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Real-Time Industrial Machine Health Monitoring and Failure Prediction Using ESP32

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***Abstract* - Machine failures occurring in industries result in unforeseen stoppage, higher maintenance cost, reduction in efficiency, and ultimately losses. The traditional approach of maintenance is based mostly on manual periodic inspection and corrective maintenance, which proves to be inefficient for modern industries. In this paper, an Internet of Things (IoT)-Based Predictive Machine Failure Monitoring System using ESP32 microcontroller for continuous health monitoring of machines and fault prediction is presented. The proposed system monitors machine health parameters like vibrations, temperature, current, and anomalous noise generated by the machine with the help of various sensors like MPU6050, ACS712, and temperature sensors. The sensor data collected from various sensors is then processed by ESP32 and the fault can be predicted using the threshold-based approach. The proposed system facilitates remote monitoring using various IoT platforms. The experiment shows that the proposed monitoring system is capable of identifying and giving early notification about machine anomalies.**

***Index Terms* - Predictive Maintenance, ESP32, Industrial Automation, IoT, Machine Failure Detection, Industry 4.0, Vibration Monitoring, Machine Health Monitoring, Fault Prediction, Real-Time Monitoring**

I. INTRODUCTION

Machines are integral components of the modern manufacturing industry. The continuous working of industrial machinery like motors, pumps, compressors, conveyor belts, and other equipment ensures efficiency and helps in saving costs incurred during operations. Machine failure leads to serious problems in production, increases maintenance expenses, causes loss of productivity and equipment life and leads to financial losses. Traditional maintenance procedures like corrective and preventive maintenance do not help because, in one case, repairs are carried out only after the occurrence of faults whereas, in the latter, replacement is done even before failure occurs.

The advent of Industry 4.0 and IIoT technology has helped develop predictive maintenance techniques which are important in enhancing reliability and efficiency in operations. Predictive maintenance constantly checks the parameters of the machine and identifies the problem before its critical stage arises. This technique minimizes production downtime and enhances efficiency and effectiveness of the machine as well as saves on maintenance expenses.

In the industrial sector, faults in the machines can be identified from factors like unusual vibration, increased temperatures, high current and sound levels. Identification of these factors can assist in the detection of probable faults like bearing wear, shaft misalignment, overload and mechanical looseness. Existing industrial predictive maintenance systems are usually costly and complex to implement in industries.

This research proposes the IoT-Based Predictive Machine Failure Monitoring System utilizing ESP32 to monitor machines in real time and to predict their malfunction. The proposed system uses several sensors, including vibration sensors, current sensors, temperature sensors, and sound sensors, to collect data on the working condition of the machine. Then, the data is processed by the ESP32 microcontroller with predictive algorithms in place to detect any irregularities in the machine performance.

The suggested IoT-based monitoring system allows one to

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create a cost-effective predictive maintenance tool that can be used in automation. Early warnings regarding potential failures will benefit industries greatly.

II. LITERATURE SURVEY

Predictive maintenance has evolved into a significant field of study in industrial automation owing to the increasing importance of consistent operation of machines without any interruptions. Different authors have come up with different systems of monitoring machines using Internet of Things (IoT), vibration, thermal analysis, and artificial intelligence methodologies to mitigate unexpected equipment failures and minimize maintenance costs.

Many conventional maintenance systems employed in industries heavily rely on reactive and preventive maintenance approaches. In reactive maintenance approach, the machines are repaired when they fail to operate. Consequently, the productivity is interrupted, and there are losses associated with production. Similarly, preventive maintenance involves maintenance of machines based on their condition, but regardless of whether they are working well. Predictive maintenance systems have been developed to overcome these challenges.

Most research studies on industrial machinery maintenance and diagnosis have emphasized the use of vibration analysis for condition monitoring. Vibrations are used for detecting problems in bearings, shaft imbalance, mechanical looseness, and many other issues. Most research studies have used accelerometers and signal processing algorithms to detect any abnormal vibrations from machinery in industries. However, one-parameter monitoring systems are not adequate for fault detection. Another common application of monitoring techniques is in industries where monitoring temperature is employed to find overheating scenarios within motor, transformer, and electrical systems. Overheating could be caused by an overloaded system, faulty insulation or mechanical friction. Nonetheless, temperature monitoring alone would not be sufficient to determine the condition of machines completely.

Research work has been done on the use of the internet of things in industrial monitoring systems, which incorporate communication networks such as Wi-Fi and MQTT. Such a system could facilitate the collection and analysis of data remotely and enable visualization through dashboard interfaces and mobile phone application. The inclusion of IoT will enhance access while allowing maintenance engineers to monitor machine performance at all times.

