IoT-Based Real-Time Vibration and Temperature Monitoring System for Industrial Machinery Using ESP32 and MQTT

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Abstract: This study presents the design and validation of an Internet of Things (IoT)–based real-time vibration and temperature monitoring system for industrial machinery using an ESP32 microcontroller and MQTT communication. The proposed system addresses limitations of periodic manual inspection by enabling continuous monitoring with on-device signal processing and direct compliance evaluation with ISO 10816-3. The main contribution of this work is the implementation of ISO-based vibration severity classification directly at the edge level, integrating multi-sensor acquisition with real-time Root Mean Square (RMS) and Fast Fourier Transform (FFT) processing without relying on predictive or machine learning algorithms. This architecture enables low-latency decision support, reduced bandwidth usage, and improved system independence from cloud computation. The system integrates two ADXL345 vibration sensors and two temperature sensors into a single ESP32 node for synchronized monitoring. Experimental validation on an industrial reciprocating compressor demonstrated stable data acquisition and 100% communication availability during testing. RMS vibration values ranged from 2.15 to 2.17 mm/s, with operating temperatures around 67 °C. FFT analysis identified dominant frequencies consistent with machine characteristics. According to ISO 10816-3 classification, the monitored condition was within safe to early warning levels, confirming the reliability and practical feasibility of the proposed edge-based monitoring approach for condition-based maintenance.

Keywords: Vibration Monitoring, Internet of Things, Data Acquisition

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Introduction

Industrial machinery reliability plays a crucial role in maintaining production continuity, operational efficiency, and workplace safety. Rotating and reciprocating machines operate under continuous mechanical and thermal stress, which may lead to gradual degradation of components such as bearings, shafts, and couplings. In many industrial environments, maintenance strategies are still dominated by reactive or time-based approaches, where machines are inspected periodically or repaired only after failures occur. Such practices often result in unplanned downtime, increased maintenance costs, and potential safety hazards. Condition-based maintenance (CBM) has emerged as an effective alternative by enabling maintenance actions based on the actual health condition of machines. CBM relies on continuous or frequent monitoring of physical parameters that reflect machine behavior, such as vibration and temperature (Bisri & Anzhory , 2024). Among these parameters, vibration is widely recognized as the most sensitive indicator of mechanical faults, while temperature provides complementary information related to friction, lubrication, and thermal loading. Continuous monitoring of these parameters allows early detection of abnormal conditions before catastrophic failures occur.

Despite its advantages, the implementation of continuous condition monitoring in industrial settings remains limited. Conventional vibration monitoring is often performed using portable instruments during scheduled inspections. Although these instruments provide accurate measurements, they are unable to capture transient events or rapid condition changes occurring between inspection intervals. Furthermore, manual data collection depends heavily on operator availability and experience, and the resulting data are often not stored in an integrated manner for long-term trend analysis (Jamil et al, 2021). The rapid development of Internet of Things (IoT) technologies offers new opportunities for overcoming these limitations. IoT enables distributed sensing, edge-level data processing, and real-time data transmission over wireless networks (Mangte et al, 2023). Low-cost microcontrollers with integrated communication capabilities, such as the ESP32, have significantly lowered the barrier for deploying monitoring systems in industrial environments. When combined with lightweight communication protocols such as MQTT, IoT-based monitoring systems can deliver reliable data transmission with minimal bandwidth and power consumption.

Several previous studies have explored IoT-based vibration or temperature monitoring systems for industrial applications. However, most of these systems emphasize cloud-based analytics or machine learning techniques for fault prediction. While predictive approaches offer advanced diagnostic capabilities, they often introduce additional algorithmic complexity, higher computational requirements, and increased implementation costs. More importantly, many existing IoT monitoring architectures focus primarily on data visualization and anomaly detection without explicitly embedding internationally recognized vibration severity standards into the system design. As a result, the monitoring outputs may not directly support practical maintenance decision-making aligned with industrial standards.

A clear research gap can therefore be identified: there is limited work that integrates standardized vibration severity evaluation directly at the edge device level within an IoT monitoring framework. In most reported systems, raw or partially processed data are transmitted to cloud platforms for further analysis, and compliance with standards such as ISO 10816-3 is either performed manually or not explicitly addressed. This separation between data acquisition and standards-based evaluation reduces real-time decision capability and increases dependence on external computation resources.

International standards such as ISO 10816-3 provide well-established guidelines for evaluating vibration severity of rotating machinery based on RMS velocity values and machine power classification (ISO 10816-3 2009). The standard is particularly relevant for industrial rotating equipment, including compressors, pumps, and motors operating within specified power ranges. In this study, the test object is an industrial reciprocating compressor whose operational characteristics fall within the classification scope of ISO 10816-3, making the standard appropriate for objective and industry-accepted condition assessment (Yusro et al. 2025). By directly referencing ISO 10816-3, vibration measurements can be interpreted in terms of acceptable, warning, or critical levels that are meaningful for maintenance engineers.

This research addresses the identified gap by developing a practical IoT-based vibration and temperature monitoring system that embeds ISO 10816-3–based severity classification directly into the edge device. The proposed system integrates multiple sensors into a single ESP32-based node and performs real-time signal processing using Root Mean Square (RMS) and Fast Fourier Transform (FFT) analysis before transmitting structured data via MQTT. Unlike cloud-dependent or prediction-oriented systems, the proposed architecture emphasizes standards-referenced edge evaluation, low computational complexity, and direct applicability to real maintenance workflows.

