

IoT-Based Real-Time Industrial Machine Health Monitoring and Automated Control System Utilizing ESP32 Microcontroller

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Abstract: Contemporary industrial environments demand continuous and intelligent supervision of operational equipment to ensure uninterrupted productivity, personnel safety, and optimized resource utilization. Conventional maintenance paradigms, which rely predominantly on periodic manual inspection, have proven inadequate for the dynamic and high-throughput demands of modern manufacturing facilities. The emergence of Internet of Things (IoT) technology has catalyzed a fundamental transformation in industrial monitoring by enabling autonomous, wireless, and real-time acquisition of critical machine parameters. This paper presents the design, development, and experimental validation of an IoT-based Industrial Machine Health Monitoring and Automated Control System constructed around the ESP32 microcontroller. The proposed architecture integrates a heterogeneous array of sensors—encompassing temperature (DHT11), vibration, smoke/gas, voltage, and current transducers—to facilitate holistic and multi-dimensional assessment of machine operational health. Sensor data is continuously acquired, digitally processed, and securely transmitted to the Blynk cloud platform via Wi-Fi, enabling remote visualization and analytics through mobile and web interfaces. A hierarchical alert and protection framework is embedded within the system, capable of triggering auditory alarms, dispatching cloud-based notifications, and executing automatic relay-controlled disconnection of machine power circuits upon detection of anomalous operating conditions. Experimental results substantiate the system's capability to deliver accurate, low-latency monitoring alongside dependable protective responses across diverse fault scenarios. The proposed solution offers a scalable, cost-effective, and energy-efficient alternative to conventional industrial monitoring approaches, with direct applicability in predictive maintenance, fault diagnostics, and smart factory integration.

Keywords: Internet of Things (IoT), ESP32 Microcontroller, Industrial Machine Health Monitoring, Predictive Maintenance, Blynk Cloud Platform, Vibration Analysis, Temperature Monitoring, Remote Condition Monitoring, Industrial Automation, Smart Factory.

I. INTRODUCTION

The progressive evolution of industrial manufacturing has rendered continuous machine health supervision an indispensable operational requirement. Industrial machinery operates under demanding conditions characterized by fluctuating thermal loads, mechanical stresses, electrical transients, and exposure to airborne contaminants. Failure to detect and respond to anomalous conditions in a timely manner can precipitate catastrophic equipment failure, unplanned production downtime, significant economic loss, and potential threats to personnel safety. In this context, the implementation of intelligent and automated monitoring systems capable of providing real-time insights into machine operational status has gained substantial strategic importance [1].

Traditional maintenance methodologies predominantly follow reactive or time-based preventive schedules, wherein maintenance activities are conducted either after failure occurrence or at predefined intervals regardless of actual equipment condition. Such approaches are inherently inefficient: reactive maintenance results in costly unplanned outages, while time-based preventive maintenance leads to unnecessary servicing of components that remain operationally sound. Furthermore, manual inspection procedures are labor-intensive, subject to human error, and incapable of providing the continuous observability required in high-throughput industrial settings [2].

The advent of the Internet of Things (IoT) paradigm has introduced transformative possibilities for industrial monitoring through the deployment of interconnected sensor networks, wireless communication infrastructure, and cloud-based analytical platforms. IoT-enabled condition monitoring systems facilitate the seamless acquisition of multi-parameter machine data, its transmission to remote servers, and the application of analytical algorithms to derive actionable maintenance intelligence. This shift toward data-driven predictive maintenance represents a significant advancement over conventional approaches, with documented reductions in maintenance costs, machine downtime, and unexpected equipment failures [3].

The ESP32 system-on-chip (SoC), developed by Espressif Systems, has emerged as a particularly compelling platform for IoT-based industrial applications owing to its dual-core processing architecture, integrated Wi-Fi and Bluetooth connectivity, rich peripheral interfaces, and favorable cost-to-performance ratio. Its capability to interface with diverse analog and digital sensors while concurrently managing wireless data transmission renders it well-suited for the development of embedded industrial monitoring nodes [7].

