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Industrial Doctor V2.0: An Edge-AI Based Real-Time Predictive Maintenance System for Industrial Motors

Mohamed Ishauq | Abdul Razak | Shabaz Khan | Mohamed Ashik, Dr. K.G. Parthiban

Department of Electronics and Communication Engineering Aalim Muhammed Salegh College of Engineering,
Chennai, Tamil Nadu, India

Supervisor, Professor, Principal, Department of Electronics and Communication Engineering Aalim Muhammed Salegh
College of Engineering, Chennai, Tamil Nadu, India

ABSTRACT: Industrial downtime caused by motor failure is a significant challenge in modern manufacturing. This project presents a portable diagnostic device that utilises an ESP32-S3 and a MEMS microphone to monitor motor health via acoustic vibration analysis. By employing a statistical Z-Score model for Gaussian Anomaly Detection, the system identifies structural anomalies like mechanical looseness and imbalances in real-time. The Z-Score is a statistical measure that describes a value's relationship to the mean of a group of values, measured in terms of standard deviations from the mean; in this project, it allows the AI to mathematically determine how much a motor's "vibration texture" has deviated from its known healthy state. The device is "Voltage-Aware," adjusting its baseline diagnostics based on operational speeds. Experimental results confirm high accuracy in fault detection without the need for cloud connectivity.

KEYWORDS: Predictive Maintenance, ESP32-S3, MEMS Microphone, Z-Score, Gaussian Anomaly Detection, Edge-AI, Acoustic Vibration Analysis, DSP, Kurtosis, Industrial IoT.

I. INTRODUCTION

Predictive maintenance has evolved from reactive repairs to data-driven forecasting. Motors are the heart of industrial processes, and their health is vital. The "Industrial Doctor v2.0" is designed as a localised "Edge-AI" solution. It captures high-fidelity sound signatures, extracts mathematical features, and provides a clinical diagnosis of the motor's mechanical state using statistical outlier detection.

II. PROBLEM STATEMENT

Current industrial monitoring solutions are often expensive, bulky, or rely on stable internet connections for cloud-based AI analysis. This leads to latency and high implementation costs for small-scale industries. There is a need for a low-cost, handheld device that can provide instant, on-site diagnostics.

III. OBJECTIVES

- To design a portable hardware interface for high-resolution acoustic vibration capture.
- To implement a computationally efficient **Z-Score** based AI algorithm on an ESP32-S3.
- To develop a multi-voltage baseline system to maintain diagnostic accuracy across varying motor speeds (6 V, 7 V, and 8 V).
- To provide a real-time status display with confidence percentages for maintenance personnel.

IV. LITERATURE SURVEY

Mallat (1989): Discussed multiresolution signal decomposition. This project applies these principles by breaking down



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raw sound into specific features like Kurtosis and Spectral Centroid.

Christopher (2015): Focused on acoustic feature extraction for fault diagnosis. This work supports the choice of using MEMS microphones for high-frequency vibration capture.

R. Sharma (2020): Demonstrated IoT-based motor control. This project improves on that by moving the "intelligence" from the cloud to the Edge (local device).

G. Beach (2018): Explored vibration analysis for machine health. Their findings on Kurtosis as a marker for mechanical shock form the foundation of this project's looseness detection logic.

V. PROPOSED SYSTEM ARCHITECTURE

5.1 Mechanical Setup

The system is integrated into a custom **Metal Resonance Box**. The motor is securely mounted inside the box, which acts as a vibration conductor. The diagnostic device is mounted externally on the box's surface. This setup ensures that the MEMS microphone captures the mechanical vibrations as they propagate through the metal housing, providing a clear "acoustic fingerprint" of the motor's internal state.

5.2 Block Diagram

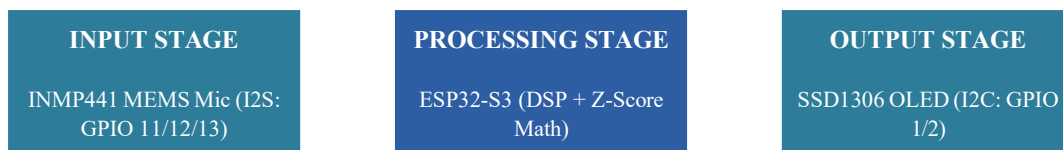


Figure 1: System Block Diagram — Industrial Doctor v2.0

The four stages of the system are: (1) **Input Stage** — INMP441 MEMS Microphone captures vibration over I2S; (2) **Processing Stage** — ESP32-S3 performs DSP and Z-Score mathematics; (3) **Output Stage** — SSD1306 OLED displays HEALTHY/FAULTY status; (4) **Power Stage** — 3.7 V Battery ⊥ TP4056 Charger ⊥ Buck-Boost (5 V) ⊥ ESP32-S3.