The main objective of this study is to design, implement, and experimentally validate a cost-effective and reliable real-time monitoring system aligned with established industrial standards for condition-based maintenance (Ibrahim et al. 2024). By combining multi-sensor acquisition, edge-level ISO-based evaluation, and IoT connectivity, this work contributes a simplified yet industrially relevant monitoring approach that bridges academic IoT research with practical maintenance implementation.

Research Method

This study adopts a research and development (R&D) approach focusing on the design, implementation, and validation of an IoT-based monitoring system for industrial machinery (Creswell 2014). The proposed system performs continuous signal acquisition, edge-level processing, and real-time transmission to a cloud platform.

Test Object and Sensor Installation

The experimental validation was conducted on a Gas Engine Reciprocating Compressor G3516 TA operating at an average speed of 931 rpm under normal load conditions. This machine falls within Group 1 classification according to ISO 10816-3, making RMS velocity evaluation relevant for vibration severity assessment. Two ADXL345 vibration sensors and two K-type thermocouples connected via MAX6675 modules were installed at two critical measurement points: point 1 Compressor drive-end bearing housing, point 2 Compressor non-drive-end bearing housing. These locations were selected because bearing housings are structurally rigid points that effectively transmit vibration energy from rotating components and are recommended for overall vibration monitoring according to ISO 10816 practices. The ADXL345 sensors were mounted using a rigid cable tease method to ensure strong mechanical coupling and minimize signal attenuation. The sensor axes were oriented such that: X-axis: radial horizontal direction, Y-axis: radial vertical direction, Z-axis: axial direction. The overall vibration was calculated from the vector combination of the three axes. Temperature sensors (K-type thermocouples) were installed adjacent to the bearing housings to monitor thermal conditions related to friction and lubrication performance.

Sensor Specification

ADXL345 Accelerometer Measurement range configurable ±2 g, ±4 g, ±8 g, ±16 g with configured range in this study: ±2 g, output data rate configured at 200 Hz and Interface using I2C communication with ESP32 Temperature Sensor MAX6675 using Type K-type thermocouple, Measurement range 0–1024 °C with Resolution 0.25 °C and Interface using SPI communication with ESP32.

Signal Processing Method

Vibration data were processed at the edge device using both time-domain and frequency-domain analysis. Acceleration data were first converted from raw digital values to acceleration in m/s^2. RMS acceleration was calculated using:

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} a_i^2} \quad (1)$$

To comply with ISO 10816-3, RMS velocity (mm/s) was obtained by numerical integration of the acceleration signal in the time domain. Fast Fourier Transform (FFT) was implemented to analyse dominant vibration frequencies. Sampling frequency (fs): 200 Hz, Number of samples per window (N): 256 samples, Frequency resolution: $\Delta f = f_s / N = 0.78$ Hz, Windowing function: Hamming window (to reduce spectral leakage), FFT computation: Cooley–Tukey algorithm implemented using embedded DSP library. The resulting frequency spectrum was used to identify dominant components corresponding to rotational frequency (1× rpm) and its harmonics. Given the machine operating speed of 931 rpm (~15.5 Hz), the expected fundamental frequency was verified in the FFT spectrum.

System Architecture

The monitoring system consists of three main layers: sensing, edge processing, and application. At the sensing layer, vibration and temperature data are acquired from the machine using two MEMS accelerometers (ADXL345) and two temperature sensors. These sensors are installed at selected measurement points on the machine structure to capture representative mechanical and thermal behavior.

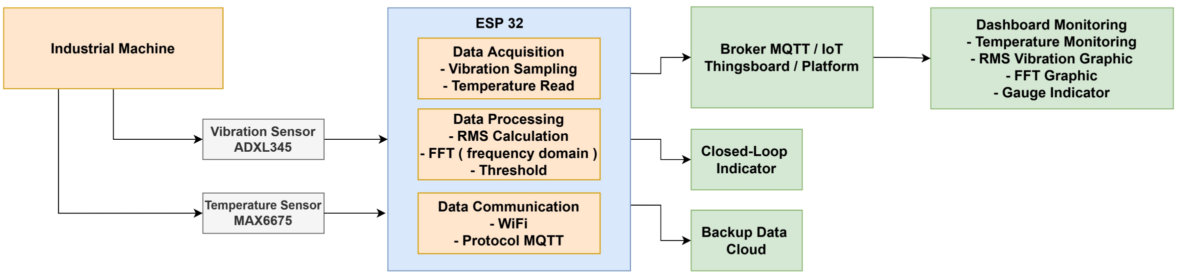

Figure 1 System Architecture

Figure 1 illustrates the architecture of the proposed IoT-based vibration and temperature monitoring system. The industrial machine serves as the physical source of mechanical vibration and thermal responses. These parameters are measured using an ADXL345 accelerometer for tri-axial vibration sensing and a K-type thermocouple with MAX6675 module for temperature measurement. Sensor data are transmitted to the ESP32 microcontroller, which functions as the edge processing unit. The ESP32 performs data acquisition through vibration sampling and temperature reading, followed by signal processing (Azhar & Nurpulaela 2024). Time-domain analysis is conducted using Root Mean Square (RMS) calculation to quantify vibration energy, while frequency-domain analysis is performed using Fast Fourier Transform (FFT) to identify dominant frequency components. The computed RMS velocity is then compared with ISO 10816-3 threshold limits to classify machine condition. Processed data, including RMS values, FFT spectrum information, temperature readings, and condition status, are transmitted via Wi-Fi using the MQTT protocol to an IoT broker and ThingsBoard platform. The cloud layer provides real-time visualization through temperature graphs, RMS vibration trends, FFT spectra, and gauge indicators.

