

Smart Pitot Tube Blockage Detection & Alert System

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Abstract - Pitot tube blockage remains a significant safety issue in aviation, as it can result in inaccurate airspeed readings and compromised flight performance. This paper presents a Smart Pitot Tube Blockage Detection and Alert System designed to identify and address such failures in real time. The system utilizes an ESP32 microcontroller integrated with a flow sensor to continuously monitor airflow within the pitot tube. A predefined threshold is used to detect abnormal airflow conditions, indicating potential blockages caused by ice, dust, insects, or moisture. Upon detection, a relay-controlled air pump is automatically activated to clear the obstruction, ensuring continued system reliability. An LCD display provides real-time updates on airflow values, system status, and warning alerts, while a push button enables manual operation for maintenance purposes. The proposed system improves aviation safety by enabling early detection, automated corrective action, and clear monitoring, making it suitable for applications in UAVs, ground testing systems, and aviation training environments.

Key Words: Pitot tube, blockage detection, ESP32, flow sensor, aviation safety.

1. INTRODUCTION

Accurate airspeed measurement is a fundamental requirement in aviation systems, where even minor discrepancies can significantly affect flight safety and performance. The pitot tube is a critical component used to measure dynamic air pressure, providing essential data for flight control, navigation, and safety-critical decision-making. Despite its importance, the pitot tube is highly susceptible to blockages caused by environmental factors such as dust, insects, ice formation, and moisture, especially when aircraft are parked or operated under adverse weather conditions. Several aviation incidents have demonstrated the serious risks associated with pitot tube blockage, including unreliable airspeed indications, pilot confusion, and improper autopilot responses, which may lead to unsafe

flight situations. Although preventive measures such as pitot covers, heating systems, and routine inspections are commonly used, these methods are largely preventive in nature and do not guarantee real-time detection or confirmation of pitot tube integrity.

Existing monitoring approaches are predominantly manual, indirect, and reactive. In most cases, blockages are identified only after abnormal airspeed readings are observed, by which time system reliability may already be compromised. Furthermore, current systems lack continuous airflow monitoring and do not provide automated solutions for blockage removal or early warning alerts.

To overcome these limitations, this paper proposes a Smart Pitot Tube Blockage Detection and Alert System based on an ESP32 microcontroller. The system continuously monitors airflow using a flow sensor, detects anomalies by comparing real-time data with predefined thresholds, and responds by activating a relay-controlled air pump to clear obstructions. Additionally, an LCD module displays real-time system status and alerts, ensuring improved safety, reliability, and proactive maintenance.

2. PROBLEM DESCRIPTION

Pitot tube blockages from environmental factors such as ice, dust, and insects present a significant threat to aviation safety by causing inaccurate airspeed readings that can lead to pilot confusion and flight control failures. Current monitoring methods are primarily manual and reactive, often identifying issues only after abnormal data has already been transmitted to the cockpit. The absence of dedicated, real time monitoring systems and automated clearing mechanisms means that obstructions may go undetected until they compromise operational safety. Consequently, there is a pressing requirement for a smart, automated solution capable of continuous airflow monitoring and immediate corrective action to ensure reliable aircraft performance.

3. LITERATURE REVIEW

This section reviews existing research related to pitot tube blockage detection, airflow monitoring, embedded safety systems, and automated alert mechanisms.

A. Pitot Tube Blockage and Airspeed Measurement Errors

Dodd analyzed various failure modes of pitot-static systems in aircraft, with particular emphasis on blockages caused by environmental factors such as ice, dust, and insects. The study explains how partial or complete blockage leads to erroneous airspeed indications, affecting flight control systems and pilot decision-making. The research highlights the need for improved detection methods beyond traditional pitot heating and manual inspection, recommending proactive monitoring solutions.

B. Embedded Sensor-Based Monitoring Systems

Kumar and Raj presented the design of embedded systems using microcontrollers for real-time monitoring applications. Various sensors were interfaced with a controller to detect abnormal conditions and trigger alerts. The study emphasizes the importance of continuous data acquisition, threshold-based decision-making, and automated response mechanisms, forming a foundational framework for sensor-based blockage detection systems.

