ESP32-BASED IOT SENSOR FUSION FOR INDUSTRIAL POWER GRID SURVEILLANCE AND AUTOMATION

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ABSTRACT

A clever and economical option for real-time monitoring and control in industrial settings is the suggested system, "ESP32-Based IoT Sensor Fusion for Industrial Power Grid Surveillance and Automation." Multiple sensors, including a vibration sensor for equipment health monitoring, a gas sensor for identifying dangerous leaks, a fire sensor for safety surveillance, and a DHT11 for temperature and humidity measurement, are integrated into the system's ESP32 microprocessor. Live video streaming is available via the ESP32-CAM module for visual surveillance of the industrial area. Automation is accomplished using relay-driven actuators based on sensor readings; during key events, a buzzer is used to sound an alert, and the BLDC fan automatically turns on when the temperature or humidity surpasses threshold limits. Through a web interface, operators can view and operate equipment remotely thanks to the ESP32 module's IoT capabilities, which provide smooth connection between the cloud server and the physical system. Online orders can be used to turn the DC motor on and off, allowing for remote operations and safety responses. Multiple sensor data fusion improves power grid infrastructures' energy efficiency, failure prediction, and situational awareness. For industrial safety and operational optimization, this IoT, automation, and surveillance integration offers a clever, flexible, and scalable platform.

Keywords:SP32, ESP32-CAM, IoT, Sensor Fusion, Industrial Automation, Cloud Monitoring, Fire Detection, Gas Sensor, DHT11, Vibration Sensor, Smart Surveillance, Power Grid Monitoring, BLDC Fan Control, DC Motor Control.

1. INTRODUCTION

More intelligent, responsive, and networked monitoring systems have to be developed due to the quick development of industrial automation and the increasing complexity of contemporary power grids. Manual inspections and isolated sensor networks are frequently used in traditional power grid surveillance methods, which are prone to errors, delays, and inefficiencies. Any delay in identifying faults, overloads, or abnormalities can lead to serious operating losses, equipment damage, or safety issues in modern industrial settings where a continuous power supply is essential. A potential answer to these problems is the combination of sensor fusion techniques and Internet of Things (IoT) technologies, which provide automated, real-time monitoring and control capabilities for industrial power grids. By merging data from several sensors and sources, this method offers a holistic view that transcends the constraints of individual sensors and allows for a thorough knowledge of system activity.

A technique called sensor fusion combines data from various sensors to create a more precise, trustworthy, and useful evaluation of the world under observation. Vibration sensors, temperature and humidity monitors, gas leak detectors, voltage and current transducers, and other pertinent devices are examples of sensors used in industrial power grids. Although each sensor records distinct elements of the system, noise, the surrounding environment, or brief disruptions can frequently affect individual results. The system can improve the quality of monitoring and enable predictive maintenance by using sophisticated fusion algorithms to filter out noise, correlate data patterns, and obtain precise measurements. For instance, the system can detect circumstances that could result in overheating, equipment deterioration, or safety violations in addition to electrical failures by integrating electrical data with mechanical and environmental indicators. By ensuring that decisions are based on a complete dataset rather than discrete signals, this multi-dimensional monitoring approach greatly increases operational efficiency and dependability.

An essential part of the design of industrial monitoring systems enabled by the Internet of Things is the ESP32 microcontroller. It is the perfect option for real-time data processing and acquisition because of its powerful processing capabilities, built-in Wi-Fi and Bluetooth modules, and compatibility for several sensor interfaces. The ESP32 can concurrently collect data from multiple connected sensors in industrial power grid applications, locally preprocess the data, and send important insights to cloud-based platforms or centralized control systems. This feature allows intelligent edge processing, lowers latency, and uses less network traffic. Furthermore, advanced algorithms for anomaly detection, fault classification, load management, and predictive maintenance may be implemented thanks to the ESP32's programmability, which successfully converts the conventional monitoring infrastructure into an intelligent, self-governing, and adaptable system.

