Design and Implementation of an IoT-Based Indoor Monitoring and Warning System

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Received: 23 June 2025 | Revised: 31 August 2025 and 16 September 2025 | Accepted: 18 September 2025

DOI: https://doi.org/10.48084/etasr.12887

ABSTRACT

This study designs and implements an Internet of Things (IoT) indoor monitoring, control, and warning system for smart-warehouse scenarios. The system centers on an ESP32 gateway that aggregates multiple-sensor data via Inter-Integrated Circuit (I²C), Serial Peripheral Interface (SPI), and a low-power nRF24L01 mesh network, enabling distributed nodes for environment sensing and equipment control. Security and personalization are enhanced via on-device face detection/recognition for access control and role-based permissions. A cloud backend provides real-time data synchronization, event logging, and remote actuation, whereas a responsive web interface supports cross-platform supervision and configuration. A modular hardware–software architecture is described that emphasizes interoperability and cybersecurity through authenticated messaging, secure key provisioning, and adherence to embedded and web standards. A prototype was developed and evaluated in a warehouse-like testbed in Vietnam, assessing end-to-end latency, alert delivery reliability, recognition accuracy, node power budget, and Radio Frequency (RF) link robustness under typical indoor obstructions. Results demonstrate reliable data acquisition, responsive closed-loop control, and stable multi-device operation with seamless cloud integration, indicating suitability for day-to-day warehouse operations such as secure entry, device management, and environmental compliance.

Keywords-indoor monitoring; control system; warning system; ESP32 microcontroller; nRF24L01 communication protocol; Internet of Things (IoT)

I. INTRODUCTION

The advent of the Internet of Things (IoT) has revolutionized the way we interact with built environments, accelerating the emergence of smart spaces that offer enhanced convenience, security, and energy efficiency. A smart indoor system integrates diverse devices and services, enabling seamless communication and automation through IoT technologies. This interconnected ecosystem allows users to monitor, control, and optimize their environments remotely, improving day-to-day operations and user experience [1]. The primary objective of this paper is to develop an IoT-based indoor monitoring, control, and warning system that integrates sensing, actuation, and intelligent decision-making. By combining IoT devices with Artificial Intelligence (AI), the system aims to create a responsive living/working space in which real-time data streams are analyzed to drive automated actions. Core building blocks include sensors, microcontrollers, communication protocols, and cloud services that collaborate to support real-time analytics and closed-loop control.

IoT deployments typically encompass sensors, controllers, and smart appliances that collect and exchange data over a network [2, 3]. The incorporation of AI enables these devices to learn from behavioral patterns and environmental conditions, facilitating predictive adjustments and personalized services [4]. For example, algorithms can fuse temperature and lighting data to automatically adapt settings for comfort and energy efficiency. Communication within the system is enabled by protocols such as Inter-Integrated Circuit (I²C), Serial Peripheral Interface (SPI), and Radio Frequency (RF) wireless links. I²C provides synchronous serial communication for low-speed peripherals in embedded systems [5], whereas SPI supports high-speed transfers between microcontrollers and devices [6]. RF communication extends coverage for low-power nodes and is essential for remote monitoring and control in large, obstructed indoor spaces [7]. To enhance security and personalization, the system integrates face detection/recognition, leveraging machine learning to achieve accurate, real-time identification for access control and user-aware services [8].

Cloud services such as Firebase are employed for data storage, event streaming, and real-time database synchronization [9]. This cloud layer enables multi-device coherence, remote access, and scalable processing for AI workloads generated at the edge. Web technologies, including HTML, CSS, and JavaScript, provide a responsive user interface, whereas Application Programming Interfaces (APIs) connect the front end with backend services to support multi-platform monitoring and control [10]. Despite these advances, practical challenges persist, including data security and privacy, heterogeneous device interoperability, and robust operation in cluttered indoor environments [11].

