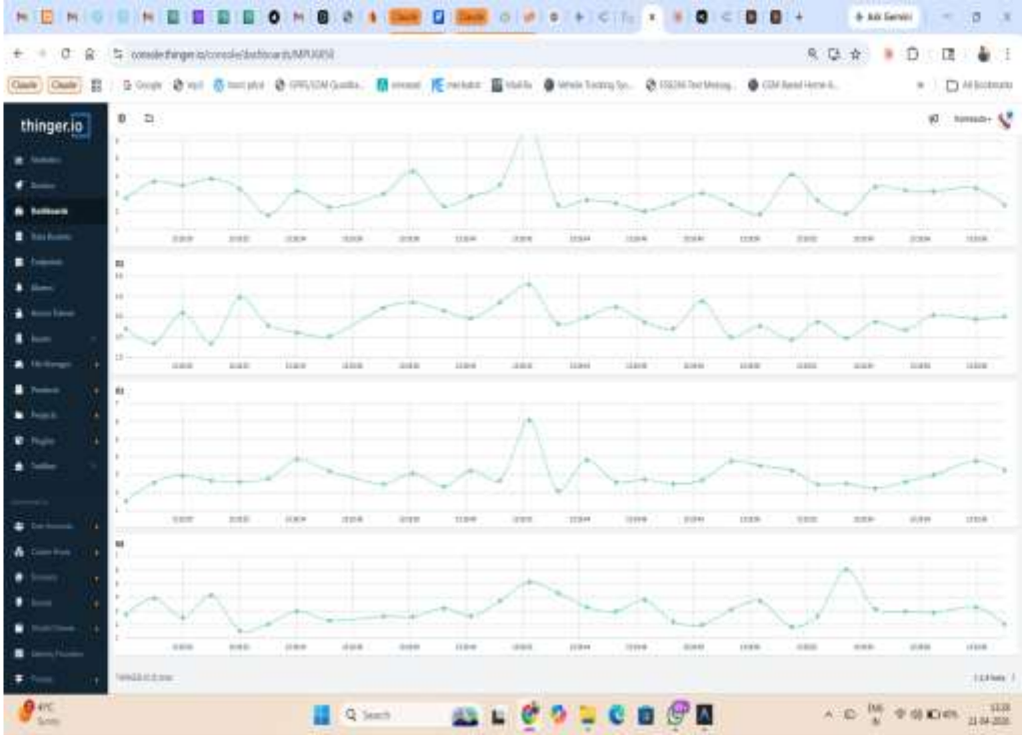


Fig. 8.Graphical Representation.

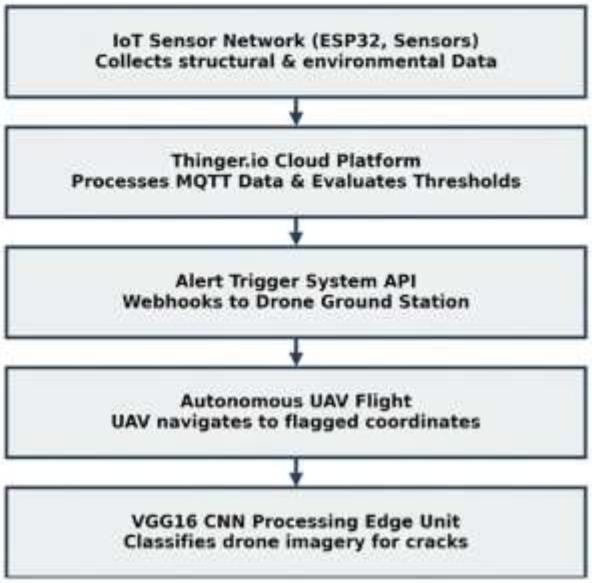
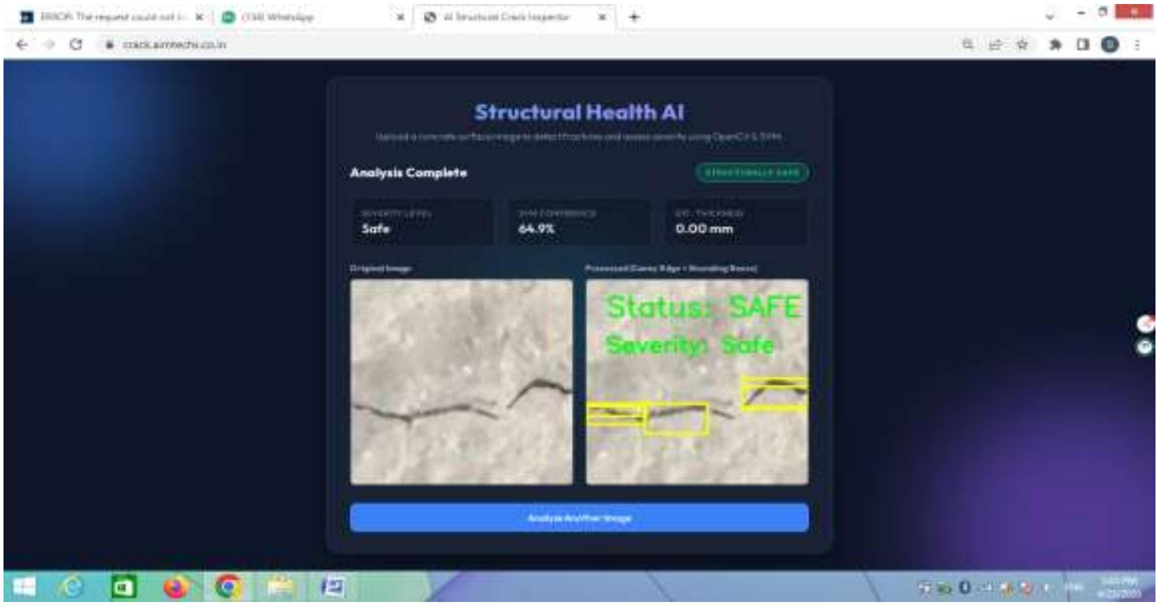


