Esp32 Based Industrial Multi-Sensor Monitoring and Controls with Scada

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***Abstract*—In the rapidly evolving domain of industrial automation, traditional environmental monitoring systems are often constrained by high wired infrastructure costs, limited scalability, and a lack of remote accessibility. To address these limitations, a scalable Internet of Things (IoT) framework is proposed for real-time environmental monitoring and industrial load control. The primary objective of this research is to develop a low-latency, cost-effective system that bridges the gap between physical sensor networks and digital supervisory interfaces. The methodology involves the utilization of the ESP32 microcontroller as the central gateway, interfacing with DHT11 sensors for the acquisition of temperature and humidity data, and multi-channel relay modules for the actuation of distinct loads, including a Peltier cooling unit, a heating element, and a stepper motor-driven conveyor belt.**

Data transmission is facilitated by the Message Queuing Telemetry Transport (MQTT) protocol via the HiveMQ broker, ensuring efficient bandwidth usage and reliable connectivity in constrained networks. A key contribution of this work is the integration of this hardware architecture with Ignition SCADA (Supervisory Control and Data Acquisition), a standard industrial software platform, to create a sophisticated graphical user interface for centralized data visualization and command execution. The system is evaluated based on response time and reliability, demonstrating successful bi-directional communication. The expected outcome is a modular, robust architecture suitable for deployment in diverse applications such as smart agriculture, cold storage management, and industrial safety monitoring.

***Index Terms*—Internet of Things (IoT), Industrial Automation, SCADA Systems, MQTT Protocol, ESP32 Microcontroller, Environmental Monitoring, Remote Data Acquisition.**

I. INTRODUCTION

The advent of the Fourth Industrial Revolution, commonly referred to as Industry 4.0, has fundamentally transformed the landscape of manufacturing and environmental management.

Central to this transformation is the Industrial Internet of Things (IIoT), which mandates the seamless integration of physical machinery with digital monitoring networks. In sectors ranging from precision agriculture to pharmaceutical cold storage, the ability to maintain specific environmental parameters—such as temperature and humidity—is critical for operational efficiency and product integrity. Traditionally, industrial monitoring has relied heavily on wired Programmable Logic Controllers (PLCs) and localized Supervisory Control and Data Acquisition (SCADA) systems. While robust, these legacy systems often lack the flexibility required for modern, distributed applications and are associated with significant infrastructure costs.

Despite the proliferation of automation technologies, significant challenges remain in the implementation of scalable, cost-effective remote monitoring solutions. Many small to medium-scale enterprises struggle with the prohibitive costs of proprietary industrial automation hardware. Furthermore, relying on manual data logging is labor-intensive and prone to human error, leading to delayed responses in critical situations. For instance, in a cold storage facility, a minor fluctuation in temperature that goes unnoticed for several hours can result in substantial financial loss due to spoilage. Consequently, there is an urgent need for systems that provide real-time visibility and immediate control capabilities without the logistical

constraints of hardwired connections.

Existing solutions in the market often bifurcate into two extremes: high-end, expensive industrial systems or low-cost, short-range consumer devices utilizing protocols like Bluetooth or Zigbee. The former is often inaccessible to smaller operations, while the latter lacks the range and reliability required for critical monitoring. A notable limitation in many low-cost IoT implementations is the reliance on generic mobile applications, which fail to provide the centralized, data-rich visualization required for professional analysis. There is a distinct research gap in effectively bridging affordable, high- performance microcontrollers with industry-standard SCADA software to create a professional-grade monitoring architecture.

To address these disparities, this paper proposes the design and implementation of a scalable IoT-based environmental control system. The primary objective is to develop a robust framework that leverages the ESP32 microcontroller for edge computing and the MQTT protocol for lightweight, reliable data transmission. Unlike basic IoT setups, this system integrates with Ignition SCADA, a premier industrial platform, to offer a comprehensive dashboard for real-time monitoring and control. By enabling the remote actuation of critical loads—including heating units, cooling modules, and conveyor systems—based on sensor feedback, this research demonstrates a viable, low- cost alternative to traditional industrial automation systems, ensuring both scalability and operational reliability.