Hardware Configuration

The ESP32 microcontroller serves as the core processing unit due to its integrated Wi-Fi capability, sufficient computational resources, and low power consumption (Espressif System, 2023). Vibration signals are obtained from ADXL345 accelerometers (Analog Devices – ADXL345 2022), which provide tri-axial acceleration data suitable for machine condition monitoring. MEMS-based accelerometers have been widely used for vibration measurement due to their compact size, low power consumption, and sufficient sensitivity for industrial monitoring applications (Ahmed et al. 2023; Anggana & Solikin 2025). Temperature measurements are collected using thermocouple-based sensors interfaced through a digital converter module to ensure stable and accurate readings (Analog Devices – MAX6675 2021).

Figure 2 below illustrates the hardware architecture of the proposed IoT-based machine condition monitoring system designed to measure vibration and temperature parameters of industrial machinery and provide visual condition feedback. The system utilizes an ESP32 microcontroller as the central processing and communication unit, interfacing with vibration sensors, temperature sensors, visual indicators, and a regulated power supply module. Vibration measurement is performed using ADXL345 triaxial accelerometers installed at multiple machine measurement points. Each ADXL345 sensor communicates with the ESP32 via the I²C interface, enabling real-time acquisition of acceleration data along three axes (X, Y, Z). The acquired vibration data are processed at the edge device for Root Mean Square (RMS) calculation and Fast Fourier Transform (FFT) analysis to evaluate mechanical condition in accordance with ISO-based severity criteria.

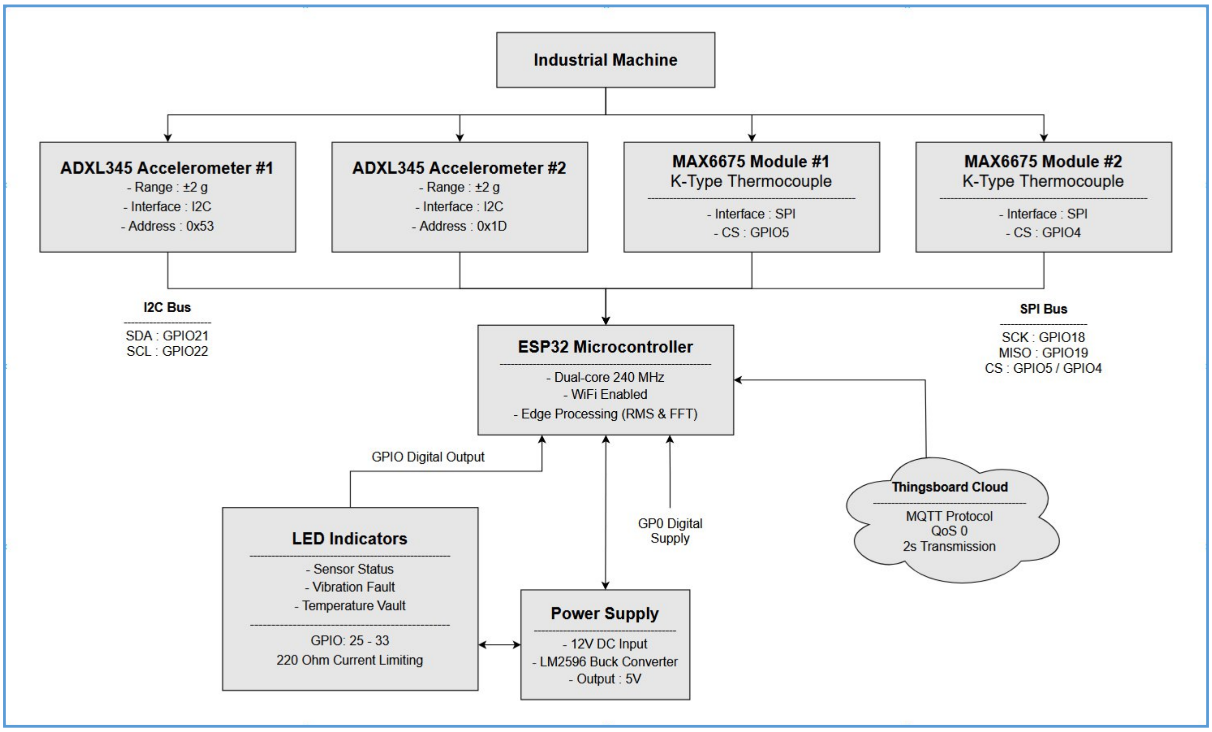

Figure 2 Hardware Design

Temperature monitoring is implemented using MAX6675 modules connected to K-type thermocouples. These modules interface with the ESP32 through the Serial Peripheral Interface (SPI), enabling digital temperature acquisition from critical machine locations. The use of multiple temperature sensors allows comparative thermal monitoring across different structural points. Visual feedback is provided through Light Emitting Diodes (LEDs), categorized into sensor indicators and fault indicators. Sensor indicators confirm sensor operational status, while fault indicators are activated when vibration or temperature values exceed predefined thresholds. All LEDs are connected to ESP32 GPIO pins via current-limiting resistors to ensure safe operation. The system is powered by a 12 V DC supply, which is stepped down to 5 V using a DC–DC buck converter. The regulated voltage ensures stable operation of the ESP32 and peripheral components during continuous monitoring.

