

EDGE COMPUTING–BASED PREDICTIVE MAINTENANCE (PdM) FRAMEWORK WITH RASPBERRY PI

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Abstract

Predictive Maintenance (PdM) has emerged as a key enabler of Industry 4.0, providing industries with the ability to anticipate equipment failures and schedule repairs proactively. Unlike traditional maintenance practices, which are either reactive or preventive, PdM integrates real-time monitoring with intelligent data analysis to minimize unexpected breakdowns, optimize productivity, and extend the operational lifespan of machinery. With the growing demand for cost-effective and scalable solutions, the Raspberry Pi has gained significant attention as a low-cost embedded computing platform for implementing PdM frameworks. The proposed system leverages Raspberry Pi boards to collect continuous sensor data from industrial machines, including parameters such as vibration, temperature, and pressure. This data is preprocessed and analyzed locally on the device using lightweight machine learning algorithms to detect abnormal patterns and forecast potential failures. By shifting computation from cloud servers to the edge, the framework effectively reduces latency, enhances reliability, and ensures greater data security, especially in

mission-critical industrial environments where network disruptions may occur. Furthermore, the use of edge computing minimizes bandwidth usage by transmitting only essential or aggregated information to cloud platforms for long-term storage and big data analytics. This hybrid architecture not only lowers operational costs but also enables real-time decision-making close to the source of data generation. The experimental outcomes highlight that Raspberry Pi–based PdM systems can serve as a cost-efficient, energy-efficient, and scalable alternative to conventional industrial monitoring platforms, thereby contributing to smarter, more sustainable, and resilient manufacturing operations under the Industry 4.0 paradigm.

Introduction

The rapid advancement of the Internet of Things (IoT) and Industry 4.0 has significantly changed the landscape of industrial monitoring and maintenance. Conventional maintenance strategies, such as reactive maintenance, which addresses issues only after a breakdown, or preventive maintenance, which schedules servicing at fixed intervals, often result in inefficiencies. Reactive approaches cause unplanned downtime and financial losses, while

preventive strategies may lead to unnecessary inspections and resource usage. To address these limitations, Predictive Maintenance (PdM) has emerged as a smarter alternative by utilizing real-time sensor data and machine learning techniques to forecast equipment failures before they occur. In recent years, low-cost embedded computing platforms have gained attention as practical solutions for implementing PdM in industrial settings. Among these, Raspberry Pi boards have proven particularly effective due to their affordability, portability, and sufficient processing capability. When integrated with industrial sensors, the Raspberry Pi can continuously acquire parameters such as vibration, temperature, and pressure. Unlike cloud-only architectures, the system processes data locally at the edge, thereby minimizing network latency, reducing operational costs, and improving data security. This edge computing-based PdM framework ensures timely fault detection and decision-making, making it highly suitable for industries seeking reliable, scalable, and cost-efficient maintenance solutions.

Review of Literature

Several studies in recent years have emphasized the growing importance of integrating edge computing and Internet of Things (IoT) technologies into predictive maintenance (PdM) systems. Sharma et al. (2022) designed and implemented a Raspberry Pi-based PdM framework that focused on vibration analysis of industrial motors. Their work demonstrated how continuous monitoring and localized data processing using Raspberry Pi could significantly reduce unplanned downtime in manufacturing units, thereby improving productivity and operational efficiency. This study highlighted the effectiveness of using

low-cost embedded systems for real-time predictive analytics in industrial environments.

In another notable work, Kumar and Gupta (2021) investigated an IoT-cloud hybrid model for predictive fault detection. Their system utilized IoT sensors to collect machine health data and transmit it to the cloud for analysis. While this approach improved prediction accuracy by leveraging cloud computing resources, the researchers identified significant limitations related to network latency, bandwidth consumption, and dependence on uninterrupted internet connectivity. These constraints revealed challenges in adopting cloud-only architectures for time-sensitive industrial applications, where even minor delays could impact decision-making. Similarly, (2020) Brown and Zhang (2020) explored the deployment of lightweight machine learning algorithms on embedded platforms such as the Raspberry Pi. Their study confirmed that embedded edge devices are capable of executing predictive models efficiently, enabling real-time decision-making without relying heavily on external computing infrastructure. Collectively, these studies affirm the potential of Raspberry Pi-based PdM systems as scalable, cost-efficient, and practical solutions. However, they also underline the need for further research into optimizing low-latency frameworks that combine edge intelligence with cloud integration for enhanced scalability and reliability in Industry 4.0 applications.