IoT integration in industrial power grid surveillance offers a number of revolutionary advantages. Operators can get immediate notifications regarding anomalous conditions, such voltage swings, current overloads, or environmental dangers, thanks to real-time monitoring. Then, automated control systems can intervene quickly to prevent possible harm, for as by turning on cooling systems, redistributing load, or isolating a damaged area. Continuous sensor data collection over time makes predictive analytics possible, which analyzes past trends to foresee failures before they happen. In addition to decreasing downtime, this predictive capability maximizes energy use, prolongs the life of vital equipment, and improves overall operating efficiency. Additionally, remote monitoring is made possible by the use of IoT-enabled sensor fusion, which enables managers and engineers to supervise power grid operations from a distance without sacrificing performance or safety.

Developing a successful IoT sensor fusion system for industrial power grids using ESP32 presents a number of difficulties. To guarantee reliable operation, important factors such sensor calibration, data synchronization, network dependability, cybersecurity, and energy efficiency must be taken into account. Sensor performance may be impacted by the hard conditions seen in industrial settings, which frequently include mechanical vibrations, temperature extremes, and electromagnetic interference. Thus, it is crucial to choose robust sensors, put error-correcting algorithms into place, and make sure that there are secure, redundant communication links. The system must also be scalable in order to handle future grid expansions or extra monitoring needs. The architecture should facilitate smooth interface with current supervisory control and data acquisition (SCADA) systems, adaptive firmware upgrades, and the modular integration of new sensors. An ESP32-based IoT sensor fusion platform may balance intelligence, efficiency, and dependability by resolving these technical issues, offering a progressive solution for contemporary industrial power grids.

The applicability of ESP32-based sensor fusion systems has been further supported by recent developments in industrial IoT. Large volumes of sensor data may now be processed in real time with little assistance from humans thanks to the convergence of edge computing, machine learning, and wireless networking. Edge processing, which can be carried out directly on the ESP32 or on adjacent microcontrollers, minimizes latency and lessens reliance on cloud connectivity by enabling the system to assess crucial metrics instantaneously. Early anomaly detection and automatic response plans are made possible by the ability of machine learning models to identify typical operating patterns and identify deviations. By connecting several nodes and enabling synchronized operations, wireless communication—supported by Wi-Fi and Bluetooth—ensures smooth data transfer throughout the plant. When these technologies are combined, a highly intelligent and adaptable monitoring system is created that can satisfy the changing needs of industrial power grids.

In summary, industrial power grid automation and surveillance have advanced significantly with the ESP32-based IoT sensor fusion technique. This technology overcomes the drawbacks of conventional monitoring systems by combining several sensor inputs, permitting real-time edge processing, and facilitating wireless communication. It also adds features for automated fault response, predictive maintenance, and data-driven decision-making. Deploying such smart monitoring technologies will be crucial to maintaining safety, improving efficiency, and ensuring operational continuity as industrial activities grow more complex and energy-dependent. IoT and sophisticated sensor network integration is a crucial area of research and development in the manufacturing and energy industries since it not only enhances current grid management but also establishes the groundwork for future advancements in industrial automation.

2. LITERATURE SURVEY

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3. EXISTING SYSTEM

To assess voltage, current, temperature, and other operational characteristics, industrial power grid monitoring systems now in use mostly rely on isolated sensor networks and traditional SCADA (Supervisory Control and Data Acquisition) frameworks. Single-type sensors are usually used in these systems, and they are coupled to local controllers that send data to a central server for processing. Although these configurations work well for simple monitoring, they frequently have issues with delayed problem detection, limited scalability, and susceptibility to inaccurate data because of environmental disturbances or sensor noise. Many current systems lack adaptive intelligence and only offer periodic measures as opposed to continuous real-time monitoring. They also mostly rely on manual or rule-based decision-making. The overall effectiveness, dependability, and responsiveness of the power grid management process are also diminished by the restricted remote monitoring and the difficulty of integrating various data sources for thorough situational awareness.

4. PROPOSED SYSTEM

The suggested solution makes use of an IoT sensor fusion architecture based on ESP32 to facilitate intelligent, real-time industrial power grid automation and monitoring. It combines several heterogeneous sensors, such as temperature, humidity, gas, voltage, and current sensors, onto a single microcontroller platform, in contrast to traditional systems. The sensor data is gathered, preprocessed, and fused locally by the ESP32, which also applies algorithms to detect anomalies and filter noise. Compared to conventional single-sensor monitoring, this fusion approach guarantees that defects, overloads, or dangerous circumstances are recognized more quickly and accurately. Additionally, the system has Bluetooth and Wi-Fi wireless connectivity capabilities, which allow data to be seamlessly sent to local monitoring dashboards or cloud servers for distant access and centralized analysis.