Signal Processing and Condition Evaluation

Raw acceleration data acquired from the vibration sensors are processed at the ESP32 level. The Root Mean Square (RMS) value is calculated to represent the effective vibration level of the machine. RMS velocity values are derived from acceleration data to align with industrial vibration evaluation practices (Yudistira et al. 2023). In addition to RMS analysis, Fast Fourier Transform (FFT) is applied to convert time-domain vibration signals into the frequency domain. FFT analysis enables identification of dominant frequency components associated with machine rotational speed and potential mechanical faults (Muhlisin et al. 2021). Machine condition evaluation is performed by comparing RMS velocity values with the thresholds defined in ISO 10816-3 (Adinarto & Romahadi 2024). Based on this classification, machine conditions are categorized into acceptable, warning, or critical levels. A closed-loop visual feedback mechanism is implemented using LED indicators to provide immediate local status information.

Data Communication and Visualization

Processed data are transmitted from the ESP32 to the IoT platform using the MQTT protocol. MQTT is selected due to its lightweight publish–subscribe architecture, which ensures efficient and reliable data transmission under limited bandwidth conditions (Austin et al. 2022). The IoT platform provides real-time dashboards displaying vibration levels, temperature trends, and frequency spectra, enabling remote monitoring and historical data analysis.

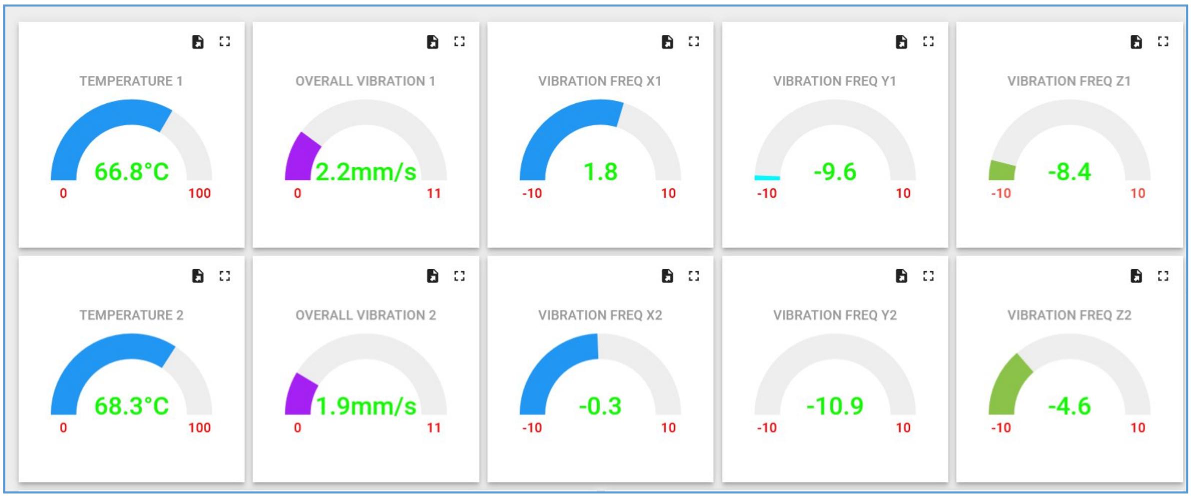

Figure 3 User Interface from Thingsboard

Figure 3 shows the real-time gauge visualization on the ThingsBoard dashboard. The upper row represents data from Sensor 1, while the lower row corresponds to Sensor 2. For each measurement point, the dashboard displays three main parameters: (1) temperature in degrees Celsius (°C), measured using a K-type thermocouple with MAX6675 module; (2) overall vibration expressed as RMS velocity in millimeters per second (mm/s), calculated at the edge device in accordance with ISO 10816-3 evaluation; and (3) directional vibration components along the X, Y, and Z axes obtained from the ADXL345 triaxial accelerometer. The gauge format enables immediate visualization of parameter magnitude relative to predefined operational thresholds. RMS values represent vibration severity, while directional components provide insight into vibration orientation. This real-time display supports rapid condition assessment, whereas detailed historical trends and FFT analysis are presented in subsequent figures for comprehensive evaluation.

Experimental Setup

Experimental validation was conducted on an industrial reciprocating compressor (ISO 10816-3 Group 1) operating under normal load conditions. The monitoring system was deployed continuously for 14 days as shown in the graph.

Monitoring Duration and Sampling

The monitoring system was operated continuously for 14 consecutive days under normal machine operating conditions. Vibration signals were acquired at a sampling frequency of 200 Hz, with an FFT window size of 256 samples, resulting in an update interval of 1.28 seconds for both FFT computation and RMS. Processed data were transmitted to the cloud platform at a fixed interval of 2 seconds. Based on this transmission interval, the expected number of MQTT messages per day is:

$$30 \times 60 \times 24 = 43{,}200 \text{ messages/day}$$

Over the 14-day monitoring period, the total expected number of transmitted messages is:

$$43{,}200 \times 14 = 604{,}800 \text{ messages}$$

Communication Configuration

Data transmission was implemented using the MQTT protocol over TCP/IP. The system operated at QoS level 0 (at most once delivery), meaning messages were transmitted on a best-effort basis without delivery acknowledgment. Therefore, message delivery is not guaranteed by protocol design. Network connectivity was provided via a 4G cellular modem (Telkomsel), and data were published to the ThingsBoard MQTT broker for real-time visualization and storage.