There are modern predictive maintenance systems using machine learning and AI to analyze and determine machine conditions based on historic data and hidden faults. Such systems are capable of predicting machine failures by analyzing the machine's behavior. However, most predictive maintenance systems using AI involve costly sensors, computation, and high costs of implementation and thus would not be appropriate for smaller industries.

Based on the literature review, it is clear that most of the existing systems have only focused on single parameter monitoring or expensive industrial systems. Therefore, there is a need to develop a cost-effective and multisectional monitoring system that predicts machine failure and monitors its performance through vibration, sound, temperature and current monitoring in real time.

A. Problem statement

In industrial machines like motors, pumps, compressors, and conveyors used in industrial manufacturing units to process huge quantities of items or goods, any failure of machines will cause loss in terms of production downtime, higher maintenance expenses, damages, and loss of money. The use of maintenance strategies like reactive maintenance and preventive maintenance in such a situation is inefficient since reactive maintenance repairs the equipment after any failure occurs and preventive maintenance does so by replacing any machine component without knowing the exact state of the machine.

Small-scale and medium-scale industries do not make use of predictive maintenance due to their unaffordable price tag and complexity. Even today, many industrial industries do not have any predictive maintenance tools that enable automatic health monitoring of machines. As a result, the faults that may arise in any machine including excess vibration, temperature rise, abnormal current usage, or unusual sounds in machine operation cannot be easily detected before causing serious damage.

Thus, there is a need for the development of an affordable system for real-time predictive monitoring and alerting of critical machine states so as to avoid any machine failure and its consequences. Therefore, the proposed IoT-based machine monitoring tool with the help of ESP32 and other sensors is designed with the above objective in view.

III. PROPOSED SYSTEM

This study has proposed an Internet of Things-based Predictive Machine Failure Monitoring System that continuously monitors the industrial machine condition and predicts machine failure based on their abnormal behavior and conditions. This monitoring system includes the use of multiple sensors integrated with the ESP32 microcontroller, which is capable of continuous machine monitoring and analyzing machine health conditions wirelessly.

The IoT-based predictive machine failure monitoring system mainly focuses on the collection of vital parameters that affect machine performance. It involves monitoring the machine's vibration, temperature, current consumption, and sound levels. Multiple sensors are attached to an industrial machine to collect data on these parameters, which is then processed through an ESP32 microcontroller to compare the measured values against threshold values.

The vibration sensor is used to check the abnormality in machine vibration. It is caused due to bearing wear, shaft imbalance, and mechanical looseness. Temperature sensor checks whether the machine has any overheating issues or not. Current sensor checks the motor current consumption. Sound sensor detects unusual sounds produced when machines malfunction.

The collected sensor readings are then evaluated using the multi-parameter predictive logic. Rather than evaluating

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just one reading, the suggested approach correlates several machine conditions to improve the accuracy of fault prediction. If there is any anomaly in the operations of the machine, the system triggers alarm alerts via the buzzer, OLED display alerts, and wireless IoT messaging.

The ESP32 chip can connect to the internet to enable remote machine monitoring using IoT platforms like Blynk and ThingSpeak. Remote monitoring of the real-time sensor readings and overall condition of the machines can be carried out using smartphones and cloud-based dashboards.

Some of the benefits associated with the proposed system include low cost of installation, real-time evaluation of the readings, wireless connection, easy installation, and scalability for industry use. The suggested machine monitoring system is well-suited for Industry 4.0 use and could be used by industries to minimize machine breakdowns through predictive maintenance strategies.

IV. SYSTEM ARCHITECTURE

Predictive Machine Failure Monitoring System Design

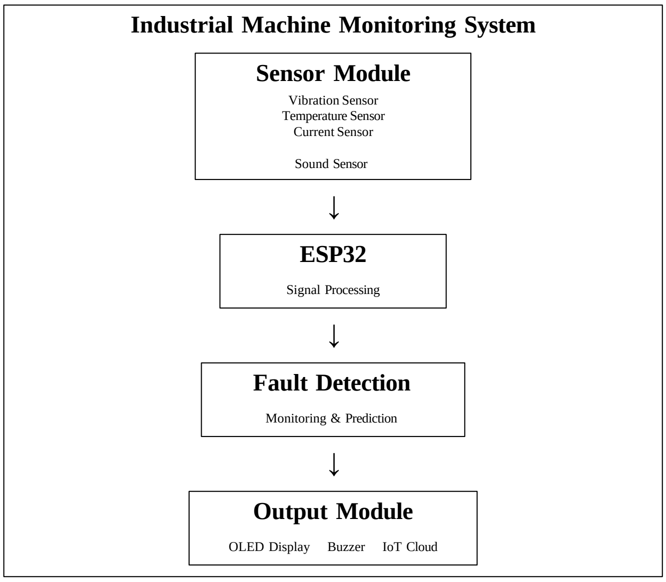
A multi-sensing approach is proposed for the design of the Predictive Machine Failure Monitoring System integrated with the ESP32 Microcontroller to be applied in real-time monitoring and predictive maintenance for industrial machines. The architecture of the proposed system includes sensing units, processing units, alarm systems, and IoT communication modules.