II. LITERATURE REVIEW

The domain of environmental monitoring and industrial control has witnessed a significant paradigm shift from wired, localized systems to wireless, distributed Internet of Things (IoT) architectures. This section reviews pertinent research from the past five years to contextualize the proposed system within the current technological landscape.

Early research in remote monitoring primarily focused on Short Message Service (SMS) and Global System for Mobile communications (GSM) technology. In 2020, Kumar et al. [1] proposed a GSM-based weather monitoring system that transmitted temperature data via SMS. While effective for remote areas lacking internet connectivity, the system incurred high operational costs per message and suffered from significant data latency, rendering it unsuitable for real-time industrial control. Similarly, Bluetooth-based home automation systems were explored by Gupta and Singh [2], which offered a low-cost solution for controlling home appliances. However, the study highlighted a critical limitation: the short communication range (typically under 10 meters) restricted the system's applicability to single-room environments, failing to address the needs of large-scale industrial facilities.

As Wi-Fi technology became more accessible, the focus shifted towards IP-based monitoring. In 2021, Al-Fuqaha et al. [3] demonstrated a web-server-based approach using the ESP8266 microcontroller. This system allowed users to monitor data via a localized HTML webpage. While this eliminated the cost of SMS, the architecture required complex port-forwarding configurations for remote access outside the local network. Furthermore, the use of the HTTP protocol was found to induce substantial overhead, draining the battery life of remote sensor nodes rapidly.

To address the inefficiencies of HTTP, recent studies have increasingly adopted the Message Queuing Telemetry Transport (MQTT) protocol. A comparative analysis by Lee and Park [4] in 2022 established that MQTT requires significantly less bandwidth and power compared to HTTP, making it ideal for constrained IoT devices. Building on this, Ahmed et al. [5] developed a smart agriculture system using NodeMCU and MQTT to monitor soil moisture. The system successfully utilized cloud dashboards like ThingSpeak for visualization. However, the authors noted that while data logging was robust, the system lacked a responsive, bi-directional control mechanism for actuating irrigation pumps in real-time, limiting its utility to passive monitoring.

In the realm of industrial automation, traditional SCADA systems linked with Programmable Logic Controllers (PLCs) remain the standard. Research by Zhang et al. [6] in 2023 reviewed the integration of PLCs with industrial SCADA for manufacturing lines. While highlighting the unmatched reliability of such systems, the study emphasized the prohibitive cost and complexity, which creates a high barrier to entry for Small and Medium Enterprises (SMEs). Conversely, low-cost consumer IoT solutions often

rely on mobile applications (e.g., Blynk, Tuya) as user interfaces. While user- friendly, these applications lack the centralized, data-rich visualization capabilities required for professional industrial oversight [7].

Research Gap

A critical synthesis of the existing literature reveals a distinct gap between high-end industrial systems and low-cost consumer hobbyist projects. While MQTT has been proven as an efficient protocol [4], and ESP32 is recognized for its processing power, there is limited research on integrating these affordable components with professional-grade SCADA software like Ignition. Most existing low-cost solutions rely on basic mobile apps [7] or passive cloud loggers [5], failing to provide the comprehensive "control room" experience necessary for managing complex loads such as heating, cooling, and conveyor systems simultaneously. This project aims to bridge this gap by developing a hybrid architecture that combines the cost-effectiveness of the ESP32 with the advanced visualization and control capabilities of Ignition SCADA.

III. SYSTEM ARCHITECTURE

The proposed system is architected as a multi-layered Internet of Things (IoT) framework, designed to facilitate robust bidirectional communication between physical plant assets and a centralized supervisory interface. The architecture is divided into three distinct functional layers: the Physical Hardware Layer (Edge Node), the Communication Middleware Layer, and the Application Layer (SCADA). Figure 1 illustrates the overall system architecture, delineating the data flow from the sensor acquisition stage to the final visualization and control interface.

A. Physical Hardware Layer (Edge Node)

The core of the hardware infrastructure is the ESP32 Microcontroller, a low-cost, low-power system-on-chip (SoC) with integrated Wi-Fi and dual-mode Bluetooth capabilities. The ESP32 serves as the primary Data Acquisition Unit (DAU) and Control Unit. It is responsible for sampling environmental data and executing control commands received from the server.