Existing System with Limitations

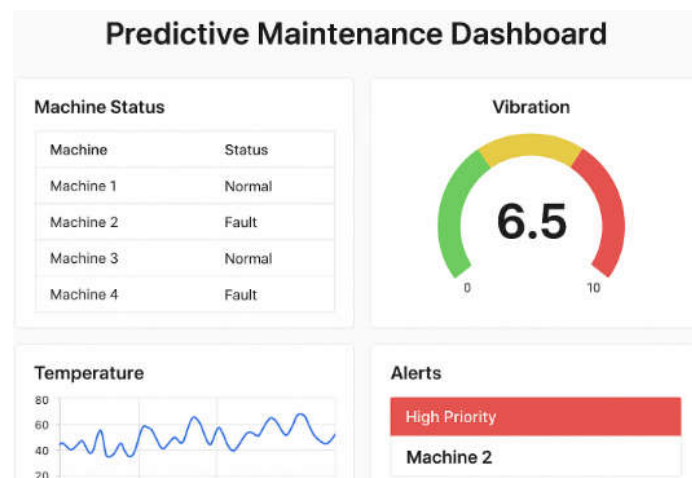
In existing predictive maintenance (PdM) systems, the most widely adopted approach involves cloud-based architectures where data collected from industrial sensors

is transmitted to remote cloud servers for analysis. In such systems, parameters such as vibration, temperature, and pressure are continuously monitored and sent to the cloud, where advanced analytics and machine learning models process the data to identify fault patterns and predict equipment failures. While cloud computing offers high storage capacity and powerful processing resources, reliance on this architecture introduces several significant challenges that limit its effectiveness in real-time industrial environments.

One of the primary limitations of cloud-based PdM systems is the high dependency on stable internet connectivity. In many industrial settings, particularly in remote or harsh environments, network reliability cannot always be guaranteed, and disruptions in connectivity can lead to data loss or delays in fault detection. Additionally, transmitting large volumes of sensor data to cloud servers results in increased latency, which is problematic for time-sensitive applications where immediate fault detection and rapid response are critical. Another drawback is the higher operational costs associated with continuous data transmission and cloud service subscriptions, making such systems less affordable for small- and medium-scale enterprises. Finally, data security and privacy concerns are particularly relevant in industries dealing with sensitive or proprietary information. Transferring raw equipment data over public or third-party cloud platforms increases the risk of unauthorized access and cyber threats.

Proposed Solution

The proposed system introduces a Raspberry Pi-based edge computing framework for predictive maintenance



(PdM), designed to address the challenges of traditional cloud-centric approaches. In this architecture, industrial sensors such as vibration, temperature, and pressure sensors are directly interfaced with a Raspberry Pi, which functions as the primary edge device. The Raspberry Pi continuously acquires real-time operational data from machines, enabling immediate monitoring of equipment health. Instead of transmitting raw data to the cloud, the system incorporates local preprocessing techniques such as filtering, normalization, and feature extraction, thereby reducing noise and preparing the data for efficient analysis.

To enable intelligent decision-making, the Raspberry Pi is equipped with lightweight machine learning algorithms capable of fault classification and failure prediction. By performing this analysis at the edge, the system ensures rapid response with minimal latency, which is particularly crucial in scenarios requiring real-time fault detection. Additionally, the architecture offers optional cloud integration for long-term data storage, historical trend analysis, and big data-driven insights, thereby combining the strengths of edge and cloud computing in a hybrid model.

The framework also includes a user-friendly dashboard for visualization and alert management. This interface provides operators with real-time insights into machine performance, graphical representations of sensor data, and early warnings when anomalies are detected. As a result, industries can minimize downtime, optimize maintenance schedules, and reduce overall operational costs. By leveraging the affordability and efficiency of Raspberry Pi, the proposed system presents a scalable, reliable, and cost-effective solution for predictive maintenance in Industry 4.0 environments.