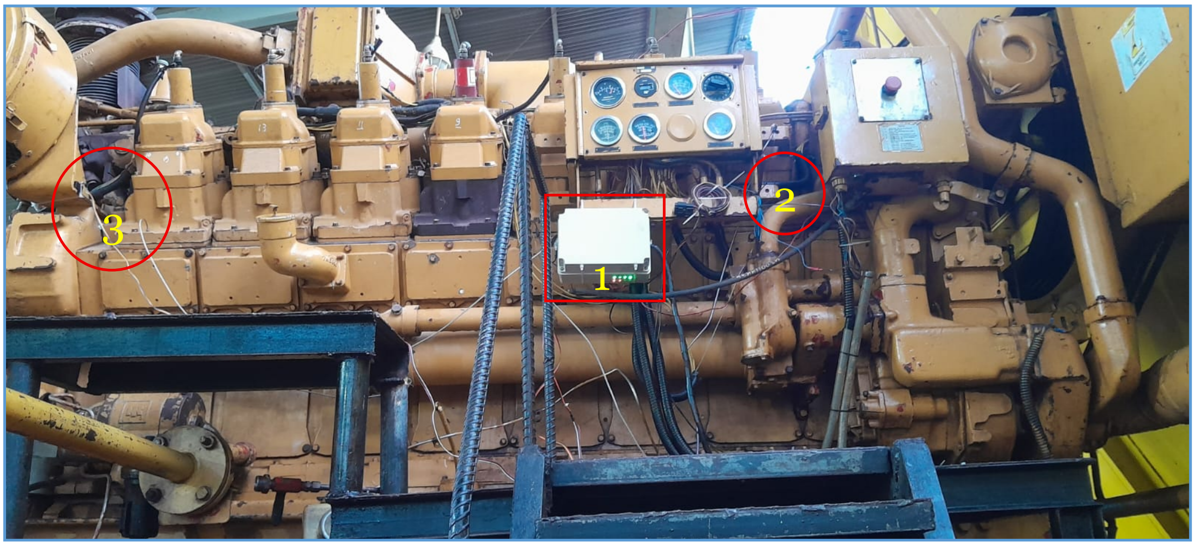

Figure 4 Reciprocating Compressor CAT G3516 TA Gas Engine

Figure 4 shows the practical implementation of the proposed monitoring system on the CAT G3516 TA Gas Engine reciprocating compressor. The installation layout was designed considering safety, structural rigidity, signal representativeness, and maintenance access. Point (1) indicates the monitoring unit installed inside a protective electrical panel box. The enclosure isolates the ESP32 module, power supply, and communication circuitry from harsh industrial conditions such as dust, elevated temperature, and excessive vibration. This configuration enhances system durability and operational stability. Point (2) shows the placement of Vibration Sensor #1 and Temperature Sensor #1 on one side of the gas engine, specifically near the bearing housing region. The vibration sensor is mounted on a rigid structural surface mechanically coupled to rotating components to ensure accurate transmission of dynamic responses. The adjacent thermocouple monitors local thermal behaviour associated with friction and load conditions. This co-located configuration enables simultaneous mechanical and thermal assessment at the same measurement point.

Point (3) presents Vibration Sensor #2 and Temperature Sensor #2 installed on the opposite side of the machine. This second measurement point provides comparative data from another structural location, allowing spatial validation of vibration severity and temperature distribution across the compressor body. Overall, the installation configuration ensures reliable real-time acquisition of vibration and temperature data. The measured signals are processed at the edge device and transmitted to the IoT platform for condition evaluation in accordance with ISO 10816-3, supporting practical implementation of condition-based maintenance in an industrial environment.

Result and Discussion

System Performance and Data Acquisition

The implemented monitoring system operated continuously during the 14-day testing period without observed communication interruptions. Sensor data acquisition, edge-level signal processing (RMS and FFT), and MQTT-based data transmission were maintained consistently throughout the experiment. Based on the total expected transmission cycles during the observation interval, no missing data entries were detected in the recorded dataset. Therefore, the system demonstrated full data continuity within the defined experimental timeframe. It should be noted that this observation reflects performance under the specific network and operational conditions of the test environment and does not imply guaranteed long-term availability under all industrial scenarios. Nonetheless, the results indicate that the ESP32 platform is capable of supporting real-time multi-sensor monitoring in an industrial setting (Anggana & Solikin 2025).

Vibration and Temperature Analysis

Measured RMS vibration velocity values ranged between 2.15 and 2.17 mm/s under normal operating conditions. These values indicate a stable vibration pattern with minor fluctuations attributable to operational load variations. The monitored reciprocating compressor is classified under ISO 10816-3 Group 1, which applies to large industrial machines with rated power above 300 kW installed on rigid foundations. Vibration severity assessment was conducted using RMS velocity (mm/s) in accordance with ISO 10816-3 (2009). The threshold values applied in this study are presented in Table 1.

Table 1 ISO 10816-3 Vibration Severity Classification (Group 1 – Rigid Foundation)

Condition Zone	RMS Velocity (mm/s)	Condition Interpretation
Zone A	0 – 2.3	Good / Acceptable
Zone B	2.3 – 4.5	Satisfactory / Long-term operation permissible
Zone C	4.5 – 7.1	Unsatisfactory / Maintenance planning required
Zone D	> 7.1	Unacceptable / Immediate corrective action required

Based on these criteria, the measured RMS velocity values (2.15–2.17 mm/s) fall within Zone A (Good condition). Although the measured values are close to the upper boundary of Zone A (2.3 mm/s), they remain within the acceptable vibration level defined for large industrial machines under ISO 10816-3. Following the monthly maintenance period, slight increases in fluctuation were observed; however, RMS levels did not exceed the Zone A threshold. This indicates that the machine remained within permissible operational limits during the monitoring interval. Temperature monitoring showed stable operating values between 65 °C and 74 °C during load conditions, with a decrease to approximately 18 °C during shutdown for maintenance. No abnormal thermal escalation trends were detected. By embedding ISO 10816-3 Group 1 thresholds directly into the edge device, the system enables standards-based vibration severity classification in real time, providing actionable and industry-relevant condition assessment without dependence on external analysis tools.