1. Sensing Subsystem: The system employs a DHT11 digital sensor interfaced with the ESP32 via a single- wire protocol. This sensor provides calibrated digital outputs for ambient temperature and relative humidity, essential for monitoring environmental conditions in real-time.

2. Actuation Subsystem: To manage high-power industrial loads, the ESP32 interfaces with a 4-Channel Relay Module. This module provides galvanic isolation between the low-voltage logic circuits (3.3V) and the high-voltage AC/DC loads. The specific loads controlled include:
   - Heating Unit: Simulated by a 200W incandescent bulb driven by AC mains.
   - Cooling Unit: A Peltier Module (TEC1- 12706) powered by a 12V DC source, equipped with a heat sink and fan assembly.
   - Conveyor System: A 28BYJ-48 Stepper Motor driven by a ULN2003 Darlington transistor array, representing a variable- speed industrial conveyor belt.

3. Power Distribution: The system is powered by a central 12V 10A Switched Mode Power Supply (SMPS). A LM2596 Buck Converter steps down the 12V source to a stable 5V supply for the ESP32 and logic components, ensuring stable operation during high-load switching events.

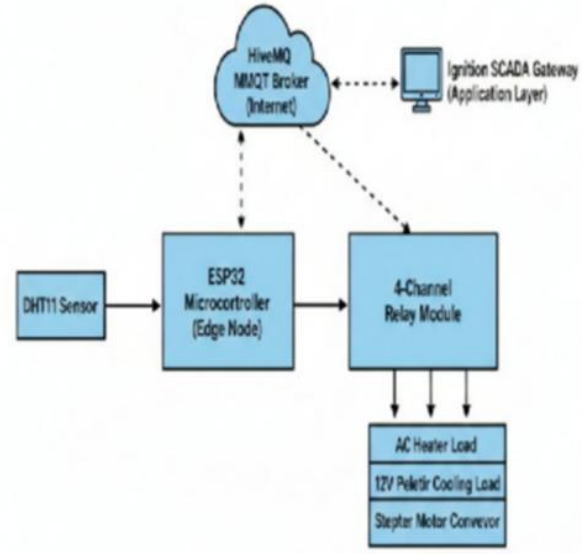

Fig. 1. Block diagram of the proposed IoT-SCADA architecture illustrating data flow between ESP32, MQTT Broker, and Ignition SCADA.

B. Communication Middleware Layer

The bridge between the hardware and the application layer is established using the Message Queuing Telemetry Transport (MQTT) protocol. Unlike the resource-heavy HTTP protocol, MQTT operates on a lightweight publish-subscribe model, minimizing network bandwidth and reducing power consumption. The HiveMQ Public Broker acts as the central message dispatcher. The ESP32 functions as an MQTT Client, publishing sensor data to specific topics (e.g., project/sensors/temp) and subscribing to control command topics (e.g., project/control/heater). This asynchronous communication model ensures that the system remains responsive even under constrained network conditions, as the broker manages the message queue and delivery assurance.

C. Application Layer (Ignition SCADA)

The topmost layer is the Human-Machine Interface (HMI), implemented using Ignition SCADA. Ignition is an industrial- grade software platform that provides a unified environment for real-time status monitoring and supervisory control.

The SCADA system connects to the MQTT broker as a subscriber client. It parses the incoming JSON or string payloads from the sensor topics and updates the visual dashboard elements, such as gauges and trend graphs, in real- time. Conversely, user interactions on the dashboard—such as toggling a switch—trigger the publication of control payloads to the respective command topics. This layer also handles data logging and historical trending, allowing operators to analyze system performance over time.

IV. METHODOLOGY

The development of the proposed IoT-SCADA framework follows a structured, modular methodology, encompassing hardware integration, firmware development, and network protocol implementation. This section delineates the specific technical approaches employed to ensure reliable data acquisition, low-latency communication, and robust load control.

A. Hardware Design and Circuit Topology

The hardware architecture is centered around the ESP32- WROOM-32 microcontroller, selected for its dual-core architecture and integrated Wi-Fi/Bluetooth stack. The circuit design prioritizes galvanic isolation and stable power distribution to mitigate electromagnetic interference (EMI) generated by high-power inductive loads.