The first stage involves sensors for measuring vibrations, temperatures, currents, and sounds of the industrial machine. Vibration sensors, temperature sensors, current sensors, and sound sensors will be installed on an industrial machine to measure parameters related to machine health conditions. For instance, the MPU6050 vibration sensor detects vibration levels, while the temperature sensor detects overheating. In addition, current consumption of motors will be measured by the ACS712 current sensor, while the sound sensor detects sound abnormalities of the machine.

The measured parameters are sent to the central processing unit which is the ESP32 Microcontroller that is capable of comparing the threshold levels. Moreover, predictive fault analysis can be performed on the basis of the processed sensor data. The controller can evaluate machine health status by correlating various parameters such as vibration, temperature, current, and sound intensity.

In order to visualize machine parameters locally, there is a possibility to use an OLED display module that displays sensor readings. In case if abnormalities are detected, a buzzer or warning LEDs activate. In case if threshold levels are exceeded, the machine generates fault alerts and notifications. Remote monitoring and IoT features of the ESP32 can help users monitor the machine condition from anywhere using Blynk and ThingSpeak applications. The collected data can be used further to analyze trends and plan preventive maintenance activities.

A. Block Diagram



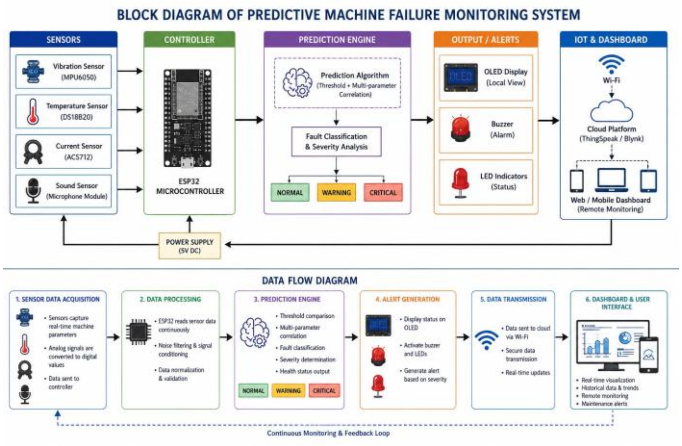


Fig. 1. Block Diagram of Predictive Machine Failure Monitoring System

V. HARDWARE COMPONENTS

The Predictive Machine Failure Monitoring System involves several hardware components that are employed for sensing, processing, communicating, and alerting purposes. The hardware modules have been chosen on the basis of their low cost, reliability, ability to operate in real time, and industrial compatibility. The hardware components of the proposed model include:

A. ESP32 Microcontroller

The ESP32 microcontroller serves as the processing module of the entire system. It is a highly reliable and cost-effective microcontroller with inbuilt support for Wi-Fi and Bluetooth connection options. The ESP32 microcontroller is responsible for collecting sensor data, analyzing machine parameters, predicting any faults, and communicating live data to IoT platforms. **Properties of ESP32:**

- Two-core microcontroller
- Integrated Wi-Fi and Bluetooth technology
- Economical in energy use
- Several GPIO pins available

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- Superior computing capacity

B. MPU6050 Vibration Sensor

The MPU6050 sensor serves as a vibration and movement detection sensor. The sensor has a 3-axis accelerometer and 3-axis gyroscope to detect any abnormal vibration or mechanical instability within machines. Abnormal vibration is considered one of the key causes of bearing damage and mechanical imbalance. **Uses in the System:**

- Detect bearing fault
- Conduct vibration analysis
- Monitor mechanical looseness
- Identify shaft imbalance

C. ACS712 Current Sensor

The ACS712 current sensor measures the motor's current consumption. It assists in detecting cases of overload, electrical anomalies, and excessive power consumption in machinery. Elevated current consumption could imply that the motor is under strain or suffers from some defects.

Uses in the System:

- Monitor current consumption in motors
- Detect overload
- Monitor power consumption
- Detect electrical faults

D. Temperature Sensor

Temperature sensors are utilized to keep track of machine temperature continuously. The occurrence of overheating may be as a result of too much friction, overload, poor lubrication, or electrical issues. Monitoring temperature assists in detecting unusual temperatures before damage to machinery.