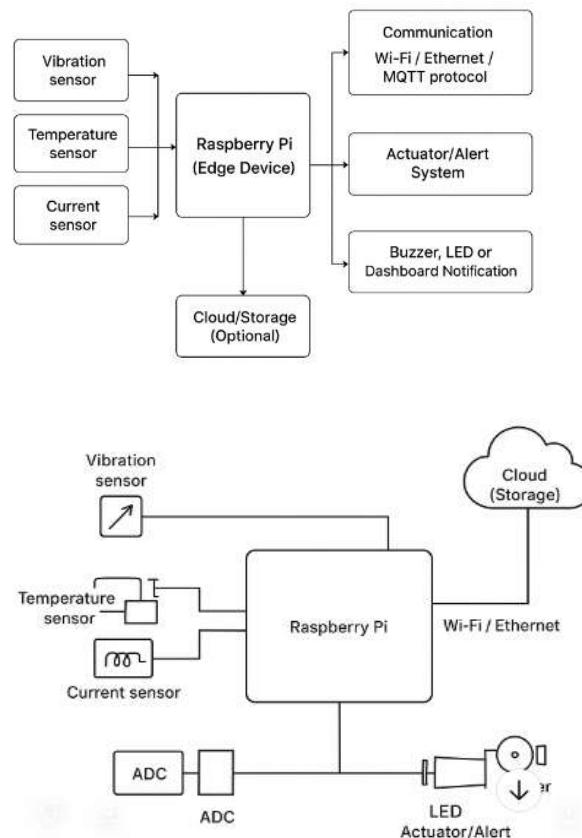
Circuit Diagram

The proposed predictive maintenance framework is designed with a structured block diagram that integrates sensing, processing, communication, alerting, and storage components to ensure efficient monitoring of industrial equipment. At the first stage, various sensors are deployed to capture real-time operational parameters. These include vibration sensors to monitor abnormal mechanical oscillations, temperature sensors such as DHT11 or DHT22 to track overheating or cooling issues, and current sensors to observe electrical load variations. Collectively, these sensing devices provide critical insights into the health status of machinery and help in identifying early signs of potential failures.

The collected sensor data is transmitted to the processing unit, which in this case is a Raspberry Pi functioning as the edge computing device. The Raspberry Pi serves as the central hub for data acquisition, preprocessing, and machine learning-based fault classification. By handling computations locally, it reduces dependency

on external servers, thereby improving latency, reliability, and security. For data communication, the system supports Wi-Fi and Ethernet connections, while lightweight IoT protocols such as MQTT can be employed for seamless data transfer between sensors, edge devices, and optional cloud platforms.

The framework also incorporates an actuator and alert system to provide timely notifications. This may include triggering a buzzer or LED indicator in the event of anomalies, as well as generating alerts through a user-friendly dashboard for remote monitoring. Additionally, cloud integration can be optionally included to store historical data, which can later be analyzed for trend detection, big data analytics, and long-term decision-making. Overall, this block diagram ensures an end-to-end predictive maintenance solution that is cost-effective,



scalable, and capable of addressing modern industrial challenges.

Code

[Vibration: MPU6050]--I2C--(SDA->GPIO2, SCL->GPIO3)-->[Raspberry Pi]

[Temperature: DHT22]--Data->GPIO4 (10k pull-up)-->[Raspberry Pi]

[Current: ACS712]--Analog Out-->[MCP3008 CH0]--SPI-->(MOSI,MISO,SCLK,CE)-->[Raspberry Pi]

[Raspberry Pi GPIO17]--220Ω-->[LED]-->GND

[Raspberry Pi GPIO27]--1kΩ-->Base(BC547)

Collector-->Buzzer(-)

Buzzer(+)-->5V

Emitter-->GND

[Raspberry Pi]--WiFi/Ethernet-->Network (MQTT Broker / Cloud)

Sample Predictive Maintenance Dataset

Timestamp	Vibration (m/s ²)	Temperature (°C)	Current (A)	Status/Condition	Alert
2025-10-03 10:00:00	1.2	28.5	2.1	Normal	No
2025-10-03 10:05:00	1.5	29.0	2.2	Normal	No
2025-10-03 10:10:00	2.8	35.5	3.0	Warning	Yes
2025-10-03 10:15:00	3.5	38.0	3.5	Fault Predicted	Yes
2025-10-03 10:20:00	4.0	40.2	3.8	Critical	Yes
2025-10-03 10:25:00	1.8	30.0	2.5	Normal	No

Explanation of Columns

Timestamp → Time of data acquisition.

Vibration → Captured from vibration sensor (threshold > 3 = fault).

Temperature → Measured from DHT11/DHT22 sensor (threshold > 37 °C = warning).

Current → From current sensor to detect overload.

Status/Condition → Classified by Raspberry Pi (Normal, Warning, Fault Predicted, Critical).

Alert → Whether buzzer/LED/dashboard notification is triggered.