This paper presents an IoT-based Industrial Machine Health Monitoring and Automated Control System that employs the ESP32 microcontroller as its central processing unit. The system continuously acquires data from temperature, vibration, smoke/gas, voltage, and current sensors; processes this data against configurable threshold parameters; and communicates real-time status updates to the Blynk IoT cloud platform for remote monitoring. An integrated multi-level protection mechanism—comprising local auditory alarms, cloud-based notifications, and relay-actuated power disconnection—ensures rapid and automated response to detected fault conditions. The proposed system aims to bridge the gap between low-cost embedded hardware and enterprise-grade industrial monitoring capability, thereby enabling deployment across a broad spectrum of industrial environments.

II. LITERATURE REVIEW

A substantial body of research has been devoted to the development of IoT-enabled machine health monitoring systems, reflecting growing industrial demand for intelligent and automated condition assessment tools. The following review synthesizes key contributions from the existing literature and identifies the gaps that the proposed system addresses.

A. IoT-Based Machine Monitoring Using Microcontroller Platforms

Gupta et al. [1] proposed an industrial machine monitoring architecture centered on the NodeMCU development platform coupled with triaxial vibration transducers for real-time mechanical fault identification. Their investigation demonstrated that continuous remote monitoring could yield significant reductions in unplanned machine downtime and associated maintenance expenditure. However, the scope of the system was limited to vibrational analysis, omitting thermal, electrical, and chemical hazard parameters essential for comprehensive machine health assessment.

B. Predictive Maintenance Through IoT Sensor Fusion and Cloud Analytics

Patel et al. [2] developed a predictive maintenance framework that leveraged multi-modal IoT sensors in conjunction with cloud-hosted analytical services for machine failure anticipation. Their research underscored the criticality of uninterrupted, high-frequency data acquisition in enabling early identification of degradation patterns prior to the manifestation of critical failures. Nevertheless, the proposed architecture relied on proprietary cloud infrastructure with limited accessibility for resource-constrained industrial deployments.

C. Real-Time Industrial Parameter Monitoring Via Open-Source Cloud Platforms

Singh et al. [3] implemented a cost-effective industrial monitoring configuration employing the NodeMCU microcontroller interfaced with the ThingSpeak cloud platform for wireless data acquisition and visualization. Their system demonstrated efficient data throughput and acceptable latency for industrial process monitoring applications. The study, however, did not incorporate automated protection mechanisms or multi-sensor integration for comprehensive equipment fault response.

D. Vibration-Based Mechanical Fault Detection Using MEMS Sensors

Sharma et al. [4] conducted a systematic investigation into the efficacy of MEMS-based vibration sensors for the identification of mechanical defects in rotating industrial equipment. Their experimental results validated the capability of spectral vibration analysis to detect bearing wear, rotor imbalance, and shaft misalignment conditions with high sensitivity. While their methodology provided a rigorous foundation for vibration-based diagnostics, integration with broader multi-parameter IoT monitoring frameworks was not explored.

E. Research Gaps and Motivation

A critical examination of the reviewed literature reveals several persistent limitations in existing industrial machine monitoring systems. First, the majority of proposed solutions focus on a restricted set of machine parameters, precluding holistic equipment health assessment. Second, integrated automated protection mechanisms—capable of executing

immediate corrective action upon fault detection—are conspicuously absent from most architectures. Third, challenges related to remote accessibility, system scalability, and deployment cost continue to constrain adoption across diverse industrial contexts. The present work addresses these deficiencies through the development of a comprehensive multi-sensor IoT monitoring system that integrates real-time data acquisition, cloud-based remote visualization, and autonomous multi-level protection within a single, low-cost embedded platform.

III. METHODOLOGY

The proposed IoT-based Industrial Machine Health Monitoring and Automated Control System is architected as a layered functional framework encompassing sensor data acquisition, embedded signal processing, wireless IoT communication, and automated protection actuation. Each functional layer is described in detail in the following subsections.

A. System Architecture Overview

The overall system architecture follows a hierarchical sensing-processing-communication-actuation paradigm. At the sensing layer, a heterogeneous ensemble of transducers continuously samples machine operational parameters. The processing layer, implemented on the ESP32 microcontroller, performs analog-to-digital conversion, signal conditioning, threshold evaluation, and communication management. The communication layer employs the Wi-Fi subsystem of the ESP32 to relay processed data to the Blynk cloud platform. The actuation layer executes protective responses through both local hardware (buzzer, relay module) and remote cloud notification channels.