Uses in the System:

- Overheating detection
- Temperature detection
- Preventive maintenance
- Machine safety evaluation

E. Sound Sensor Module

The sound sensor module can be used to detect unusual noises from the machine caused by improper functioning. Unusual sounds from the machine may suggest that parts are worn out.

Uses in the System:

- Unusual sound detection
- Detection of problems

F. OLED Display

OLED display helps in viewing the real-time information about machine parameters like temperature, vibration, current, and status of the machine.

Functionality of OLED Display:

- To display sensor data
- To indicate machine status
- To send warning alerts

G. Buzzer and LED Alerts

Buzzer and LEDs help in generating alerts whenever any abnormal condition exists with the machine. The warning alerts help in taking timely action by maintenance personnel so that there are no issues in future.

Functionality:

- Fault detection
- Warning alerts

H. Power Supply Unit

The power supply unit serves to provide the necessary voltage regulation to the ESP32 and other sensor modules. Reliable performance of the PMFS is dependent on a stable power source.

VI. SOFTWARE IMPLEMENTATION

The software implementation of the proposed Predictive Machine Failure Monitoring System is based on the development platform, which includes the Arduino IDE with ESP32 microcontroller support. The software module serves for monitoring machine parameters via sensor readings, prediction of possible faults, generation of alert signals, and IoT communication. Thus, continuous monitoring and real-time analysis of sensor data is performed.

Programming of the ESP32 microcontroller is done using the Embedded C/C++ programming language with the help of Arduino IDE software platform. Additionally, various sensor libraries are incorporated into the software program for better management of communications between sensors and ESP32. Data from vibration sensors, current sensors, temperature sensors, and sound sensors are read by the software and analyzed for faults prediction.

Fault prediction is done with the use of threshold values. All of the sensor readings are compared against certain values. If the machine parameters exceed the allowed limit, the software will issue warnings in the form of alerts, buzzer, OLED display messages, and IoT communication. Main components of the software implementation are the following:

A. Data Collection from Sensors

Sensor data related to machine parameters is obtained by the ESP32. This is accomplished by the use of different kinds of sensors. The MPU6050 sensor measures vibration and acceleration, ACS712 sensor gives details about motor current consumption, temperature sensor provides data regarding machine temperature, and sound sensor detects sound produced by the machine.

B. Analysis of Sensor Data

The obtained data from the sensors will be analyzed on the basis of the logic of predictive maintenance. The system analyzes vibration, temperature rise, variation in current consumption, and unusual sound at the same time to detect any possibility of machine fault.

C. Fault Detection Logic

The obtained results from the sensors are compared to predefined conditions. If there are more than one abnormal readings, then the possibility of machine failure is predicted. This includes failure due to bearing failure, motor overload,

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overheating, and mechanical looseness, etc.
Examples:

- High vibration and increased temperature -¿ Predicts bearing failure
- High current consumption and overheating -¿ Predicts motor overload
- High vibration and abnormal sound -¿ Detects mechanical looseness

D. OLED Display Interface

The OLED display unit helps display the parameter values from the machine locally. This interface displays the sensor readings, machine state, warnings, and fault conditions for maintenance engineers.

E. Generation of Alerts

Whenever any anomaly is found in the working conditions of the machine, the software generates alerts using buzzing tones and LEDs for maintenance engineers to take action before breakdowns.

F. IoT Connectivity

Wi-Fi connectivity feature in ESP32 is utilized to send machine data in real time to IoT cloud services such as Blynk or ThingSpeak. Machine status can be monitored by maintenance engineers via mobile or web apps. Also, machine data can be saved and analyzed for predicting any possible failures in future.

G. Software Tools and Libraries Used

- Arduino IDE
- ESP32 Board Package
- Wire.h Library
- Adafruit MPU6050 Library
- WiFi.h Library
- OneWire Library
- DallasTemperature Library
- Adafruit SSD1306 OLED Library

The developed software guarantees reliable and scalable solutions for predicting machine failures, which can be used in industrial environments during Industry 4.0 implementations.

VII. WORKING METHODOLOGY

The suggested Predictive Machine Failure Monitoring System works according to an approach based on monitoring machine parameters and analyzing machine health conditions. The system uses multiple machine parameters such as vibration, temperature, current, and sound as a basis for performing predictive machine monitoring and detecting machine faults prior to their occurrence.

The proposed methodology includes the following stages: data collection from sensors, data processing, fault analysis, execution of machine learning algorithms, alert generation, and remote IoT-based monitoring.