The suggested method facilitates predictive maintenance and automated control in addition to monitoring. The ESP32 can minimize downtime and avoid equipment damage by initiating quick corrective actions, such as isolating a malfunctioning area, modifying load distribution, or triggering safety systems, based on the fused sensor data. Machine learning algorithms are able to anticipate possible problems before they happen by storing historical sensor data for trend analysis. By combining automation, intelligent fusion, and real-time monitoring, the conventional industrial power grid is transformed into a responsive, intelligent system that improves operational efficiency, safety, and dependability while facilitating scalable integration with upcoming industrial IoT applications.

Block diagram:

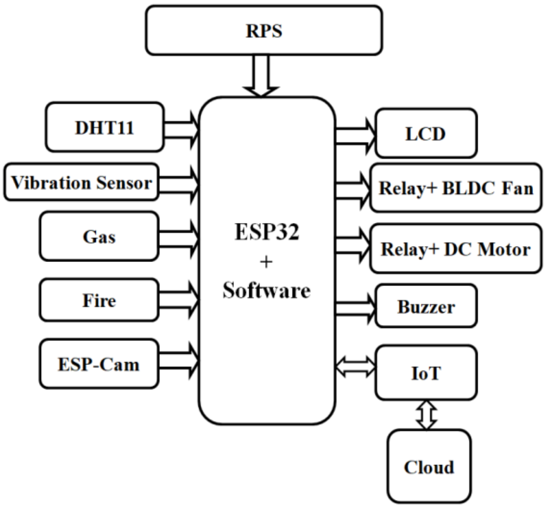

Fig. 1: Block diagram of the proposed ESP32-based IoT sensor fusion system

The ESP32-based industrial monitoring and automation system's architecture is depicted in the block diagram. The ESP32 microcontroller, which serves as the system's central processing unit and runs the required software to regulate inputs, outputs, and communication, is at its core. The ESP32 receives data from a number of sensors, including an ESP-CAM for visual monitoring, a DHT11 sensor for temperature and humidity, a vibration sensor for mechanical anomalies, and gas and fire sensors for environmental danger identification. The industrial setup's operating and environmental variables may be monitored in real time thanks to these sensors.

Incoming sensor data is processed by the ESP32, which also runs control and fusion algorithms and sends commands to many output devices. Sensor readings can be seen in real time on an LCD display. A BLDC fan and a DC motor are both controlled by relays, enabling automated reaction to defects or changes in the environment. For instant hazard notifications, a buzzer produces auditory alarms. Additionally, the system is linked to the Internet of Things module, allowing for remote control and monitoring through a cloud platform that guarantees data storage, accessibility, and sophisticated analytics. Furthermore, all components receive steady power from the regulated power supply (RPS), guaranteeing reliable functioning of the ESP32 and its attached peripherals. Effective, automatic, and remotely accessible industrial monitoring and control are made possible by this integrated configuration.

4. RESULTS

The proposed ESP32-based IoT sensor fusion system successfully monitored environmental and safety parameters in real time and detected abnormal conditions such as fire, gas leakage, high humidity, and vibration. Upon fault detection, the system reliably triggered local alerts through the LCD and buzzer and actuated relay-controlled devices. Simultaneously, alert data were transmitted to the IoT cloud and mobile interface for remote monitoring. Experimental results confirm stable operation, timely fault alerts, and effective automation for industrial power grid surveillance.

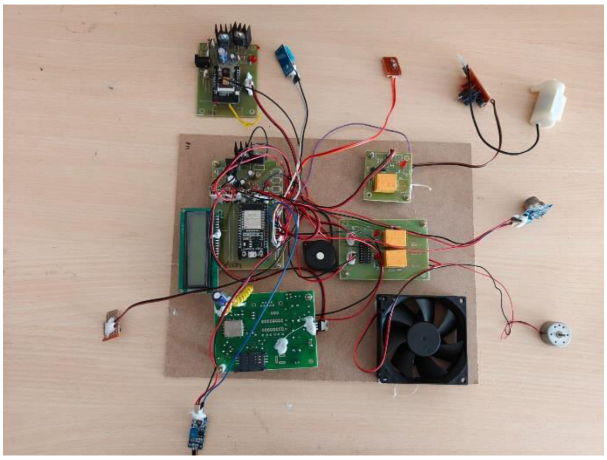

Fig.2: Hardware prototype of the industrial power grid surveillance system

The figure shows the complete ESP32-based hardware implementation integrating multiple sensors, relay modules, BLDC fan, DC motor, LCD, buzzer, and regulated power supply, validating real-time data acquisition and control.