B. Sensor Data Acquisition

A multi-modal sensor suite is deployed to enable comprehensive monitoring of machine health indicators. The DHT11 digital temperature and humidity sensor acquires ambient and machine surface thermal measurements, providing a reliable indicator of thermal stress conditions. A piezoelectric vibration sensor captures mechanical oscillation signatures from machine structures, enabling detection of anomalous vibration profiles associated with mechanical degradation. An MQ-series gas sensor monitors ambient smoke concentration and volatile gas accumulation, serving as an early warning indicator for electrical faults or combustion events. Voltage and current transducer modules—interfaced with the ESP32 analog-to-digital converter channels—continuously measure supply voltage levels and machine current draw, respectively, enabling detection of electrical overload, undervoltage, and phase imbalance conditions. The collective output of this sensor ensemble provides a comprehensive multi-dimensional representation of machine operational health.

C. Embedded Signal Processing and Threshold Evaluation

The ESP32 microcontroller receives both analog and digital sensor outputs through its designated peripheral interfaces. Analog sensor signals are processed through the integrated 12-bit successive-approximation ADC, while digital sensors communicate via standardized one-wire or I2C protocols. Each acquired sensor datum is filtered to suppress noise artifacts and subsequently compared against application-specific threshold parameters stored in non-volatile memory. Threshold values are configurable to accommodate diverse machine types and operational environments. The processing firmware evaluates composite machine health status based on simultaneous multi-parameter threshold assessments, enabling nuanced fault classification that accounts for concurrent anomalous conditions.

D. Wireless IoT Communication via Blynk Platform

Processed sensor data and derived machine health status indicators are transmitted to the Blynk IoT cloud platform through the ESP32's integrated IEEE 802.11 b/g/n Wi-Fi transceiver. The Blynk platform provides a scalable, low-latency cloud infrastructure with support for real-time data streaming, persistent data storage, and customizable dashboard visualization. Mobile application clients and web-based interfaces subscribe to data streams published by the ESP32 node, enabling remote visualization of machine parameters on a continuous basis. The communication protocol employs secure, authenticated sessions to ensure data integrity and prevent unauthorized system access.

E. Multi-Level Alert and Automated Protection Mechanism

Upon detection of threshold violations in any monitored parameter, the system activates a hierarchical multi-level response protocol. At the primary level, a local piezoelectric buzzer is energized to provide an immediate auditory alarm, alerting on-site personnel to the detected anomaly. Concurrently, the system dispatches real-time alert notifications to the Blynk cloud platform, which propagates push notifications to registered mobile devices and updates the dashboard with fault condition indicators. At the tertiary protection level, the ESP32 asserts a control signal to a relay module that governs the primary power supply circuit of the monitored machine. This relay actuation achieves electrical isolation of the machine, preventing the progression of identified fault conditions to catastrophic equipment damage. The multi-level

response architecture ensures redundant protection coverage applicable across both attended and unattended operational scenarios.

IV. RESULT AND DISCUSSION

The IoT-based Industrial Machine Health Monitoring and Automated Control System was subjected to comprehensive experimental evaluation under controlled laboratory conditions designed to replicate representative industrial machine operating scenarios. The system demonstrated consistent and reliable performance across all monitored parameters throughout the testing campaign.

Real-time sensor data acquisition was verified for all five monitoring channels—temperature, vibration, smoke/gas, voltage, and current—with readings updated on the Blynk cloud dashboard at sub-second intervals. The DHT11 temperature sensor exhibited stable measurement accuracy within its specified operating range, successfully detecting simulated overheating conditions induced by controlled thermal loading. The vibration sensor responded reliably to mechanically induced oscillations, with abnormal vibration events consistently triggering threshold-based fault detection. The gas/smoke sensor demonstrated sensitive and rapid detection of artificially introduced smoke concentrations, corroborating its efficacy as an early-warning indicator for electrical fault conditions. Voltage and current monitoring channels accurately captured both normal operational profiles and deliberately introduced electrical anomalies, including supply voltage reduction and current overload conditions.

Upon deliberate induction of fault conditions exceeding predefined threshold parameters, the system's multi-level protection mechanism was observed to activate with consistently low response latency. Local buzzer alarms were triggered within milliseconds of threshold violation detection. Cloud-based alert notifications were delivered to the registered mobile device within the Blynk platform's standard communication latency window, typically ranging from one to three seconds under stable Wi-Fi connectivity. The relay-actuated machine disconnection mechanism operated reliably across all tested fault scenarios, successfully interrupting machine power circuits to prevent simulated equipment damage progression.