A. Data Collection from Sensors

In the first stage of the system work, there is a continuous monitoring of the industrial machine's parameters by using multiple sensors attached to the ESP32 microcontroller.

- MPU6050 sensor is used to measure machine vibration and movement.
- ACS712 sensor monitors the amount of current consumed by the machine's motor.
- Temperature sensor is employed to measure machine temperature.
- Sound sensor identifies unusual machine noise.

Sensor measurements continue to be recorded regularly by the ESP32 device for machine health evaluation purposes.

B. Data Processing

The ESP32 processes the obtained sensor values to derive machine health parameters after sensing. The device filters noise from the obtained sensor value and analyzes them against pre-set threshold values to detect machine faults.

Simultaneous analysis of all the obtained machine parameters improves the reliability of predictive maintenance operations. Using multiple parameters during sensing improves fault detection capabilities compared to using single sensor measurement devices.

C. Fault Prediction

This section contains the key functionality of the proposed system. Predictive maintenance logic is executed by the ESP32 based on the obtained sensor values. Machine faults are identified based on the correlation of their behaviors as explained below.

Some of the examples of fault prediction are provided below:

- Combination of high vibrations and increase in temperature shows bearing wear.
- High current consumption with overheating shows motor overload.
- Abnormal vibrations accompanied with unusual sound shows mechanical looseness.
- Increase in both temperature and vibrations shows machine fault possibility.

The predictive maintenance process always analyzes the health of machines and makes predictions regarding their abnormal operations before they suffer damage.

D. Generation of Alerts

In case any fault is detected, the system will generate alert messages. The OLED will display machine information and alerts in case of abnormality. In addition, an LED and buzzer will provide signals to alert the maintenance operators.

Through this, industries can prevent any machine failure and take necessary actions to reduce maintenance cost.

E. Remote Machine Monitoring Using IoT Technology

The ESP32 chip utilizes Wi-Fi connectivity technology to send data from the machine to remote IoT clouds. Parameters like machine vibration, machine current consumption, machine status, and machine temperature are sent to Blynk/ThingSpeak cloud in real-time.

The IoT monitoring system also records historic machine parameters for future analysis and monitoring.

F. Operation of the Whole System

Overall system operation involves the following processes:

1) Machine parameter monitoring by sensors
2) Data collection using ESP32
3) Processing of sensor data
4) Detection of abnormality in the machine using prediction logic
5) Alert message generation in case of fault detection
6) Transmission of data to the IoT dashboard
7) Remote monitoring of machine information by maintenance operators

The methodology described above provides a cost-effective and efficient predictive maintenance approach for monitoring the health of machinery in Industry 4.0.

VIII. PREDICTION LOGIC

The prediction logic constitutes the central element of the suggested Predictive Machine Failure Monitoring System. In essence, the system constantly monitors machine parameters, including vibration, temperature, electricity usage, and sound characteristics, in order to identify signs of machine damage. In contrast to traditional monitoring systems, which analyze individual machine parameters in isolation from each other, the suggested solution uses the concept of multi-parameter analysis for reliable prediction.

Firstly, the ESP32 microcontroller constantly collects data from the vibration, current, temperature, and sound sensors. The acquired sensor values are then analyzed against defined thresholds, which allows the system to assess the operating state of the machine.

A. Threshold-Based Analysis

For each machine parameter, there is a predefined threshold value, which corresponds to normal machine operation. Any deviation of the measured sensor values from the safe limits signals an abnormal machine operating state.
Some threshold values are mentioned below:

- Vibration Threshold: Presence of excessive vibration implies machine instability.
- Temperature Threshold: Overheating of machine implies high temperature.
- Current Threshold: Presence of high current in machine implies overload.
- Sound Threshold: Any abnormal sound implies mechanical wear/looseness.

The threshold values can be modified according to the machine that needs monitoring.

B. Multi-Parameter Correlation Logic

Multi-parameter correlation improves the accuracy of the prediction system since the prediction process relies on correlating several parameters rather than using a single sensor parameter. The system uses several sensor parameters to predict machine faults in various conditions.

Some of the predictions made in the machine are listed below:

- Increase in vibration along with increase in temperature: Bearing wear fault prediction.
- High current along with increase in temperature: Machine motor overload condition.
- Increased vibration along with an abnormal sound: Mechanical looseness fault.
- Sudden change in all parameters: Machine failure fault possibility.

The use of multiple sensors makes the machine fault detection process more efficient as compared to traditional machines.

C. Machine Health Status

The ESP32 device constantly monitors machine operations and predicts machine health status based on sensor values. The machine health status categorizes machines according to their conditions as:

- Normal condition.
- Machine warning condition.
- Critical condition of machine operation.