Fig. 9. Time Series Vibration Profiles by Sensor Node.

C. Visual Inspection and AI Accuracy

Drone imagery underwent preprocessing via OpenCV (Canny Edge Detection and Contour Mapping) before classification by the VGG16 CNN. The AI model, optimized using transfer learning on the Concrete Crack Images dataset, achieved an accuracy of 99.2%, precision of 98.8%, and recall of 99.1%. Structural anomalies were rapidly enclosed in visual bounding boxes and delivered to site engineers in tandem with IoT telemetry data.


Structural Health AI

Analysis Complete

Safe

64.9%

0.00 mm

Status: SAFE

Severity: Safe

Fig. 10. Cracks Detection and Contour Mapping

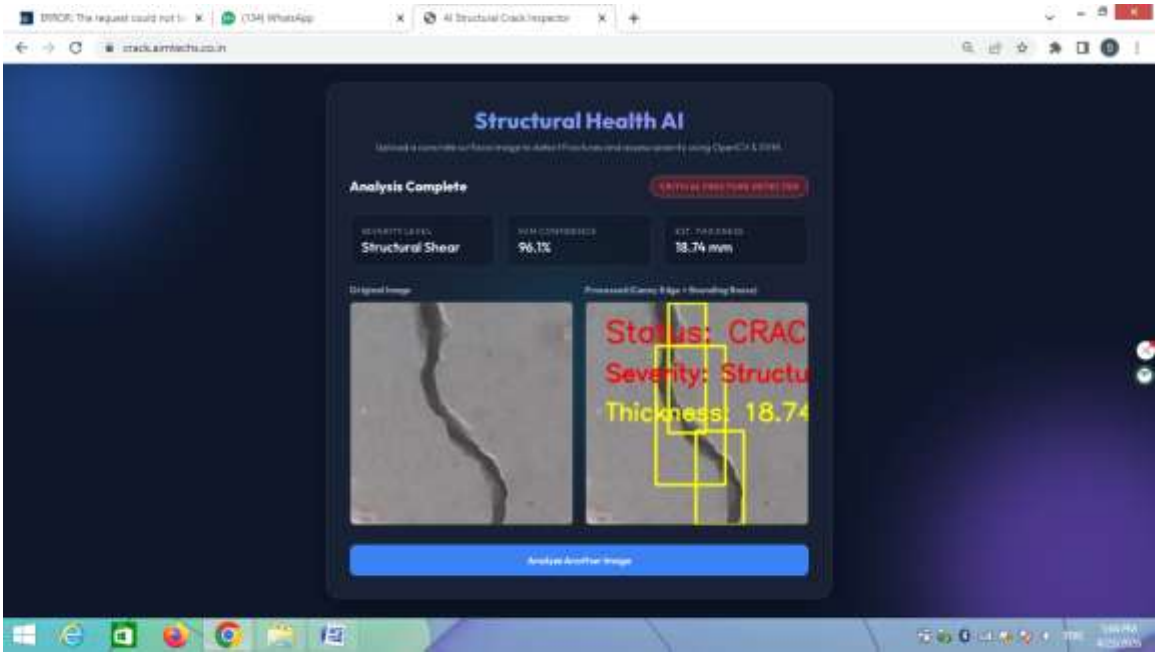


Fig. 11. Vision-Based Concrete Crack Detection with Bounding Box Localization

V. DISCUSSION AND COST BENEFIT ANALYSIS

The system radically alters the incident response timeline. By linking IoT threshold triggers to drone APIs, the interval between a structural anomaly and the availability of verified visual data was reduced from hours to just 8-12 minutes. Questionnaire surveys involving 85 construction professionals indicated overwhelming support (Weighted Mean = 4.22) for the integrated approach, citing early hazard detection and improved accident investigation as critical advantages.

Cost-benefit analysis revealed that the deployment of low-cost ESP32 modules (approx. INR 2,187 per node) coupled with free-tier cloud infrastructure, against traditional fixed systems or frequent third-party audits, yields a 50% to 80% cost reduction over a 24-month construction timeline.

VI. CONCLUSION

This research validates a unified, multi-modal structural health monitoring system. By bridging physical IoT sensors (ESP32, MPU6050, DHT22) with autonomous drone deployments and VGG16-based edge AI, the framework establishes a reliable early-warning safety matrix for complex construction environments. The 20-day empirical deployment confirmed robust communication, predictive vibration trending, and rapid visual confirmation, establishing a highly scalable, cost-effective paradigm for modern construction safety.

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