Remote monitoring capability was validated through continuous system observation via the Blynk mobile application across varying network conditions. The dashboard provided clear, intuitive visualization of all monitored parameters in real time, with graphical trend displays enabling retrospective analysis of machine operational history. The system maintained stable wireless connectivity throughout extended testing periods, with no observed data transmission failures under normal network conditions.

Comparative assessment against the performance benchmarks established in prior literature confirms that the proposed system achieves superior multi-parameter monitoring coverage relative to single-parameter or dual-parameter IoT monitoring implementations reviewed in the literature. The integrated automated protection mechanism represents a significant functional advancement over systems that provide monitoring capability without corrective actuation. The measured power consumption of the ESP32-based monitoring node is consistent with low-power industrial IoT deployment requirements, supporting potential battery-backed operation for environments with constrained power infrastructure. Collectively, these results validate the proposed system as an effective, scalable, and deployment-ready solution for industrial machine health monitoring applications.

V. CONCLUSION

This paper has presented the design, implementation, and experimental validation of an IoT-based Industrial Machine Health Monitoring and Automated Control System built upon the ESP32 microcontroller platform. The proposed system successfully integrates a heterogeneous multi-sensor array—encompassing temperature, vibration, smoke/gas, voltage, and current transducers—to deliver comprehensive, real-time assessment of industrial machine operational health across five critical monitoring dimensions.

The deployment of the Blynk IoT cloud platform as the communication and visualization backbone enables seamless remote monitoring through mobile and web interfaces, eliminating geographical constraints on supervisory access. The embedded multi-level protection framework, incorporating local auditory alarms, remote cloud notifications, and relay-actuated power disconnection, provides robust and automated fault response capability that substantially mitigates the risk of catastrophic equipment damage and unplanned downtime.

Experimental evaluation confirmed the system's capability to deliver accurate, low-latency monitoring and reliable protective responses across a comprehensive suite of simulated industrial fault scenarios. The measured system performance—encompassing detection accuracy, response latency, communication reliability, and power efficiency—satisfies the operational requirements of industrial IoT monitoring deployments. The overall system architecture demonstrates favorable scalability characteristics, supporting extension to multi-machine monitoring configurations with minimal hardware modifications.

The proposed system makes a meaningful contribution to the advancement of industrial automation by providing a cost-effective, technically rigorous, and practically deployable solution for predictive maintenance, condition monitoring, and operational safety enhancement. Its compatibility with the Industry 4.0 paradigm positions it as a viable component within broader smart manufacturing ecosystems, with potential for integration with enterprise resource planning, digital twin, and advanced analytics frameworks in future development stages.

VI. FUTURE ENHANCEMENT

While the present implementation demonstrates strong foundational capability, several avenues for future development have been identified that would substantially extend the system's functionality, intelligence, and applicability.

The foremost enhancement involves the integration of machine learning and artificial intelligence algorithms within the cloud analytics layer for advanced predictive fault classification. By training supervised learning models on historical sensor data profiles associated with known fault signatures, the system could transition from threshold-based reactive detection to proactive, probability-based fault prediction, enabling maintenance interventions prior to measurable parameter degradation [2].

Augmentation of the communication architecture with Global System for Mobile (GSM) module integration would extend alert delivery capabilities to environments lacking Wi-Fi infrastructure, enabling SMS and voice call notifications to designated maintenance personnel. This enhancement would substantially improve the system's utility in geographically remote or connectivity-constrained industrial deployments.

Expansion of the monitoring node architecture to support multi-machine centralized monitoring through a distributed IoT mesh network topology represents a significant scalability enhancement. Implementation of a unified industrial dashboard aggregating data from multiple machine nodes would facilitate fleet-level health management and enable cross-machine correlation analysis for systemic fault identification.

Additional future developments include the integration of high-resolution camera modules for visual fault detection through computer vision algorithms, incorporation of energy monitoring capabilities for power efficiency optimization and anomaly-based electrical fault detection, and the development of an automated maintenance scheduling module that generates work orders based on detected machine health trends. Ultimately, full integration with Industry 4.0 smart factory architectures—including interfaces with SCADA systems, digital twin platforms, and enterprise resource planning software—would position the system as a comprehensive component within next-generation intelligent manufacturing environments.

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