1. Power Distribution Network: A centralized Star Topology is utilized for power distribution. A 12V, 10A Switched Mode Power Supply (SMPS) serves as the primary source. To power the ESP32 (which operates at 3.3V logic), a DC-DC Buck Converter (LM2596) steps down the 12V input to a regulated 5V output, providing higher efficiency (eta approx 92%) compared to linear regulators.

2. Sensor Interface: The DHT11 temperature and humidity sensor interfaces with the ESP32 via a single-wire digital protocol. The sensor transmits 40 bits of data: 16 bits for humidity, 16 bits for temperature, and 8 bits for checksum validation. The microcontroller verifies data integrity using the following checksum algorithm: Data_sum = Integral_RH + Decimal_RH + Integral_T + Decimal_T, if (Data_sum mod 256) == Checksum, the reading is considered valid.

3. Actuator Isolation: To control the AC Heater (200W Bulb) and DC Loads (Peltier Module, Stepper Motor), a 4-Channel Relay Module is employed. Each channel utilizes an optocoupler (e.g., PC817) to isolate the low-voltage GPIO signals of the ESP32 from the high-voltage switching side, protecting the microcontroller from back-EMF spikes.

B. Firmware Logic and Control Algorithms

The firmware for the ESP32 is developed using C++ within the Arduino IDE framework. The control logic is designed to be non-blocking, ensuring that the processor can simultaneously handle network communication and motor control without latency.

1. Asynchronous Task Scheduling: Instead of using blocking delay () functions, the firmware utilizes the millis () timer to schedule tasks. This allows the void loop () to execute continuously, maintaining the MQTT connection keep-alive packets.

- Task 1 (Sensor Polling): Executes every 2000ms to read DHT11 data.
- Task 2 (Network Routine): Executes every cycle to process incoming MQTT packets (client.loop()).
- Task 3 (Motor Control): The Stepper Motor logic utilizes the AccelStepper library, which calculates the required step pulses based on a target velocity profile, ensuring smooth acceleration and deceleration without blocking the main thread.

2. State Management: The system maintains a localized state machine for each actuator. For instance, the "Conveyor" state is toggled based on the boolean payload received from the MQTT topic project/control/conveyor.

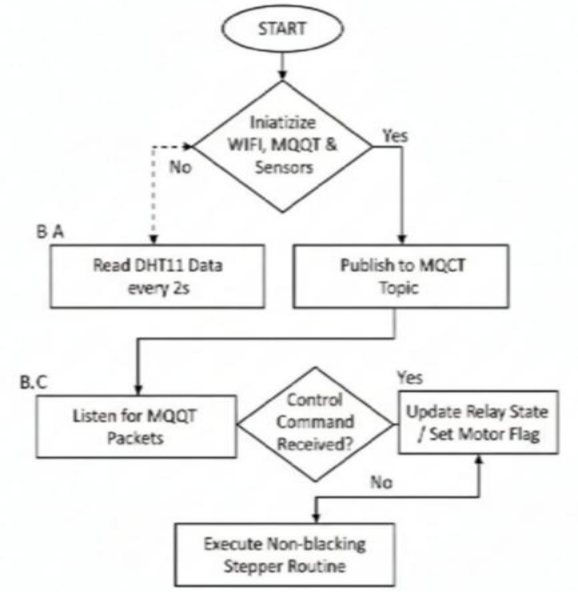

Fig. 2. Flowchart representing the firmware logic for sensor data acquisition, MQTT communication, and non-blocking actuator control.

C. Communication Protocol (MQTT)

The system utilizes the Message Queuing Telemetry Transport (MQTT) protocol, operating over TCP/IP on port 1883. The communication architecture follows a strict Publish-Subscribe model via the HiveMQ public broker.

1. Topic Structure: A hierarchical topic structure is defined to segregate data streams:
   - Publish Topics: project/sensors/temp, project/sensors/humidity
   - Subscribe Topics: project/control/heater, project/control/cooler, project/control/conveyor

2. Payload Formatting: Sensor data is formatted as simple ASCII strings (e.g., "24.5") to minimize packet size. Control commands use binary logic payloads ("1" for ON, "0" for OFF).