In case the machine is observed with abnormal activity, the machine warning alerts are raised using buzzers, OLED screen notifications, and IoT cloud service.

D. Prediction Algorithm

The algorithm for predictive maintenance process is mentioned below:

1) Sensor readings of vibration, temperature, current, and sound are acquired.
2) Reading values of each sensor are matched with threshold values.
3) Correlation among several sensor parameters is analyzed.
4) Identification of abnormal machine behavior is performed.
5) Prediction of machine fault condition.
6) Generation of alert message notifications through IoT cloud.

E. Prediction Logic Example

Prediction example logic implemented in the system are as follows:

- If vibration exceeds limit and temperature increases, bearing failure is predicted.
- If there is increasing consumption of current due to increase in temperature, then motor overload is predicted.
- Mechanical looseness is predicted if abnormal sound occurs alongside vibration.

As such, the proposed prediction algorithm provides an inexpensive and effective method for industrial machine predictive maintenance and machine health monitoring applications.

IX. EXPERIMENTS' CONFIGURATION

The experimental setup of the Proposed Predictive Machine Failure Monitoring System is structured to investigate the performance of the system under different machine operational situations. The experiments consist of an industrial machine prototype, sensors, ESP32 microcontroller board, display unit, warning alarm system, and IoT based monitoring software system. The Predictive Machine Failure Monitoring System continuously monitors machine vibration, temperature, consumption of current, and sound patterns to predict machine problems.

The DC motor acts as the machine test prototype where machine fault simulation takes place. This is to ensure that the Predictive Machine Failure Monitoring System is able to predict machine faults. Different kinds of sensors are installed on or around the industrial machine.

MPU6050 vibration sensor is used to measure vibration changes that occur within the machine caused by imbalance, looseness, and bearing fault. An ACS712 current sensor is connected between the machine and its power source to measure current consumption by the machine. Temperature sensor monitors machine temperature changes when running. Sound sensor is installed close to the machine.

The ESP32 microcontroller serves as the central processor of the control system. The sensors' output signals are connected to ESP32 input pins for immediate processing. ESP32 processes sensor data continuously in real-time based on the principles of predictive maintenance. ESP32 determines the presence of abnormality within the machine operation.

A graphical OLED display is also connected to the microcontroller for monitoring machine data including vibration values, temperature levels, current values, and overall condition of the machine. A buzzer and an LED indicator light are used to provide alert when there is an abnormality in the machine operations.

ESP32 uses integrated Wi-Fi connectivity to send machine data to IoT Cloud services like Blynk or Thing Speak. Machine parameter data can be accessed remotely through IoT apps like Blynk or ThingSpeak websites.

The following conditions will be considered in testing the proposed experimental setup:

- Normal machine performance
- Elevated mechanical load
- Vibration induction
- Motor overheating scenario
- Loose mechanical parts scenario

Several types of faults were deliberately introduced to study the behavior of the proposed predictive maintenance system. Sensor data was constantly collected and compared to determine normal and faulty machine states.

The whole experiment proved that the suggested system is capable of performing real-time machine state monitoring, predictive analysis of potential machine faults, and wireless industrial monitoring by means of IoT technology.

A. *Experimental Components*

Listed below are all of the hardware components employed in the experiment:

- ESP32 Microcontroller
- MPU6050 Vibration Sensor
- ACS712 Current Sensor
- Temperature Sensor
- Sound Sensor Module
- OLED Display
- Buzzer and LED Lights
- DC Motor
- Power Supply Device

X. RESULTS AND ANALYSIS

The Predictive Machine Failure Monitoring System was successfully implemented and tested for various machine operation scenarios. The system constantly monitored vibrations, temperature, electricity consumption, and sound levels generated using several sensors attached to the ESP32 microcontroller. Several experiments were conducted using a DC motor with normal and faulty operating conditions to evaluate the predictive maintenance system's efficiency.

The system efficiently gathered data about machine parameters and identified faulty situations based on multiple criteria. The obtained data was constantly monitored on the OLED display and at the same time was sent to the IoT dash board for remote access.

A. *Normal Operating Condition*

For normal machine operation, all of the following parameters remained within the acceptable limit. Machine performance was continuously analyzed and reported as normal on the display screen.

The following normal operation values were observed in the experiment:

- Vibration Level: Low and constant
- Temperature: Within safe operating limits
- Current Consumption: Normal load current
- Sound Level: Constant machine noise

In healthy machine operating conditions, the system did not generate any warning alerts.

B. *Analyze of Abnormal Behavior*

Abnormal conditions in machine operating conditions were simulated to study the performance of the system.