C. Airflow Measurement Using Flow Sensors

Martinez reviewed different airflow measurement techniques and evaluated the performance of digital flow sensors in low and medium flow conditions. The study discusses sensor accuracy, response time, and integration with microcontrollers. It concludes that flow sensors are effective for detecting airflow abnormalities and can be used in real-time monitoring systems to identify obstructions in air channels.

D. Automated Fault Detection Systems

Verma and Singh focused on the development of automated fault detection systems using microcontrollers and relay-based actuators. The system detects abnormal sensor readings and triggers corrective actions such as activating motors or pumps. The paper demonstrates how automation reduces human dependency and improves system reliability for critical safety applications.

E. ESP32-Based Intelligent Monitoring

Fernandez and Rao explored the capabilities of the ESP32 microcontroller in smart monitoring applications. Features such as high processing speed, low power consumption, and wireless connectivity make ESP32 suitable for real-time embedded systems. The study demonstrates implementations involving sensor integration, LCD display, and alert mechanisms.

F. Automatic Cleaning Mechanisms

Sharma presented automated cleaning mechanisms for sensors exposed to dust and debris. Using air pumps and relay controlled actuators, the system clears obstructions without manual intervention. The study concludes that automatic cleaning improves sensor accuracy, extends system lifespan, and reduces maintenance effort.

G. IoT-Based Aircraft Sensor Monitoring Systems

Patel and Mehta investigated the integration of Internet of Things (IoT) technology in aircraft sensor monitoring systems. Their study demonstrates how real-time data from critical sensors can be transmitted to ground stations or cockpit displays using wireless communication protocols. The research highlights that IoT-enabled systems improve situational awareness by providing continuous updates on sensor health and performance. In the context of pitot tube systems, such connectivity allows early detection of airflow inconsistencies and enables predictive maintenance strategies, reducing the risk of in-flight failures.

H. Machine Learning for Anomaly Detection in Aviation Systems

Zhang et al. explored the application of machine learning algorithms for anomaly detection in aviation sensor data. By analyzing patterns in airflow, pressure, and environmental conditions, the system can identify deviations from normal behavior that may indicate blockages or sensor faults. The study emphasizes the advantage of adaptive learning models over traditional threshold-based systems, as they can detect subtle changes and reduce false alarms. This approach is particularly useful for pitot-static systems, where early-stage blockages may not immediately trigger conventional alerts.

I. Redundant Sensor Systems for Fault Tolerance

Almeida and Costa examined the use of redundant sensor architectures to improve reliability in critical

aerospace systems. Their research focuses on deploying multiple sensors to measure the same parameter and using comparison logic to detect discrepancies. In the case of pitot tube systems, redundancy helps identify faulty or blocked sensors by cross verifying airspeed and airflow data. The study concludes that redundancy significantly enhances fault detection capability and ensures continued system functionality even in the presence of sensor failure.

A. Advantages of the Proposed System

- **Real-Time Blockage Detection:** Continuous airflow monitoring enables instant identification of pitot tube blockages.
- **Automated Obstruction Removal:** The relay-controlled air pump automatically clears blockages without manual intervention.
- **Improved Safety and Reliability:** Accurate airflow detection prevents incorrect airspeed readings.
- **Early Warning System:** Blockages are detected before they cause serious measurement errors.
- **Detection of Partial Blockages:** Even small airflow reductions are identified, often missed in conventional systems.
- **Low-Cost and Compact Design:** Uses readily available components, making the system economical and easy to implement.
- **Scalable and Upgradable:** ESP32 enables future enhancements such as wireless alerts, data logging, and cloud monitoring.

4. PROPOSED SYSTEM

The proposed Smart Pitot Tube Blockage Detection & Alert System is an intelligent, embedded solution designed to continuously monitor airflow in the pitot tube and automatically respond to blockage conditions. The system is built around an ESP32 microcontroller, which serves as the central processing and control unit.

A flow sensor is installed in the pitot tube airflow path to measure real-time airflow. Under normal conditions, the sensor provides stable flow readings to the ESP32. When a blockage occurs due to dust, insects, moisture,

or debris, the airflow decreases significantly or becomes zero. The ESP32 continuously analyzes this data and identifies abnormal conditions based on predefined threshold values.

Once a blockage is detected, the ESP32 immediately triggers a relay module to activate an air pump, which generates a burst of air to clear the obstruction from the pitot tube. Simultaneously, the system generates an alert message and displays the blockage status, airflow value, and system mode on an LCD display. A push button allows manual control during maintenance, testing, or emergency situations.