Prior studies spanning foundational IoT surveys to recent implementations cover RF communication, Firebase-based dashboards, face recognition, and standard embedded protocols; however, these studies typically treat these components in isolation or within consumer smart-home contexts. There is limited evidence of an integrated, cost-aware blueprint that unifies distributed RF sensor nodes with an ESP32 edge gateway, performs on-device biometric access control to reduce cloud exposure, and quantifies end-to-end latency, alert reliability, and link robustness in warehouse-like indoor environments common in emerging markets. Moreover, Wi-Fi- or Zigbee-centric designs reported in the literature often under-address RF performance amid metallic shelving and long aisles and rarely tie biometric authentication to role-based device permissions.

Accordingly, this work designs and implements an indoor monitoring, control, and warning system using IoT technology with the ESP32 as the core hardware component. Targeting smart-warehouse operations, the system incorporates facial recognition for secure access control, device management, and real-time monitoring through a web interface connected via Firebase. The implementation develops both hardware and software components, integrates sensor data using the nRF24L01 communication protocol, and employs cloud services for data synchronization and analysis. Empirical evaluation in a warehouse-like testbed in Vietnam demonstrates reliable data acquisition, responsive actuation, and robust alerting, indicating applicability to day-to-day operations in resource-constrained settings.

II. DESIGN AND IMPLEMENTATION

A. *Face Recognition System*

The block diagram of the system includes the following main blocks, as shown in Figure 1:

- Input image pre-processing: This block prepares the input image before it is fed into the recognition process. Pre-processing steps may include brightness normalization, resizing the image to a standard size, and rotating the image to ensure the accuracy of the recognition process.
- Feature extraction: This block extracts facial features from the input image. The extracted features include unique points such as nose, eyes, and mouth, which are used to determine the unique characteristics of each face.
- Classifier: This block compares the extracted features with those stored in the face database. The classification process determines whether the face has been registered in the database.
- Face database: This block stores registered faces in the form of their extracted features.

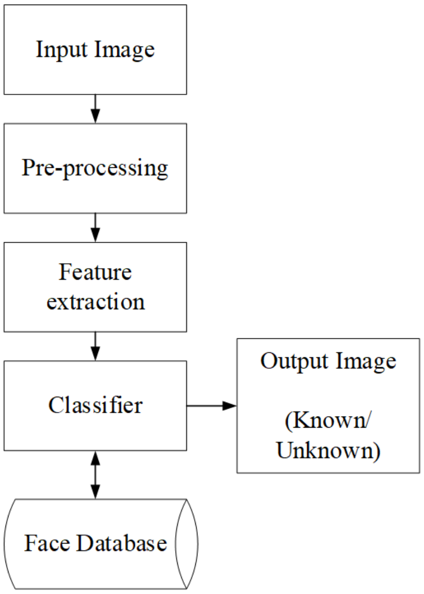


Fig. 1. Block diagram of the face recognition system.

The face recognition system is implemented in Python using OpenCV, which provides a set of tools for image processing and computer vision. The system employs machine learning algorithms to perform face recognition based on the extracted features. It can be applied to various applications such as access control, attendance tracking, and security surveillance.

B. *Smart Warehouse System*

The system utilizes two nodes that communicate wirelessly using the nRF24L01 transceiver modules (shown in Figures 2–4). These nodes are strategically placed in two separate rooms: the operation room and the warehouse. Each room is equipped with its own set of sensors and control devices to monitor and manage environmental conditions. Node 1, designated as the root node, includes a control panel for Node 2, enabling direct communication even in the absence of Wi-Fi connectivity. Additionally, Node 1 serves as a gateway to the mobile application and Firebase cloud services, facilitating seamless integration and remote access to the system's functionalities.

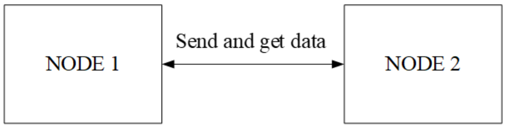


Fig. 2. Communication between Node 1 and Node 2.