1) Bearing Fault: The mechanical vibration was increased artificially to simulate bearing wear and shaft imbalance. The vibration and temperature sensors detected abnormal vibration patterns with gradual rise in temperature. As such, abnormal condition was recognized and the system predicted potential bearing failure.

Behavioral characteristics observed in bearing fault:

- Increase in vibration level
- Gradual temperature rise
- Small increase in current
- Generation of fault alert

2) Motor Overload Condition: Extra load on the motor was provided to simulate motor overload condition. The current and temperature sensors recorded high load current and rapid temperature rise, respectively. Hence, predictive algorithm classified the abnormal condition as motor overload.

Behavioral characteristics observed in motor overload:

- High load current
- Fast temperature rise

International Journal of Engineering Research & Technology (IJERT)
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- Small vibration increase
- Overload alert generated

3) Mechanical Looseness Simulation: Unsteady mechani- cal operations were simulated using loose mounting of equip- ment. This was sensed by vibration and noise sensors. The sys- tem generated machine fault alert for maintenance purposes.

Behavioral characteristics observed in machine looseness:

- Vibration abnormalities
- Increased noise
- Unsteady machine operation
- Machine fault alert generation

C. Results of IoT Monitoring

ESP32 was able to transmit real-time sensing information to IoT via communication in the form of Wi-Fi. Parameters such as vibrations, temperature, current, and machine status were wirelessly and remotely monitored on mobile apps and IoT dashboards.

The following benefits were observed due to IoT monitoring systems:

- Visualization of machine status in real time
- Remote wireless monitoring
- Sensor data updates continuously
- Fault notification alerts
- Historical data analysis feature

D. Analysis of Performance

As shown in the experimental result, the proposed Predictive Machine Monitoring and Fault Analysis Systems can efficiently operate with the use of multi-sensor correlation techniques. This method is more effective than traditional approaches to monitoring in terms of identifying machine faults and early warnings.

Some of the benefits associated with the proposed approach include:

- Inexpensive implementation
- Real-time machine monitoring
- IoT communication
- Predictive maintenance capabilities
- Scalability for industrial uses

Based on the obtained results, it can be said that the proposed Predictive Machine Failure Monitoring System can minimize unexpected machine downtimes and increase industry maintenance efficiency.

XI. ADVANTAGES

In general, Predictive Machine Failure Monitoring System can provide many benefits for machine health monitoring and predictive maintenance. It can offer real-time monitoring, early fault detection, wireless communication, and low-cost implementation.

The main advantages of the proposed system are:

- **Real-Time Monitoring:** The system allows the machine parameter monitoring such as vibration, temperature, current consumption and sound in real-time for continuous analysis of machine health.
- **Predictive Maintenance Ability:** The system predicts the possibility of faults in machines before they fail completely, helping the industries to prevent failures and unnecessary breakdown of machines.
- **Cost Effective Solution:** The cost of using various low-cost sensors and the ESP32 make the system cost- effective and feasible for small/medium scale industries.
- **Multi Sensor Analysis:** Multiple sensors used in the system increase fault detection ability than using single sensor parameter monitoring system.
- **Wi-Fi IoT based monitoring:** ESP32 allows the monitoring of machines from anywhere using IoT dashboards and mobile applications.
- **Reducing Maintenance Costs:** Early detection of faults can help industries to lower the overall maintenance costs.
- **Reducing Machine Breakdowns:** The system prevents the machine from failing due to any fault as it warns about possible machine breakage.
- **Ease of installation and Scalability:** The system can be installed on different kinds of machines for industry-wide maintenance.
- **Increased Reliability of Machines:** It allows machines to perform better and safely.
- **Industry 4.0:** The proposed solution is useful for smart industrial automation and Industry 4.0 through predictive maintenance using IoT.
- **Remote Supervision:** Engineers can monitor the machines remotely from the cloud platform or mobile phone.
- **Ability to Detect Possible Fault Conditions:** Possible faults such as bearing wear, overload condition, overheating and mechanical looseness are identified by the system.

XII. LIMITATIONS

Although the designed Predictive Machine Failure Monitoring System provides a cost-effective approach to industrial predictive maintenance, there are several limitations of the system which should be kept in mind during the design and installation.