5. HARDWARE AND SOFTWARE DESCRIPTION

A. ESP32 Microcontroller

The ESP32 is a single 2.4 GHz Wi-Fi-and-Bluetooth combo chip designed using TSMC ultra-low-power 40 nm technology. It features a dual-core Xtensa 32-bit LX6 microprocessor operating at up to 240 MHz, 520 KB SRAM, 448 KB ROM, and 34 programmable GPIOs. Its 12-bit SAR ADC supports up to 18 channels, enabling precise analog data acquisition. The chip includes hardware security features such as secure boot, flash encryption, and AES/RSA cryptographic acceleration [7].

The ESP32 acts as the central controller in the proposed system, receiving digital signals from the flow sensor, processing the data, and controlling the relay and LCD. Its low power consumption and wireless capability also make it suitable for future IoT-based enhancements.

B. Flow Sensor

The flow sensor is interfaced with the ESP32 to measure real-time airflow through the pitot tube. The sensor generates electrical signals proportional to the airflow rate. The ESP32 reads these signals and converts them into airflow values, which are continuously compared against predefined threshold levels to identify normal and abnormal conditions.

C. Single Channel Relay Module

A single-channel relay module is used to control the air pump. The relay operates as an electromechanical switch activated by the ESP32 digital output. It allows

the microcontroller to control high-power devices safely using low-power control signals. The relay module includes a driver circuit (ULN2003A), an isolation circuit (IN4007), and input voltage of 12 VDC.

D. Air Pump

The air pump is an electromechanical device that generates airflow by converting electrical energy into mechanical energy. Controlled via the relay module, it supplies bursts of pressurized air through the pitot tube to clear obstructions. Its compact size, low power consumption, and ease of relay control make it ideal for embedded automation systems.

E. LCD Display (16x2)

A 16x2 alphanumeric LCD display is used to present real-time system information to the user. It displays startup messages, current airflow values, blockage detection warnings, and system operational modes. The LCD is interfaced with the ESP32 and provides clear, immediate visual feedback without requiring additional external hardware.

F. Push Button

A push button provides manual ON/OFF control of the system. Based on momentary contact principles, it allows the user to start or stop system operation during testing, maintenance, or emergency conditions, thereby enhancing user control and system safety.

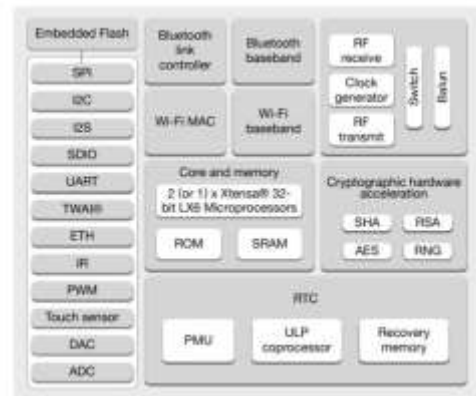
G. Power Supply (12V, 1A Adapter)

The system is powered by a 12V, 1A AC/DC adapter that converts 220-230 VAC mains supply to regulated 12 VDC required for the relay, air pump, and ESP32 subsystem. The adapter provides stable and consistent power, ensuring reliable operation of all system components.

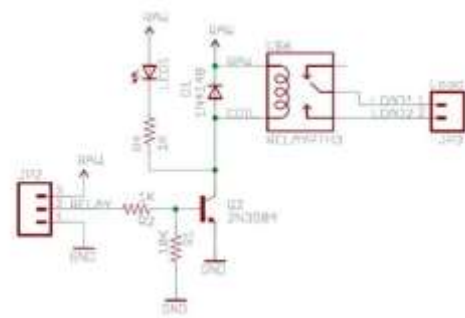
H. Software: Arduino IDE and Embedded C

The system firmware is developed using the Arduino Integrated Development Environment (IDE) with Embedded C as the programming language. The Arduino IDE provides a text editor, compiler, and serial monitor for code development and debugging. Embedded C extensions support fixed-point arithmetic, memory-mapped I/O, and real-time peripheral control, making it well-suited for microcontroller-based safety applications.