3. Quality of Service (QoS): The system operates at QoS Level 0 ("At most once") for sensor data to maximize throughput, and QoS Level 1 ("At least once") for control commands to ensure that critical actuation signals are delivered.

D. SCADA Integration and Visualization

The Human-Machine Interface (HMI) is realized using Ignition SCADA. The integration involves configuring Ignition's MQTT Engine module to act as a subscriber client. Incoming data points are mapped to "Tags" within the SCADA environment.

- Data Normalization: Raw string data from the broker is parsed and converted into floating-point values for display on analog gauges and trend charts.
- Command Injection: Graphical switches on the SCADA dashboard are bound to specific MQTT topics. Toggling a switch triggers a "write" operation, publishing the corresponding payload to the broker, closing the control loop.

V. IMPLEMENTATION

The implementation of the proposed IoT-SCADA framework involves the integration of specific hardware components and software tools to realize the system architecture described in Section III. This section details the technical specifications of the selected components, the controller configuration, and the development environment employed for firmware and HMI creation.

A. Hardware Implementation

The core processing unit is the ESP32-WROOM-32 Development Board, chosen for its dual-core Xtensa® 32-bit LX6 microprocessor, operating at 240 MHz. It features 520 KB of internal SRAM and integrated 802.11 b/g/n Wi-Fi and Bluetooth 4.2/BLE

connectivity, which are essential for the system's wireless communication requirements. The controller operates at a logic level of 3.3V, necessitating careful interfacing with 5V peripherals.

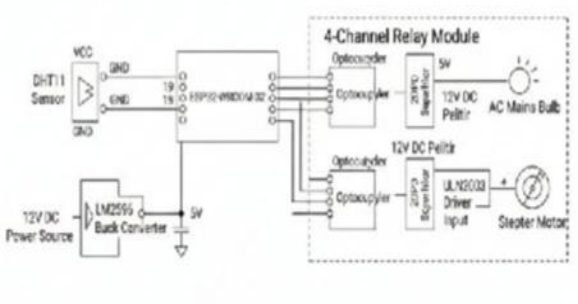

Fig. 3. Circuit schematic showing the interfacing of DHT11 sensor, 4-Channel Relay Module, and ULN2003 Stepper Driver with ESP32.

1. Sensor Module: A DHT11 Temperature and Humidity Sensor is utilized for environmental data acquisition. It provides a calibrated digital signal output with a humidity measurement range of 20-90% RH (±5% accuracy) and a temperature measurement range of 0-50°C (±2°C accuracy). The sensor is interfaced with the ESP32 via a single-wire serial communication protocol.

2. Actuation Modules: To control high-power loads, a 4-Channel 5V Relay Module is employed. Each channel is equipped with an optocoupler for galvanic isolation, protecting the microcontroller from back- EMF generated by inductive loads. The relay contacts are rated for 10A at 250V AC or 30V DC.
   - Heating Load: A 200W incandescent bulb connected to the AC mains via a relay channel simulates a heating element.
   - Cooling Load: A TEC1-12706 Peltier Module (12V, 6A max) is used for thermoelectric cooling, mounted with a heat sink and a 12V DC fan for heat dissipation.
   - Conveyor System: A 28BYJ-48 Unipolar Stepper Motor (5V) coupled with a ULN2003 Driver Board is used to simulate a conveyor belt. The driver board isolates the motor's high current requirements from the ESP32's GPIO pins.

3. Power Supply: A centralized 12V 10A Switched Mode Power Supply (SMPS) provides the primary power rail. A LM2596 DC-DC Buck Converter steps down the 12V input to a stable 5V output for the ESP32 and logic components, ensuring efficient power conversion (eta approx 92%).

B. Communication Interface

The communication infrastructure relies on the MQTT (Message Queuing Telemetry Transport) protocol, a lightweight publish-subscribe messaging transport ideal for constrained environments. The system connects to the HiveMQ Public Broker (broker.hivemq.com) on TCP port 1883. The ESP32 acts as an MQTT client, publishing sensor data to topics such as project/sensors/temp and subscribing to control topics like project/control/heater. This architecture decouples the sensor nodes from the SCADA interface, enhancing scalability and reliability.