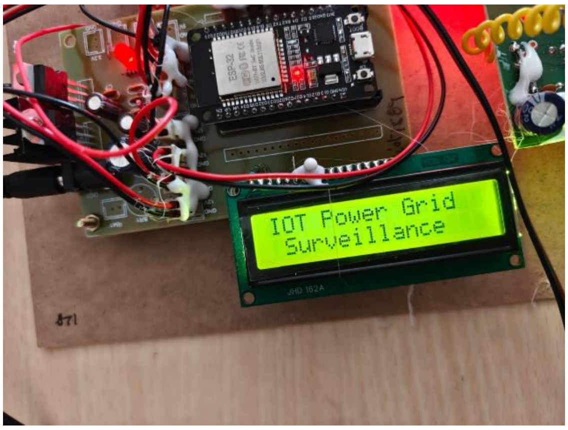

Fig. 3. LCD display showing IoT power grid monitoring status

The LCD displays system status and monitored parameters, confirming successful sensor fusion, local visualization, and correct operation of the embedded controller.

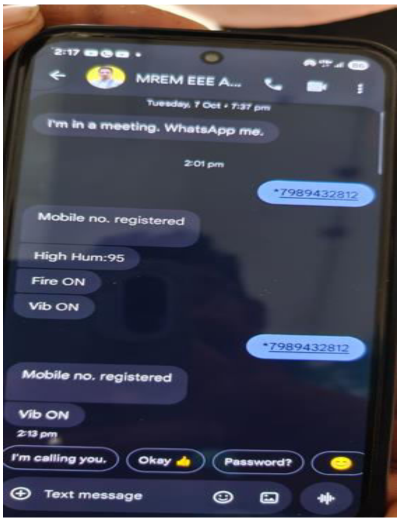

Fig. 4: GSM-based alert notifications for detected abnormal conditions

The mobile interface shows automatic alerts generated for events such as high humidity, fire detection, and vibration, demonstrating reliable fault notification and remote supervision.

6. CONCLUSION

For real-time monitoring, safety management, and automation in industrial power grid environments, the suggested system, "ESP32-Based IoT Sensor Fusion for Industrial Power Grid Surveillance and Automation," offers a clever and dependable solution. Through the integration of several sensors, cloud connectivity, and automated control mechanisms, the system improves fault responsiveness, situational awareness, and operational efficiency.

A variety of sensors, including vibration sensors for equipment health monitoring, gas sensors for hazardous leak detection, fire sensors for early fire identification, and the DHT11 sensor for temperature and humidity measurement, can be seamlessly integrated thanks to the ESP32 microcontroller, which serves as the central processing unit. The ESP32-CAM module offers visual surveillance in real time, enabling operators to remotely monitor industrial areas and confirm anomalous circumstances. This combination of video surveillance and sensor data greatly increases fault detection accuracy and lowers false alarms.The system's automation is one of its main advantages. Without human assistance, relay-driven actuators ensure prompt defensive actions by automatically reacting to sensor threshold violations. While the buzzer offers prompt alerts during crucial occurrences, the BLDC fan is triggered when temperature or humidity surpasses safe limits, preserving a steady operating environment. An additional example of the system's adaptability and scalability for industrial automation applications is the remote control of the DC motor using cloud-based commands.

Because IoT connectivity makes it possible for data to be transmitted continuously to a cloud server, operators can monitor system status and operate equipment from anywhere at any time via a web interface. Sensor fusion reduces downtime and increases energy efficiency by detecting early indicators of equipment breakdown, which improves predictive maintenance capabilities. For industrial facilities, substations, and vital power infrastructure, the suggested system provides an all-around affordable, scalable, and future-ready platform. With additional improvements like cybersecurity integration and analytics based on machine learning, the system can develop into a powerful smart grid automation and monitoring system.

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