6. SYSTEM ARCHITECTURE DIAGRAM



BLOCK DIAGRAM



CIRCUIT DIAGRAM

7. WORKING PRINCIPLE

The system operates on the principle of continuous airflow monitoring, intelligent decision-making, and automated corrective action.

A. System Initialization

Upon power-on, the ESP32 initializes all connected components including the flow sensor, LCD display, relay module, and air pump. The LCD displays a startup message and the ESP32 sets predefined airflow threshold values representing normal pitot tube conditions.

B. Airflow Monitoring and Blockage Detection

The flow sensor continuously measures airflow through the pitot tube. Under normal conditions, steady airflow values are detected and compared against threshold

levels by the ESP32. If the pitot tube is partially or fully blocked, the airflow decreases significantly or becomes zero. When the measured airflow falls below the threshold for a specified duration, the ESP32 identifies the condition as a pitot tube blockage.

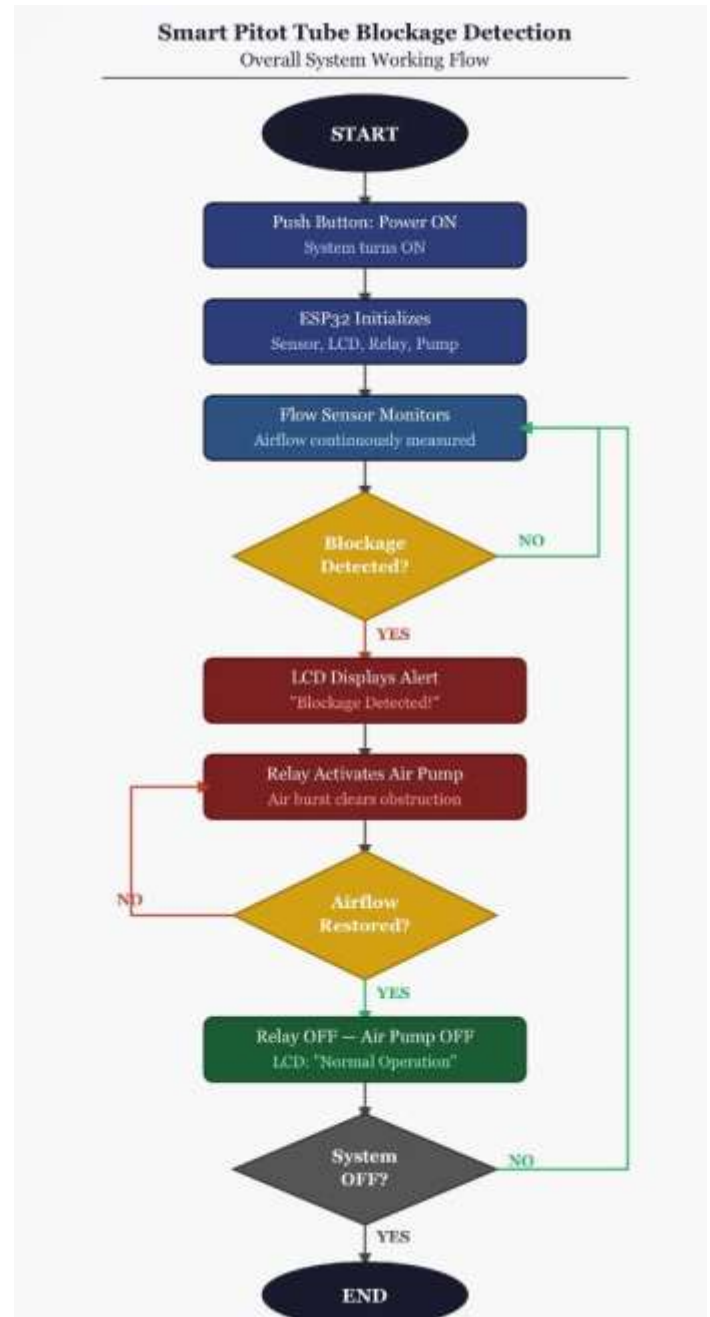
C. Alert and Automatic Blockage Removal

Once a blockage is detected, the ESP32 immediately generates an alert displayed on the LCD as "Blockage Detected" with the current airflow status. The ESP32 then activates the relay module to switch ON the air pump, which supplies a burst of pressurized air through the pitot tube to remove the obstruction. After clearing, the flow sensor detects normal airflow, the ESP32 deactivates the relay, and the LCDs "Normal Operation".