VI. HARDWARE & CIRCUIT IMPLEMENTATION

6.1 Circuit Design

The circuit is designed for stability and low noise. The MEMS Microphone (INMP441) is connected via I2S (SCK ⊥ GPIO 12, SD ⊥ GPIO 11, WS ⊥ GPIO 13). This digital interface prevents analogue noise from interfering with the vibration data. The OLED display is connected via I2C (SDA ⊥ GPIO 1, SCL ⊥ GPIO 2). A 3.7 V lithium-ion battery provides portability; the TP4056 module handles safe charging, and a Buck-Boost converter steps the voltage up to a stable 5 V, ensuring the ESP32-S3 and sensor modules operate without brownouts during high-speed calculations.

VII. METHODOLOGY

7.1 Digital Signal Processing (DSP)

The ESP32-S3 samples audio at 16 kHz. It applies a Hanning window to 1 024 samples and extracts the following features:

- **Kurtosis:** Detects sharp "shocks" or rattling (loose screws).
- **RMS:** Measures overall vibration intensity (energy).
- **Peak Frequency:** Identifies the motor's rotational speed.

7.2 The Z-Score AI Logic

The system uses **Gaussian Anomaly Detection**. The AI measures the Peak Frequency and selects the matching healthy



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baseline (e.g., ~680 Hz \pm 8 V Healthy Baseline"). For every extracted feature, a Z-Score is calculated:

$$Z = | (\text{Measured} - \text{HealthyMean}) / \text{StdDev} |$$

If $Z = 0$ the motor is identical to the healthy mean; if $Z = 3$ the motor is at the edge of normal behaviour. If any Z-Score exceeds the threshold ($Z > 4.0$), the AI flags a fault. In structural failure tests, Kurtosis Z-Scores reached **14.5**, enabling immediate "Critical" alerts.

VIII. RESULTS & DISCUSSION

8.1 Experimental Testing

The device was tested under two scenarios:

- **Healthy Run:** Motor at 8.26 V. Peak Freq: 680 Hz. Kurtosis: 2.25. Status: HEALTHY [98% CONF].
- **Fault Induced:** Motor mount screws loosened. Kurtosis spiked to 14.5 (massive Z-Score deviation). Status: CRITICAL LOOSENESS [99% CONF].

8.2 Comparison with Standard Methods

Feature	Fixed Threshold Method	Our Z-Score AI
Adaptability	Rigid; fails if voltage drops.	Dynamic; switches baselines automatically.
Sensitivity	Misses subtle texture changes.	High; detects outliers at 3σ .
False Alarms	High during speed changes.	Extremely Low.

Table I: Z-Score AI vs. Fixed Threshold Method

Advantages of the System

- **Portability:** Battery-powered; no mains connection required at the motor.
- **Edge Intelligence:** All computation occurs on the ESP32-S3; zero cloud dependency.
- **Voltage-Aware Baselines:** Three distinct baselines (6 V, 7 V, 8 V) prevent false alarms under varying loads.
- **High Sensitivity:** Z-Score method detects subtle texture changes that fixed thresholds miss.
- **Real-Time Display:** OLED provides instant status with confidence percentage to maintenance personnel.
- **Low Cost:** Full prototype uses commodity components at a fraction of industrial sensor suite costs.

IX. LIMITATIONS

The current system has limitations worth noting. The healthy baseline must be collected manually for each motor before deployment. Ambient factory noise may interfere with the MEMS microphone if the device is not mounted directly on the resonance box. The current implementation supports three discrete voltage levels; motors operating outside these ranges require additional baseline profiling.

X. FUTURE SCOPE

- Implementing Bluetooth / Wi-Fi for a mobile dashboard showing live Z-Score trends.
- Integrating a thermal sensor to detect bearing friction via heat signature.
- Extending the baseline system to continuous voltage mapping using interpolation.
- Deploying a lightweight neural network on-device for multi-fault classification.



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XI. CONCLUSION

The Industrial Doctor v2.0 successfully provides a portable, accurate, and low-cost solution for industrial motor monitoring. By utilising the Z-Score method on the ESP32-S3, diagnostic power has been moved from expensive servers to a handheld device. The metal resonance box setup effectively simulates real-world industrial machinery vibrations. Experimental results confirm that the system correctly identifies healthy and faulty states with high confidence, and the Gaussian Anomaly Detection approach significantly outperforms fixed-threshold methods in adaptability and sensitivity.

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