The main limitations of the proposed system are the following:

- **Lack of Full-Scale Industry Testing:** Testing was conducted mostly on experimental setups with prototype devices. Industry-scale testing needs to be conducted.
- **Threshold-Based Prediction:** The existing system utilizes predefined thresholds for fault predictions. Depending on the machinery, the accuracy may differ.
- **Electrical Noise and Vibrational Interferences:** Industrial settings may have electromagnetic interference or vibrations that impact the efficiency of sensors and the system overall.
- **Generalized Fault Classification:** While the proposed system identifies basic problems like increased vibrations or overheating, more detailed classification may require more advanced methods.
- **Dependence on Internet Connection:** The IoT-based system operates via the internet or Wi-Fi connection; thus,

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unstable connections may result in poor perfor- mance.

- **Limited Memory:** ESP32 board has limited memory, meaning storing historical data and implementing advanced analytics may be impossible.
- **Calibration of Sensors:** Different types of industrial machinery need to be calibrated separately to ensure their proper performance.
- **Basic Prediction Algorithm:** Multi-parameter analysis and threshold-based prediction were implemented. How- ever, more advanced ML models could be used.
- **Stable Power Supply Requirements:** Since the system needs to be working all the time, continuous power source is necessary.
- **Limited Focus on Mechanical Faults:** The system can detect mechanical faults and vibrations, but some specific types of problems require more sophisticated technology. With all these constraints, the suggested Predictive Machine Failure Monitoring System is still an economical and scalable method of predicting machine failures that can be adopted by real-time industrial machine health monitoring systems and

Industry 4.0 applications.

XIII. FUTURE SCOPE

The presented Predictive Machine Failure Monitoring System is a powerful foundation for real-time industrial machine health monitoring and predictive maintenance applications. While the present system efficiently monitors the machine condition through multi-sensors and IoT communication, many advanced developments can be included in the future system design to enhance its capabilities, accuracy, scalability, and practicality in the industry.

Following are the potential future developments in the suggested system:

- **Artificial Intelligence Incorporation:** Advanced machine learning and artificial intelligence techniques can be incorporated to enhance the fault prediction capability and automatic fault detection process.
- **Cloud Computing and Big Data Analysis:** Cloud computing solutions can be leveraged for the storage of the vast amount of collected data along with its predictive analysis.
- **TinyML and Edge Artificial Intelligence:** Techniques related to TinyML can be incorporated into the system and deployed on ESP32 for real-time edge-based pre- dictive maintenance without being dependent on cloud computing processes.
- **Multi-Machines Monitoring:** The system can be modified for the monitoring of multiple machines in an industrial environment through wireless networking.
- **Development of a Mobile Application:** A mobile application can be designed for the purpose of real-time machine monitoring and fault alert notifications.
- **Advanced Fault Diagnosis Capabilities:** Future iterations of the system will detect specific machine faults such as bearing faults, shaft alignment, lack of lubrica- tion, and rotor imbalances.
- **Development of Professional Industrial Dashboards:** The industrial machine health dashboards can be developed for reporting and analyzing the health of monitored machines.
- **Industrial Wireless Communications:** Industry-specific wireless communication protocols can be employed for industrial communication purposes.
- **Automatic Maintenance Management:** Future versions of the system can automatically schedule the maintenance operations after predicting machine health conditions.
- **Power Optimization and Battery Backup:** Power optimization and battery backup systems can be introduced into the system to ensure its operation during any sudden power outage.
- **Industrial Scale Testing and Optimization:** The proposed solution can be further tested and optimized on an industrial scale for large manufacturing plants and power generating stations.
- **Industry 4.0 System Integration:** Future iterations of the system can be integrated within the Industry 4.0 system framework for intelligent and automated main- tenance.

These innovations will make it possible to turn this system into an intelligent predictive maintenance platform that is capable of making industrial machines more reliable, lowering maintenance costs and enhancing industrial productivity.

XIV. CONCLUSION

The proposed Internet of Things-based Predictive Machine Failure Monitoring System based on ESP32 shows a low-cost and effective solution for the implementation of machine health monitoring and predictive maintenance in industry. The system monitors the main parameters like vibration, temperature, power usage and any unusual sounds using several kinds of sensor connected to the ESP32 microcontroller.

The system allows recognizing abnormal working conditions in the machine and forecasting its possible malfunction before the machine completely breaks down. In contrast to traditional approaches of monitoring one parameter at a time, multi-sensor correlated analysis is implemented in the proposed system that increases fault detection capability. IoT technology allows implementing the possibility of remote wireless monitoring of the machine with the use of cloud platforms and mobile devices as required by the principles of Industrial Automation 4.0.

Results obtained during experiments show that the system is able to identify overheating, overload, excessive vibrations, and loose parts in industrial machines. Early warnings provided by the system allow reducing unexpected downtime, maintenance cost and minimizing damage done to the machine. The system is scalable, easy to install, and can perform real-time monitoring of the machine parameters that makes it appropriate for the implementation in small or medium-size industries.

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