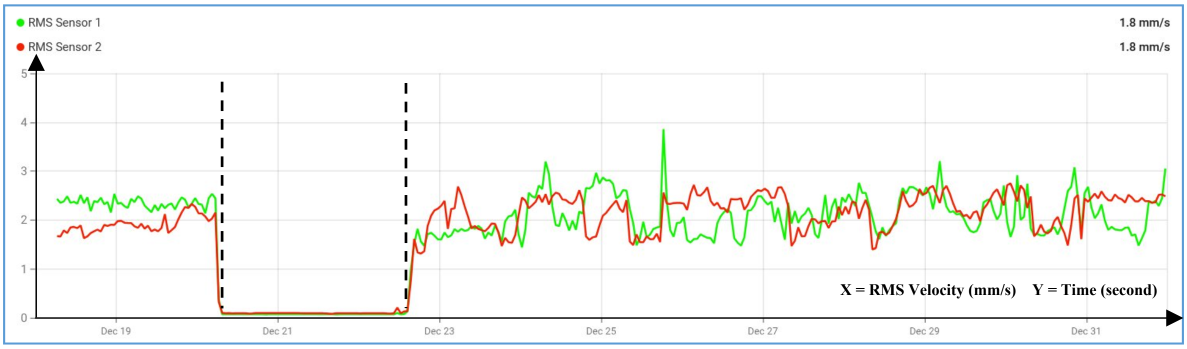

Figure 5 (Style: RMS Velocity Monitoring 14 Days from Thingsboard

Figure 5 presents the overall vibration level of the monitored machine expressed in RMS velocity (mm/s) over a 14-day observation period. The RMS velocity values were obtained from processed vibration signals acquired by the ADXL345 sensors and converted into velocity in accordance with ISO 10816-3 evaluation requirements. During normal operating conditions prior to maintenance, the RMS velocity values remained relatively stable within a narrow range, indicating consistent dynamic behavior. However, following the scheduled monthly maintenance conducted between 20 December 2025 at 06:08 and 22 December 2025 at 15:35, the RMS velocity trend exhibited increased fluctuation compared to the pre-maintenance period. This post-maintenance variation suggests a temporary change in machine dynamic response, potentially associated with reassembly, load redistribution, alignment adjustments, or lubrication effects. Although the vibration levels remained within acceptable ISO thresholds, the observed increase in variability indicates a transitional stabilization phase after maintenance. The availability of continuous historical RMS data enables longitudinal condition assessment, allowing early detection of gradual or subtle changes in vibration behavior. Such trend-based monitoring supports the implementation of condition-based maintenance by providing quantitative evidence of machine dynamic stability over time.

This study did not include a direct calibration or comparative validation against a certified high-precision vibration analyzer. Therefore, absolute measurement accuracy and metrological traceability were not formally quantified. The ADXL345 sensor was selected based on its documented sensitivity and dynamic range specifications suitable for low-to-moderate industrial vibration levels. The objective of this research was focused on system integration, edge-level processing, and ISO-based severity classification rather than instrument-grade vibration metrology. Future work will include comparative validation against a calibrated industrial vibrometer to quantify measurement accuracy, sensitivity, and repeatability.

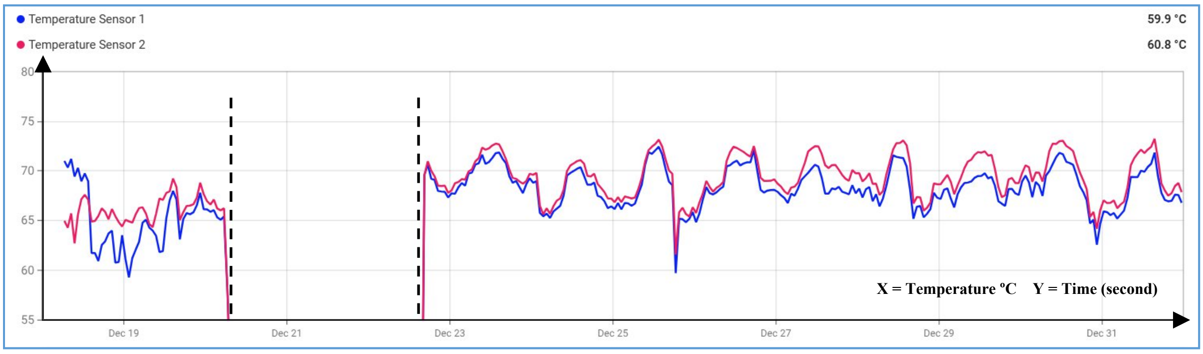

Figure 6 Temperature Monitoring 14 Days from Thingsboard

Figure 6 presents the machine temperature monitoring results over a continuous 14-day observation period, displayed as a time-series graph on the ThingsBoard IoT platform. The graph illustrates the temporal evolution of machine temperature under normal operational conditions and during scheduled maintenance. During regular operation, the recorded temperature values remained within the range of approximately 65 °C to 74 °C, indicating stable thermal behavior under load. A significant temperature decrease was observed during the scheduled monthly maintenance interval (20 December 2025, 06:08 to 22 December 2025, 15:35), when the machine was shut down. During this period, the temperature dropped to an average value of approximately 18 °C, corresponding to ambient conditions.