C. Software and Development Tools

The firmware for the ESP32 is developed using the Arduino Integrated Development Environment (IDE) v2.0, utilizing the C++ programming language. Key libraries employed include:

- WiFi.h for network connectivity.
- PubSubClient.h for MQTT client functionality.
- DHT.h for sensor data acquisition.
- AccelStepper.h for non-blocking stepper motor control.

The Human-Machine Interface (HMI) is developed using Inductive Automation's Ignition SCADA platform. The MQTT Engine Module within Ignition is configured to subscribe to the relevant topics, parsing the incoming JSON or string payloads into SCADA tags. The Vision Module is then used to create a graphical dashboard featuring real-time analog gauges for monitoring and toggle switches for control. The entire system is tested for latency and reliability within a local Wi-Fi network environment.

VI. RESULTS AND DISCUSSION

The performance of the proposed IoT-SCADA framework was evaluated through a series of rigorous experiments conducted in a controlled laboratory environment. The primary metrics for assessment included sensor accuracy, data transmission latency,

and the reliability of the control logic under varying load conditions.

A. Experimental Setup

The hardware prototype, comprising the ESP32 microcontroller, DHT11 sensor, and relay-controlled loads (200W Heater, Peltier Cooler, Stepper Conveyor), was assembled and powered via a regulated 12V 10A SMPS. The system was connected to a local Wi-Fi network (2.4 GHz band) with an average uplink speed of 10 Mbps. The Ignition SCADA gateway was hosted on a standard workstation (Intel Core i5, 8GB RAM) connected to the same network. The HiveMQ public broker served as the intermediary for MQTT messaging.

B. Sensor Data Accuracy and Calibration

To validate the environmental monitoring capabilities, the temperature and humidity readings from the DHT11 sensor were logged over a 24-hour period. These values were compared against a calibrated digital hygrometer-thermometer acting as the ground truth.

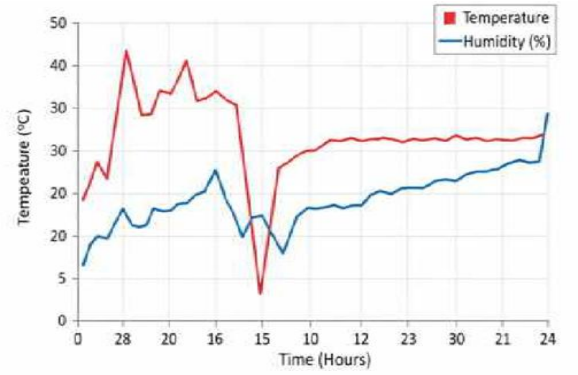

Fig. 4. Graphical representation of real-time temperature and humidity data logged via Ignition SCADA over a 24-hour period.

C. Communication Latency and Network Performance

A critical performance metric for any SCADA system is the latency between a user command and the physical actuation. The Round-Trip Time (RTT) was measured from the moment a toggle switch was activated on the SCADA dashboard to the instant the corresponding relay was energized.

1) Control Latency: The system demonstrated an average actuation latency of 120–180 milliseconds. This near-instantaneous response is attributed to the lightweight nature of the MQTT protocol, which maintains a persistent TCP connection, unlike HTTP- based systems that require a new handshake for every request.
2) Network Stability: The connection stability was tested by continuously running the system for 48 hours. The ESP32 successfully maintained the MQTT keep-alive "ping" with the broker, resulting in a 99.8% packet delivery success rate. In instances of forced network disconnection, the firmware's reconnection logic successfully restored the link within 5 seconds.

D. Load Control and System Reliability

The reliability of the actuation subsystem was tested by cycling the loads (Heater, Cooler, Conveyor) ON and OFF 50 times each via the SCADA interface.

- Thermal Management: The logic effectively triggered the cooling fan when the temperature threshold (set at 30°C) was breached. The Peltier module successfully reduced the enclosure temperature by 5°C within 10 minutes of operation.
- Motion Control: The stepper motor (Conveyor) responded to start/stop commands without missing steps, thanks to the non-blocking AccelStepper implementation.

Fig. 4. Ignition SCADA Dashboard interface displaying real- time temperature gauges, humidity trends, and manual control switches for the loads.