D. Overall Working Flow

- System power ON using the push button
- ESP32 initializes all components
- Flow sensor monitors airflow continuously
- ESP32 compares airflow with threshold values
- Blockage detected if airflow is abnormal
- Alert displayed on LCD display
- Relay activates the air pump to clear the obstruction
- System returns to normal monitoring mode

8. FLOWCHART



9. RESULTS AND DISCUSSION

A. Experimental Setup

A prototype was developed using an ESP32 microcontroller, flow sensor, relay module, air pump, 16x2 LCD display, and push button. Pitot tube blockage conditions were simulated by intentionally restricting airflow using controlled obstructions including partial and complete blockage scenarios. The system was tested under multiple conditions to evaluate accuracy, response time, and reliability.

B. Normal Airflow Condition

Under normal operating conditions, the flow sensor detected steady airflow values within the predefined threshold range. The ESP32 continuously monitored these values and displayed "Normal Operation" on the LCD. The relay and air pump remained in the OFF state, demonstrating correct system behavior under unobstructed conditions.

C. Partial Blockage Condition

When a partial blockage was introduced, the airflow value dropped below the normal range but did not reach zero. The ESP32 successfully identified this abnormal condition and displayed a "Partial Blockage Detected" alert on the LCD. The relay was activated and the air pump was turned ON for a short duration. In most test cases, the airflow returned to normal after the cleaning cycle, demonstrating the system's ability to respond to minor obstructions.

D. Complete Blockage Condition

In the case of complete blockage, the flow sensor output dropped to near-zero values. The ESP32 immediately detected the blockage and triggered a warning alert on the LCD. Multiple air bursts were applied through the air pump until airflow was restored. The system successfully cleared the obstruction and resumed normal monitoring in all test cases.

E. Performance Analysis

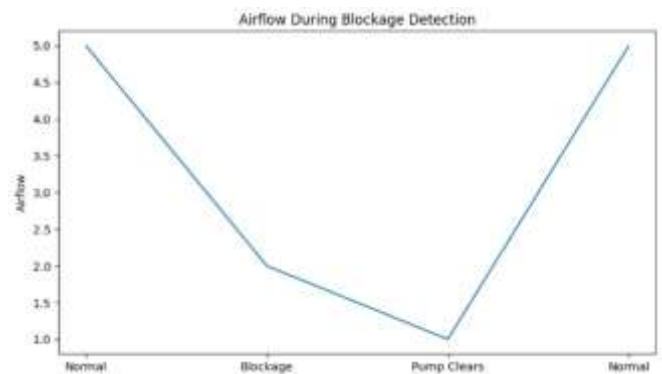
The system accurately detected both partial and complete blockages without false alarms under normal airflow conditions. Blockage detection and alert generation occurred promptly after airflow reduction. The relay-controlled air pump effectively removed obstructions, reducing manual intervention, and continuous ESP32 monitoring ensured stable operation over extended testing periods.

F. Limitations

The prototype was tested in a controlled laboratory environment and does not fully replicate extreme aviation conditions such as high altitude, icing, or rapid pressure changes. Wireless alert and data logging features are not implemented in the current version. Despite these limitations, the system demonstrates strong potential for real-world adaptation and enhancement.

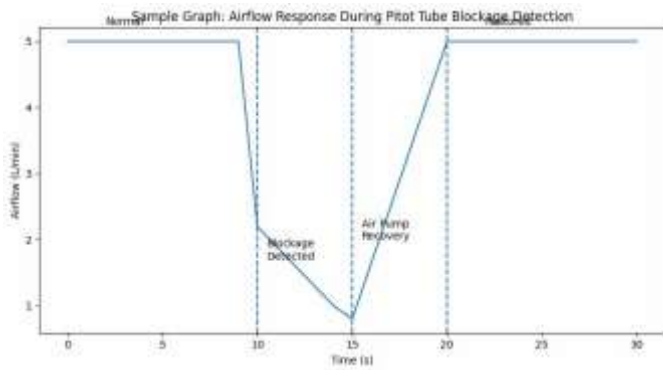
CONDITION	AIRFLOW	DETECTION TIME	REMOVAL STATUS
NORMAL	GOOD	-	YES
PARTIAL BLOCKAGE	PARTIALLY BLOCKED	2 SEC	YES
FULL BLOCKAGE	FULLY BLOCKED	2 SEC	YES