Maintenance

Maintenance of the proposed predictive maintenance framework involves preventive, software, and hardware aspects to ensure reliable performance. Preventive maintenance includes the periodic inspection of the Raspberry Pi, sensors, and power supply to verify their proper functioning and prevent unexpected failures. Regular checks of cabling, connectors, and peripheral modules help in avoiding signal interruptions and system downtime. Software maintenance plays a vital role in keeping the system updated and secure. This involves upgrading the Raspberry Pi OS, updating Python libraries, and retraining or fine-tuning the machine learning models to improve prediction accuracy. Firmware updates for communication protocols such as MQTT may also be applied to enhance compatibility and performance. Hardware maintenance, on the other hand, focuses on the physical components of the system. Sensors such as vibration, temperature, and current modules need periodic cleaning and calibration to maintain data accuracy. Loose connections, dust accumulation, or damaged components should be addressed promptly to avoid data loss and inaccurate fault detection. By following a structured maintenance routine covering these three areas, the overall system remains efficient, accurate, and capable of supporting industrial applications over extended operational periods.

Working Methodology

The working methodology of the proposed predictive maintenance system follows a systematic sequence beginning with data acquisition. Sensors such as vibration, temperature, and current modules are continuously deployed to monitor the real-time operational parameters of industrial equipment. This raw sensor data often contains unwanted noise; therefore, the next stage involves data preprocessing, where filtering techniques are applied to remove interference. Additionally, key features such as Root Mean Square (RMS), mean values, and Fast Fourier Transform (FFT) components are extracted, particularly from vibration signals, to enhance the quality and relevance of the dataset. Once the data is refined, edge processing is carried out on the Raspberry Pi, which serves as the central computational unit. Lightweight machine learning models such as Decision Trees, Support Vector Machines (SVM), or compact Convolutional Neural Networks (CNN) are executed locally on the device to classify patterns and predict potential faults. Based on the predictions, the system proceeds to the alert mechanism. If any abnormal condition is identified, immediate notifications are triggered through buzzers, LEDs, or a dashboard interface to ensure timely intervention. Additionally, an optional cloud storage module is included, allowing processed data to be archived for long-term analysis, trend monitoring, and performance optimization.

Future Enhancements

Predictive maintenance in modern industrial environments is being significantly enhanced through the integration of advanced technologies. Leveraging AI and deep

learning models, such as LSTM (Long Short-Term Memory) networks and CNNs (Convolutional Neural Networks), enables the system to analyze complex patterns in sensor data, detect anomalies, and forecast equipment failures with higher accuracy than traditional methods. These models can process temporal sequences and spatial features of data, making them ideal for vibration, temperature, and acoustic signal analysis in machinery. Complementing this, 5G and LoRaWAN technologies facilitate real-time wireless communication between sensors and edge devices like Raspberry Pi nodes, ensuring minimal latency and reliable data transfer even in large industrial spaces. To further enhance decision-making, digital twin technology is deployed, allowing a virtual replica of the machinery to simulate operational scenarios, test predictive models, and optimize maintenance schedules without disrupting actual production. Moreover, the framework is designed to be scalable, supporting multiple Raspberry Pi nodes across extensive factory setups, enabling distributed data processing, edge intelligence, and coordinated predictive insights. This holistic approach not only improves the accuracy of failure predictions but also minimizes downtime, reduces maintenance costs, and enhances overall operational efficiency, paving the way for smarter, data-driven industrial ecosystems.

Conclusion

This paper presented a comprehensive Raspberry Pi-based edge computing framework for predictive maintenance in industrial systems, highlighting its potential to transform traditional maintenance approaches. The proposed framework integrates real-time sensor monitoring with local machine

learning algorithms, enabling on-device processing of critical data and minimizing the latency typically associated with cloud-based solutions. By deploying models such as LSTM and CNN directly on Raspberry Pi nodes, the system can detect anomalies, forecast potential equipment failures, and provide timely alerts to maintenance personnel, thereby reducing unplanned downtime and operational losses. The use of edge computing also alleviates the dependency on high-bandwidth cloud communication, making the solution suitable for environments with limited connectivity or strict latency requirements. Furthermore, the framework incorporates scalable and distributed architecture, allowing multiple Raspberry Pi nodes to operate across large industrial setups, supporting coordinated monitoring and collaborative decision-making. Integration of digital twin technology and advanced predictive models enhances simulation-based analysis, enabling factory managers to test maintenance strategies virtually before implementation. Wireless communication protocols like 5G and LoRaWAN ensure seamless real-time data transmission, even across extensive production floors. Overall, the study demonstrates that low-cost embedded systems can serve as an effective and practical alternative to traditional maintenance methods while supporting Industry 4.0 objectives, including automation, efficiency, and intelligent decision-making. The framework offers a promising pathway for industries seeking to implement smart, data-driven maintenance strategies without incurring the high costs of conventional predictive maintenance infrastructures.

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