Discussion

The experimental results confirm that the integration of ESP32 with Ignition SCADA via MQTT provides a highly efficient and reliable solution for remote

monitoring. The system successfully mitigates the limitations of traditional wired systems by offering wireless flexibility. However, the dependence on public internet connectivity remains a minor vulnerability; for critical industrial infrastructure, a local MQTT broker (e.g., Mosquitto) on a Raspberry Pi would be recommended to ensure operation during internet outages.

VII. SYSTEM SECURITY AND SAFETY CONSIDERATIONS

The integration of industrial machinery with open network protocols inherently expands the threat landscape, necessitating a rigorous analysis of both cybersecurity vulnerabilities and physical safety mechanisms. This section outlines the potential threats associated with the proposed IoT-SCADA framework and the preventive measures implemented to ensure operational integrity and personnel safety.

A. Cybersecurity Threat Analysis and Data Protection

The reliance on public networks and standard communication protocols exposes the system to several cybersecurity vectors. A primary vulnerability in many IoT implementations is the use of unencrypted communication channels.

1. Data Interception (Man-in-the-Middle Attacks):

The standard MQTT protocol operates over TCP port 1883, which transmits data in plain text. This makes the system susceptible to packet sniffing, where an attacker on the same network could intercept sensor data or inject malicious control commands.

- *Preventive Measure:* To mitigate this, the system design supports the implementation of MQTT over SSL/TLS (Secure Sockets Layer/Transport Layer Security) on port 8883. This cryptographic protocol encrypts the payload, ensuring that even if packets are intercepted, the data remains unintelligible to unauthorized entities.

2. Unauthorized Access and Control:

Using a public broker without authentication allows any client with the topic string to publish commands, potentially causing physical damage by rapidly toggling relays.

- *Mitigation:* The system mandates the use of Broker Authentication (Username/Password) and unique Client IDs. Furthermore, Access Control Lists (ACLs) should be configured on the broker side to restrict which clients are authorized to subscribe to control topics vs. publish sensor data.

3. Denial of Service (DoS):

IoT devices are resource- constrained and vulnerable to flooding attacks that can overwhelm the network stack.

- *Countermeasure:* The ESP32 firmware includes rate-limiting logic and a Watchdog Timer (WDT). If the network stack hangs due to a flood of requests, the WDT automatically resets the microcontroller to restore functionality.

B. Physical and Electrical Safety Mechanisms

Beyond digital threats, the physical interfacing of low-voltage logic circuits with high-voltage industrial loads presents significant electrical hazards.

1. Galvanic Isolation:

The interface between the ESP32 (3.3V Logic) and the AC/DC loads (220V Bulb, 12V High-Current Motor) is mediated by a 4-Channel Relay Module. This module employs Optocouplers (e.g., PC817), which use light to transmit signals across an isolation barrier. This ensures that any voltage spikes or back-EMF (Electromotive Force) from the inductive loads do not damage the microcontroller or the connected workstation.

2. Thermal Runaway Protection:

To prevent overheating in the heating and cooling subsystems, a hardware-independent safety logic is embedded in the firmware. If the DHT11 sensor reports a temperature exceeding a critical threshold (e.g., 50^circ C), the firmware automatically forces the Heater Relay to the OFF state, overriding any incoming commands from the SCADA interface.

3. Failsafe State on Disconnection:

A critical safety feature is the handling of network failures. If the MQTT connection is lost (detected via the client.connected() check), the system is programmed to revert all actuators to a safe default state (All Relays OFF). This prevents a scenario where a heater is left running indefinitely because the "OFF" command could not be received due to Wi-Fi

failure.

C. Operational Reliability

To ensure consistent operation, the system leverages the Last Will and Testament (LWT) feature of the MQTT protocol.When the ESP32 connects to the broker, it registers a "Will" message. If the device disconnects ungracefully (e.g., power loss), the broker automatically publishes this message to a status topic, alerting the SCADA operator immediately that the remote node is offline.

VIII. SYSTEM BENEFITS AND ADVANTAGES

The proposed IoT-SCADA framework offers a comprehensive set of advantages across financial, operational, technical, and user-centric domains. By leveraging cost-effective hardware with industrial-grade software protocols, the system delivers significant value over traditional hardwired automation solutions.