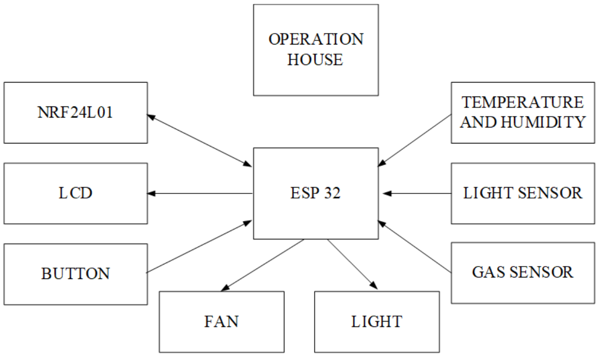


Fig. 3. Block diagram of Node 1 (operation room).

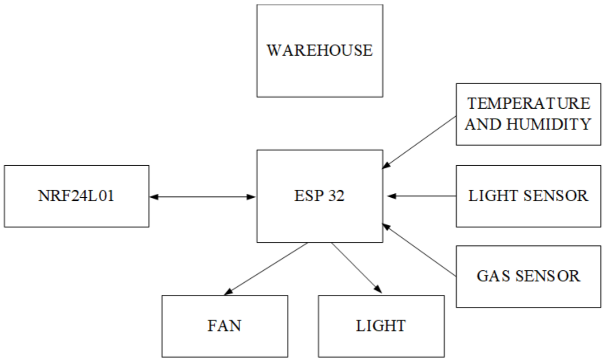


Fig. 4. Block diagram of Node 2 (warehouse).

C. *Hardware Flowchart*

Each node's program is executed using a time-sliced approach for pre-defined tasks (shown in Figures 5–7). This ensures that the tasks are completed within specified time intervals without the need for continuous execution. Furthermore, the resting periods of the tasks do not interrupt or affect other tasks.

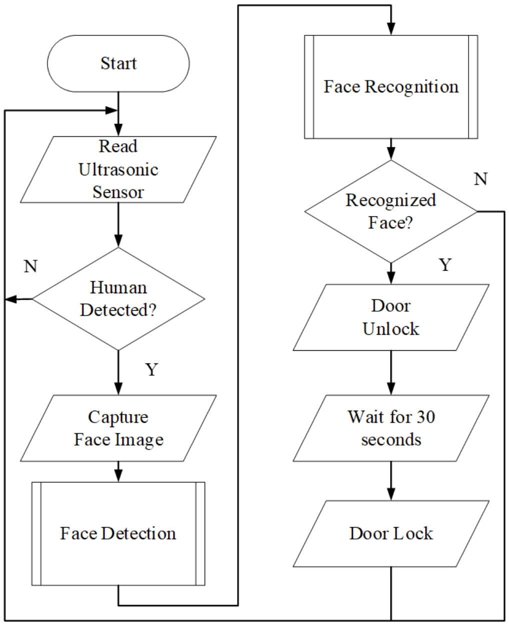
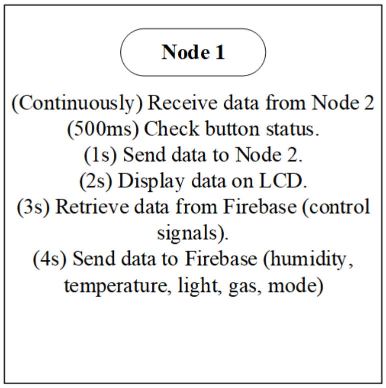
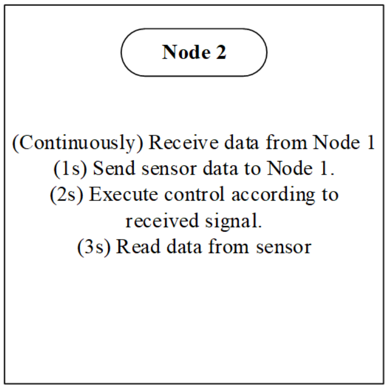


Fig. 5. Flowchart of the face recognition process.



(Continuously) Receive data from Node 2
(500ms) Check button status.
(1s) Send data to Node 2.
(2s) Display data on LCD.
(3s) Retrieve data from Firebase (control signals).
(4s) Send data to Firebase (humidity, temperature, light, gas, mode)

Fig. 6. Task execution of Node 1.