10. GRAPHS



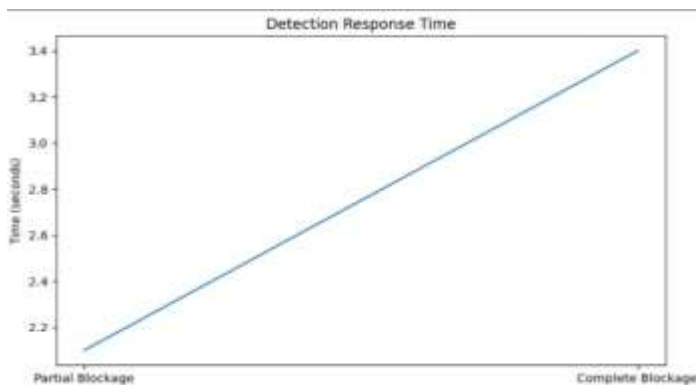
Graph 1: Airflow During Blockage Detection

This graph illustrates the variation of airflow across different stages of the system operation. Initially, under normal conditions, the airflow is at its maximum level. When a blockage occurs in the pitot tube, the airflow drops significantly, indicating restricted air passage. During the "Pump Clears" stage, the airflow reaches its lowest point as the obstruction is being addressed. After the air pump successfully removes the blockage, the airflow returns to its normal level. This graph clearly demonstrates the system's ability to detect airflow reduction and restore normal conditions through automatic cleaning.



Graph 2: Airflow Response During Pitot Tube Blockage Detection (Time Based)

This graph shows the airflow variation over time during the entire blockage detection and recovery process. Initially, the airflow remains constant at a normal level. Around the 10-second mark, a blockage is detected, and the airflow rapidly decreases. As the obstruction worsens, the airflow reaches its minimum value. After detection, the air pump is activated (around 15 seconds), and airflow begins to recover. By approximately 20 seconds, the airflow returns to normal levels, indicating successful blockage removal. The graph highlights the real-time operation of the system, including detection, response, and recovery phases.



Graph 3: Detection Response Time

This graph represents the time taken by the system to detect different levels of blockage. It shows that the response time for detecting a partial blockage is lower compared to a complete blockage. As the severity of the blockage increases, the system takes slightly more time to confirm the condition due to threshold validation and filtering mechanisms. This indicates that the system is designed to avoid false alarms while still maintaining a fast and reliable detection response.

11. CONCLUSION AND FUTURE SCOPE

A. Conclusion

The Smart Pitot Tube Blockage Detection & Alert System presented in this paper successfully addresses a critical aviation safety concern related to inaccurate airspeed measurement caused by pitot tube blockages.

By integrating a flow sensor, ESP32 microcontroller, relay module, air pump, and LCD display, the system provides a reliable and automated solution for real-time blockage detection and correction.

The experimental results demonstrate that the system can effectively detect both partial and complete blockages by continuously monitoring airflow conditions. The system generates immediate alerts and automatically activates the air pump to clear obstructions, significantly reducing dependence on manual inspection and minimizing the risk of incorrect airspeed data. The proposed system is low-cost, compact, and easy to implement, validating the feasibility of using embedded systems for intelligent aviation safety solutions.

B. Future Scope

Several enhancements can be incorporated in future versions to improve functionality and real Acknowledgment

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- **Data Logging and Analysis**: Storing airflow data and blockage events for trend analysis and predictive maintenance.
- **Cloud-Based Monitoring**: Real-time monitoring through cloud platforms for remote diagnostics.
- **Advanced Sensor Integration**: Pressure and temperature sensors to improve accuracy under varying environmental conditions.
- **Icing Detection Mechanism**: Temperature-based logic to identify ice formation in cold environments.
- **Integration with Avionics Systems**: Interfacing with aircraft avionics for direct cockpit alerts and automated safety actions.
- **Miniaturization and Rugged Design**: Compact, lightweight, aviation-grade hardware module for real-world deployment.

world applicability:

- **Wireless Alert System**: Integration of Wi-Fi or Bluetooth using ESP32 to send alerts to mobile devices and control rooms.