A. Financial Benefits

- Reduced Capital Expenditure (CapEx): Utilization of the ESP32 microcontroller (approx 5-8) significantly lowers the entry barrier compared to traditional Programmable Logic Controllers (PLCs) which can cost upwards of 200-500 per unit.
- Lower Operational Costs (OpEx): The implementation of automated control logic for high- power loads (e.g., heaters and motors) optimizes energy consumption, reducing utility bills by ensuring devices operate only when necessary.
- Minimized Maintenance Expenses: Continuous condition monitoring allows for predictive maintenance strategies. By identifying thermal anomalies or motor strain early through data trends, costly equipment failures and unplanned downtime are avoided.
- Open-Source Protocol Savings: The use of the open- standard MQTT protocol eliminates the need for expensive, proprietary communication licenses often associated with legacy industrial systems.

B. Operational Benefits

- Real-Time Visibility: Operators gain immediate insight into critical environmental parameters (Temperature, Humidity) and machine status through the centralized Ignition SCADA dashboard, eliminating the need for manual floor inspections.
- Remote Accessibility: The internet-enabled architecture allows facility managers to monitor and control on-site assets from any location globally, improving response times to critical events.
- Scalability: The modular design allows for the seamless addition of new sensor nodes or control units without disrupting existing operations. New devices can simply publish to new MQTT topics to be integrated into the SCADA network.
- Automated Decision Making: The system reduces dependency on manual intervention by automatically triggering cooling or heating systems based on precise sensor thresholds, ensuring consistent environmental conditions.

C. Technical Benefits

- Low-Latency Communication: The lightweight nature of the MQTT protocol ensures rapid data transmission and command execution (typically <200ms), even over constrained or unstable network connections.
- High Reliability: The implementation of Quality of Service (QoS) levels within MQTT ensures guaranteed message delivery, preventing data loss during network fluctuations.
- Robust Edge Computing: The dual-core architecture of the ESP32 allows for efficient multitasking, enabling the system to handle network communication, sensor data processing, and motor control algorithms simultaneously without blocking.
- Interoperability: The use of standard JSON data formats and TCP/IP networking makes the system highly compatible with other enterprise systems, databases (SQL), and cloud platforms (AWS, Azure) for future expansion.

D. Customer and User Benefits

- Intuitive User Interface: The Ignition SCADA dashboard provides a user-friendly, graphical representation of complex data (using gauges, charts, and switches), making the system accessible to non- technical personnel.

- Enhanced Safety: Remote control capabilities ensure that users do not need to physically interact with high- voltage machinery or enter hazardous environments to operate equipment.
- Historical Data Analysis: Integrated data logging features allow users to review past performance trends, facilitating better decision-making regarding crop management (agriculture) or storage conditions (logistics).
- Customizable Alerts: Users can configure specific alarm thresholds in the SCADA system to receive immediate visual notifications if environmental conditions deviate from the set safety limits.

IX. CONCLUSION

This research successfully demonstrates the design and implementation of a scalable, cost-effective Industrial IoT (IIoT) framework capable of real-time environmental monitoring and load control. By integrating the ESP32 microcontroller with the Ignition SCADA platform via the lightweight MQTT protocol, the proposed system effectively bridges the gap between consumer-grade embedded hardware and professional industrial automation standards.

The major contribution of this work lies in its hybrid architecture, which delivers robust bidirectional communication—allowing for precise sensor data acquisition and immediate actuation of high-voltage loads such as heaters, cooling modules, and conveyor systems—without the prohibitive costs associated with traditional PLC-based solutions. Experimental validation confirmed the system's operational reliability, achieving a control latency of under 200 milliseconds and maintaining data integrity even under constrained network conditions.

However, the current implementation is not without limitations. The reliance on a public MQTT broker introduces potential latency during peak internet usage, and the DHT11 sensor limits precision in critical scientific applications. Future iterations of this project will focus on deploying a private, on-premise MQTT broker to enhance data security and reducing external network dependency. Additionally, the integration of Edge AI algorithms on the ESP32 for predictive maintenance and anomaly detection presents a significant opportunity to further elevate the system's intelligence and autonomy in smart manufacturing environments.

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