(Continuously) Receive data from Node 1
(1s) Send sensor data to Node 1.
(2s) Execute control according to received signal.
(3s) Read data from sensor

Fig. 7. Task execution of Node 1.

III. RESULTS AND ASSESSMENT

The system operates with different modes, where '1' represents the ON state and '0' corresponds to the OFF state, as shown in Figures 8–10. A mode-setting feature is implemented such that mode = 1 signifies manual control mode, operated through physical buttons or via web and app interfaces, whereas mode = 0 indicates automatic mode based on preprogrammed conditions. In manual control mode (mode = 1), when set = H, the system operates through hardware buttons; when set = W, the control is performed using software through web or app interfaces.

An assessment of the system's performance revealed that the communication between the two rooms via the wireless module nRF24L01 is relatively stable. Continuous transmission tests indicated that data were fully received, although delays ranging from 0.5 to 0.75 s occurred depending on the distance and intermediate obstructions. The buttons in the system are designed based on a low-level active circuit principle, enhancing processor safety by avoiding over-current and over-voltage situations and providing high sensitivity. Observations during extended operation showed that the delay in button response is approximately 0.3 to 0.5 s, ensuring that the button statuses are updated quickly.

The 16 × 2 LCD, although limited in size, is capable of displaying essential parameters for controlling lights and fans. The LCD updates every 3 s, reducing the processing load in the program while maintaining adequate display functionality. Regarding sensors, the system employs a DHT11 temperature and humidity sensor, a light sensor, and a gas sensor (MQ4). Short-term experimental runs demonstrated that the temperature and humidity readings have an accuracy of approximately 95%. For the light sensor, an increase in light intensity resulted in a decrease in the analog value; when the analog value was around 425, the light was considered strong. The gas sensor showed an analog value above 1,000 when exposed to an igniter, indicating a high gas concentration.

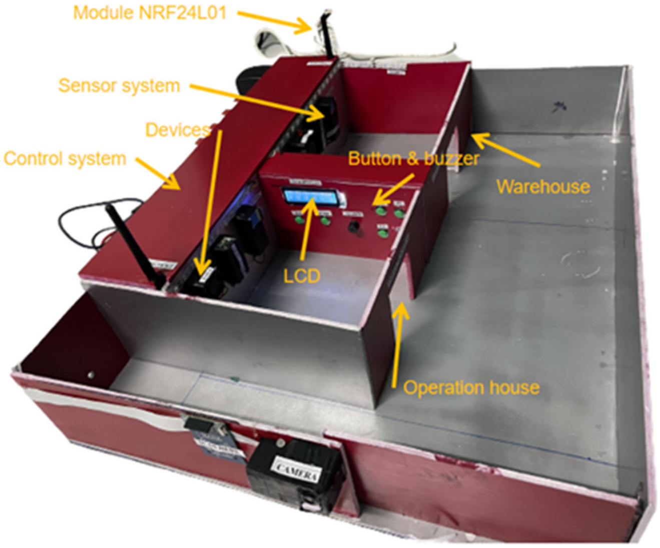


Fig. 8. System model.

Fig. 9. Sensor and device arrangement.

Fig. 10. LCD display of the system.

Control commands issued from the web and app interfaces via Firebase to the hardware exhibited a delay of approximately 3–5 s, depending on internet conditions. This level of latency is acceptable for systems that do not require immediate responsiveness. Overall, the system operates reliably with low latency; however, sensor accuracy was not optimal due to the use of non-high-precision sensors and environmental factors.

When buttons were pressed, they generated a low-level signal that the microprocessor detected and activated, after which they returned to a high-level state. The button, LCD, DHT11, MQ4, and light sensor components in the indoor monitoring, control, and warning system using IoT technology functioned normally, with low error rates and satisfactory accuracy and stability. The button components for device control exhibited low latency and reliable operation, ensuring smooth user interactions.