The consistent temperature trend throughout the monitoring period demonstrates the stability and continuity of data acquisition and transmission. The temperature variations did not correspond to significant changes in RMS vibration velocity. No direct linear correlation was observed between short-term thermal fluctuation and vibration amplitude under normal load conditions. This indicates that within the observed operating range, thermal variation did not significantly influence dynamic vibration behavior. However, long-term thermal degradation effects were not evaluated in this study.

Frequency Domain Characteristics

FFT analysis identified dominant spectral components corresponding to harmonics of the machine's rotational frequency. The compressor operates at approximately 931 rpm, equivalent to a fundamental rotational frequency of: $931/60 = 15.52$ Hz. For Sensor 1, the dominant peak was observed at approximately 29.9 Hz, which closely corresponds to the 2× rotational frequency (≈31 Hz). For Sensor 2, the dominant spectral component appeared at approximately 45.3 Hz, consistent with the 3× rotational harmonic (≈46.5 Hz). The presence of stable harmonic components (2× and 3×) indicates that the vibration response is primarily governed by normal rotational dynamics and structural transmissibility rather than fault-induced excitation. Importantly: No significant sideband modulation was observed around the main harmonic peaks, No abnormal high-frequency broadband energy increase was detected, No irregular non-synchronous frequency components were identified.

In rotating machinery diagnostics, excessive 1× amplitude typically indicates imbalance, strong 2× components may suggest misalignment, and broadband high-frequency components are often associated with bearing defects. In this study, the harmonic peaks remained consistent over time without progressive amplitude growth, indicating stable mechanical behavior during the monitoring period. Therefore, frequency-domain analysis complements RMS evaluation by not only quantifying vibration severity but also confirming that the dominant excitation mechanisms are rotationally synchronous and consistent with normal machine operation Analysis revealed dominant frequency components corresponding to the machine's rotational characteristics (Muhlisin et al. 2021). The presence of consistent frequency peaks indicates normal mechanical behavior without significant abnormal excitation. Frequency-domain analysis complements RMS evaluation by providing insight into the source and nature of vibration components, which is essential for condition-based maintenance (Adinarto & Romahadi 2024).

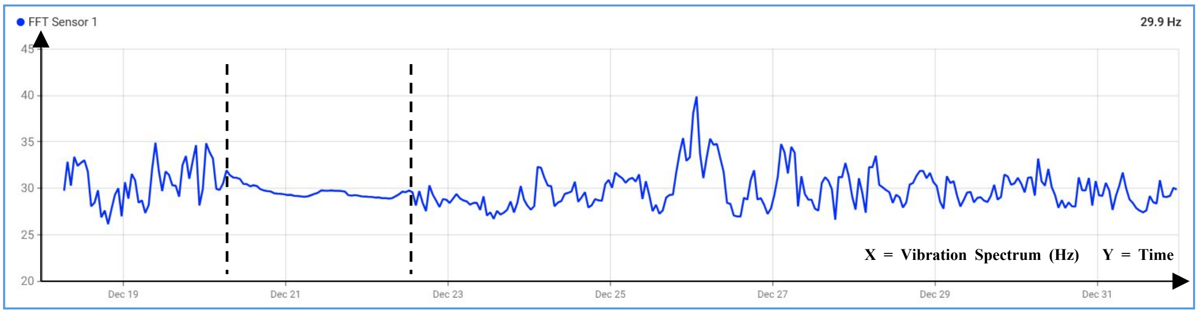

Figure 7 Sensor 1 Vibration Spectrum Monitoring 14 Days from Thingsboard

Figure 7 presents the vibration spectrum obtained from Fast Fourier Transform (FFT) analysis of Sensor 1 over a continuous 14-day monitoring period. the dominant peak was observed at approximately 29.9 Hz, which closely corresponds to the 2× rotational frequency (≈31 Hz). The spectrum represents the distribution of vibration amplitude as a function of frequency, enabling identification of dominant frequency components associated with machine operation. The observed spectrum shows a clear concentration of vibration energy around the fundamental rotational frequency of the machine and its harmonic components. This indicates that the dominant vibration behavior is primarily related to normal rotational dynamics rather than irregular high-frequency impulsive events. The absence of significant broadband frequency elevation or abnormal sideband patterns suggests stable mechanical operation during the monitoring period.

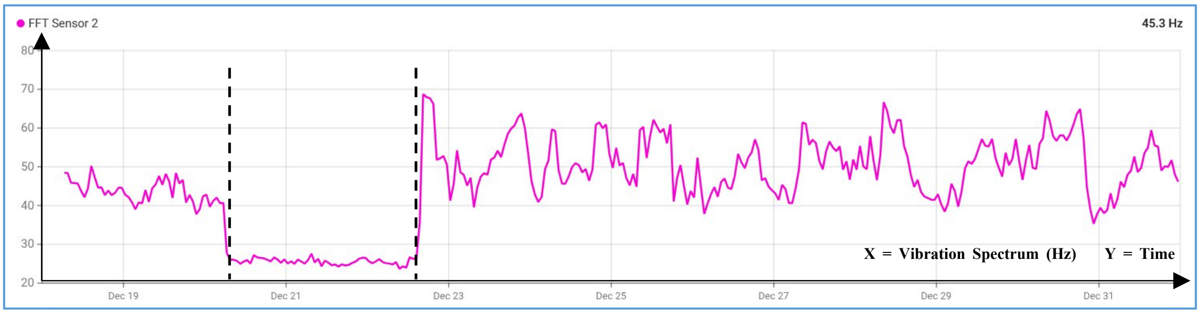

Figure 8 Sensor 2 Vibration Spectrum Monitoring 14 Days from Thingsboard

Figure 8 presents the frequency-domain vibration spectrum obtained from Sensor 2 over the same 14-day monitoring interval. the dominant spectral component appeared at approximately 45.3 Hz, consistent with the 3× rotational harmonic (≈46.5 Hz). This spectrum serves as a comparative reference to Sensor 1 in order to evaluate spatial consistency and detect localized variations in machine dynamic behavior. The spectral distribution reveals noticeable changes in frequency amplitude patterns following the scheduled monthly maintenance conducted between 20 December 2025 at 06:08 and 22 December 2025 at 15:35. Compared to the pre-maintenance condition, the post-maintenance spectrum exhibits temporary redistribution of vibration energy across certain frequency components, indicating transient mechanical stabilization effects.