The nRF24L01 communication protocol facilitated wireless communication between two different rooms without requiring a physical connection. The tests showed that the connection was stable and reliable, allowing users to access their devices and monitor their indoor environment without interruptions. The DHT11 and MQ4 sensors demonstrated reasonable accuracy and stability in measuring temperature, humidity, and air quality, providing users with reliable information about their indoor environment. The light sensor component also functioned effectively, offering accurate readings of indoor lighting conditions.

The control and monitoring of devices using the ESP32 hardware were successfully implemented. The system controlled various devices such as lights, fans, and air conditioners, enabling users to adjust their indoor environment remotely. The use of the nRF24L01 communication protocol ensured reliable data transmission between the devices and the ESP32, providing accurate and timely information for users to act upon. The system's ability to monitor sensor data was a critical feature that ensured users had up-to-date information about their indoor environment. By employing Firebase to store and retrieve data, the system guaranteed that information was always available, even if the ESP32 was offline.

IV. DATA VISUALIZATION

The data visualization feature on the website and app of the indoor monitoring, control, and warning system using IoT technology has been evaluated and found to be highly effective. The system can accurately read sensor data from Firebase and display them on the website in real time, providing users with up-to-date information about their indoor environment.

The data visualization feature is also highly intuitive, with various charts and graphs that make it easy for users to track changes in their indoor environment over time. The system can display data on temperature, humidity, light levels, and gas concentrations, providing users with a comprehensive overview of the indoor environment, as shown in Figure 11.

The indoor monitoring, control, and warning system using IoT technology includes an innovative feature that allows users to control their devices remotely through buttons on the website. The buttons transmit signals through Firebase, allowing the hardware to read the signals and execute the requested actions.

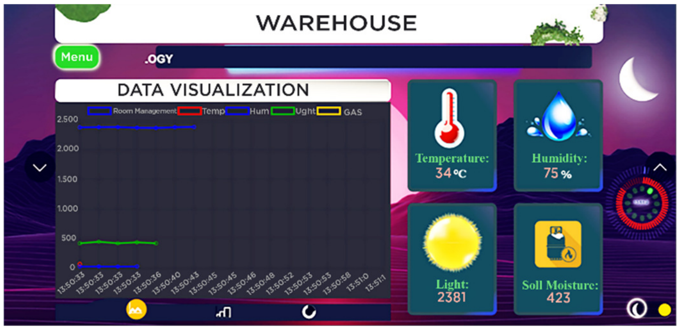


Fig. 11. Data visualization on the web interface.

This feature provides users with an easy and convenient way to control their devices remotely, without the need to physically interact with the hardware. Users can adjust the settings on their devices simply by clicking the buttons on the website, making it a user-friendly and accessible feature, as shown in Figure 12.

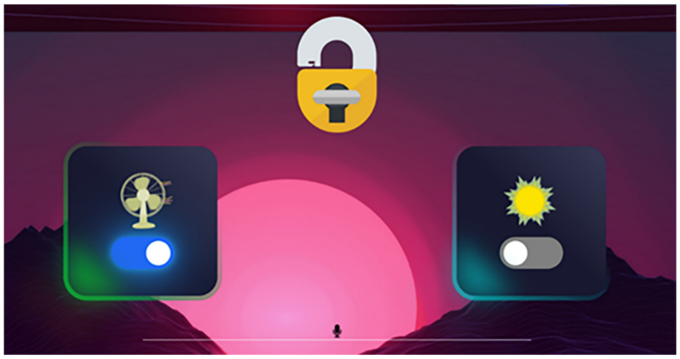


Fig. 12. Device control via the web interface.

V. DATA ANALYTICS WITH POWER BI

The Power BI-based store management system is used in this study to provide an effective solution for managing sales, profits, and costs of items in a retail store, as shown in Figure 13. The tool provides a comprehensive and user-friendly interface for managing and analyzing key business factors, allowing informed decision-making. Its intuitive design and advanced analytical capabilities make it valuable for improving performance and profitability in retail operations.