Such spectral variation suggests that the machine experienced short-term dynamic adjustments after maintenance activities, potentially related to component reassembly, alignment correction, tightening, or lubrication changes. Although the dominant rotational frequency component remained observable, minor amplitude fluctuations and harmonic redistribution were detected during the post-maintenance interval. The comparative FFT analysis between Sensor 1 and Sensor 2 confirms that the observed changes were not isolated measurement artifacts but reflected actual mechanical behavior. This demonstrates the usefulness of multi-point spectral monitoring for detecting subtle dynamic changes that may not immediately produce significant variation in overall RMS vibration levels.

Closed-Loop Monitoring Effectiveness

The closed-loop monitoring mechanism using LED indicators successfully provided immediate visual feedback based on vibration and temperature thresholds. This feature enhances operator awareness without requiring direct access to the IoT dashboard, thereby improving response time to abnormal conditions. The integration of local indicators demonstrates the practicality of combining digital monitoring with simple on-site feedback mechanisms.

Figure 9 Red Light Appears from Vibration Sensor 1 & Sensor 2 indicating over threshold

Figure 9 presents the field implementation of the closed-loop monitoring mechanism integrated into the panel installed on the reciprocating compressor. The LED indicators are mounted on the lower section of the enclosure and are directly controlled by the ESP32 microcontroller based on real-time vibration and temperature evaluation. For vibration monitoring, although ISO 10816-3 (Group 1) defines the upper limit of Zone A at 2.3 mm/s, the closed-loop threshold was intentionally configured at 2.0 mm/s to validate the responsiveness of the LED mechanism under controlled experimental conditions. This adjusted threshold was used solely to demonstrate system functionality without requiring the machine to exceed ISO permissible limits. For temperature monitoring, a threshold of 80 °C was applied as the upper operational limit. When RMS vibration remains below 2.0 mm/s, the green LED remains active; values exceeding this threshold trigger the red indicator. Similarly, the red LED activates when temperature exceeds 80 °C. This configuration confirms that the edge device can perform real-time RMS computation, threshold comparison, and immediate visual feedback, demonstrate effective closed-loop monitoring while maintain ISO-based classification for formal condition assessment.

Discussion

Compared to conventional manual inspection methods, the proposed system enables continuous and real-time monitoring, eliminating the risk of missing transient events between inspection intervals. Unlike many IoT-based solutions that rely on complex predictive algorithms, this study emphasizes direct interpretation of vibration data based on established industrial standards. This approach improves interpretability and facilitates adoption by maintenance personnel who are already familiar with ISO-based vibration evaluation. The results confirm that a lightweight IoT architecture, combined with edge-level signal processing and standard-based evaluation, can provide a reliable and cost-effective solution for industrial machine condition monitoring.

Table 2 Comparation Between Manual Measurement and Monitoring Automatically

Comparison	Manual Measurement Method	Automatic Monitoring Systems
Measurement Method	Direct inspection using portable measuring instruments	Permanently installed sensors and real-time monitoring
Data Collection	Periodically performed by technicians	Continuously and automatically
Data Analysis	Manual analysis/software	Direct analysis via dashboard
Technician dependency	Very High	Low
Estimated measurement and analysis time per machine	± 40 minutes	± 12 minutes
Historical data availability	Limited	Dependent on recording
Anomaly Response	Slow (waiting inspection)	Fast (real-time)

Conclusions

This study has developed and experimentally validated an IoT-based real-time vibration and temperature monitoring system for industrial machinery using an ESP32 microcontroller and MQTT communication protocol. The proposed architecture integrates multi-sensor acquisition with edge-level signal processing, enabling continuous monitoring through RMS and FFT analysis without relying on predictive or machine learning algorithms. Experimental testing on a reciprocating compressor operating under normal conditions demonstrated stable data acquisition and consistent RMS vibration (2.15–2.17 mm/s) and temperature measurements (approximately 67 °C) during the observation period. Frequency-domain analysis using FFT successfully identified dominant vibration components corresponding to the machine's operating characteristics. By directly implementing ISO 10816-3 thresholds at the edge level, the system provides practical vibration severity classification aligned with industrial maintenance standards. The addition of a local visual indicator supports immediate on-site condition awareness.

However, this study did not include quantitative evaluation of network performance metrics such as packet loss, transmission latency, or long-term communication robustness. In addition, RMS velocity measurements were not calibrated against a certified reference vibration analyzer, which may affect absolute measurement accuracy. Future work will focus on comparative validation using industrial-grade vibration instruments, extended testing under varying load conditions, and quantitative assessment of communication performance to further strengthen system reliability and industrial applicability.

Overall, the proposed system demonstrates a feasible and cost-effective implementation of ISO-based edge monitoring suitable for supporting condition-based maintenance in industrial environments.

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