VI. WEATHER FORECASTING WITH TABLEAU

Tableau is used in this study to analyze and forecast weather patterns in Vietnam, as shown in Figure 14. Accurate weather forecasting is crucial for industries such as agriculture, transportation, and tourism, as it supports informed planning and decision-making. Historical weather data for several locations in Vietnam were collected and analyzed. Tableau was used to generate forecasts for different time periods, with parameters adjusted to tailor outputs to specific needs. Data are displayed in various formats, including maps, charts, and tables, to facilitate easy understanding and analysis for users. The results show that Tableau is highly effective in generating accurate forecasts and providing real-time weather information, making it both accessible and user-friendly.

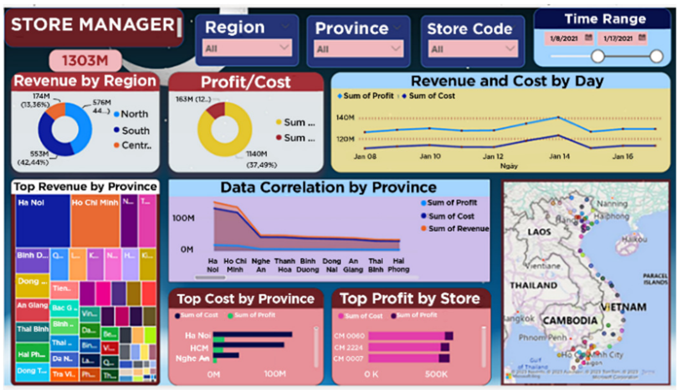


Fig. 13. Store management with Power BI.

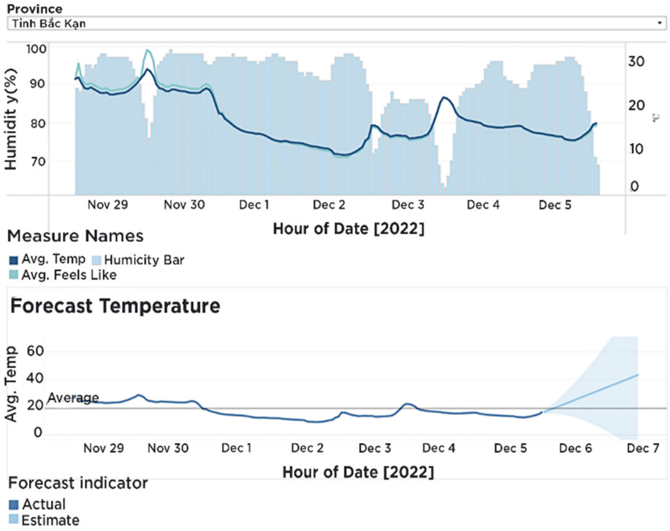


Fig. 14. Weather forecasting with Tableau.

VII. CONCLUSION

This paper presented a practical, end-to-end Internet of Things (IoT) system for indoor monitoring, control, and warning that couples an ESP32 edge gateway with nRF24L01-based distributed nodes, on-device face recognition for secure access, and a Firebase-backed web and mobile interface. Addressing a key gap in the literature, where most works either emphasize Wi-Fi/Zigbee smart-home stacks with cloud-only authentication or evaluate single components in isolation, the research contributes a cost-aware, privacy-preserving blueprint tailored to warehouse-like indoor environments in emerging markets.

Compared with Wi-Fi/Zigbee systems, our nRF24L01 tier reduces hardware cost and power consumption and maintains robustness in aisle-and-shelf layouts, albeit with reduced IP-native interoperability and throughput. In contrast to cloud-only face recognition, on-device inference reduces latency and limits biometric exposure but is bounded by edge compute capabilities.

The prototype achieved its objectives (secure access, device management, real-time monitoring and alerts, and data visualization) despite limitations such as reliance on the internet for cloud features, nRF24L01 range and throughput constraints, and commodity-sensor accuracy.

Future work will benchmark the system against representative Wi-Fi, Zigbee, and Long Range (LoRa) designs in terms of latency, reliability, energy consumption, and total cost; incorporate interoperability standards; upgrade edge Artificial Intelligence (AI) capabilities; and improve sensing calibration and end-to-end security.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

FUNDING

This research was funded by the University of Economics Ho Chi Minh City (UEH University), Vietnam.

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