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Design, Simulation, and Implementation of an IIoT-based Temperature and Humidity Monitoring System with Single-Core Infinite Loop Prevention and Fault Tolerance for Multi-Sensor and Connectivity Failures

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Abstract

The purpose of this research is to develop and implement a robust monitoring system that can function with the constraints of a single-core processing system, such as an ESP 8266, to overcome the issue of infinite loop faced when one or more subsystems malfunction, such as the loss of data or server connectivity. This paper describes a novel approach wherein the implementation of an Industrial Internet of Things (IIoT) based temperature and humidity monitoring system resolves the infinite loop issue and enables the development of highly robust monitoring solutions. The output from such a system can be subsequently integrated into other systems that can respond to the monitored values in real time without disruptions. The proposed mechanism utilizes an ESP8266 microcontroller for processing and wireless connectivity, DHT22 sensors for temperature and humidity measurements, an LCD for real-time monitoring, and the Message Queuing Telemetry Transport (MQTT) protocol to store data in the Adafruit IO platform for live off-site monitoring and data storage. Testing demonstrated that the system could handle up to three sensor failures out of four, Wi-Fi network and server disconnections, and automatic reconnections after five seconds. The system was able to perform error handling while maintaining the data flow from the sensors to the local data display LCD without interruptions during all tested scenarios. Based on several trials, the system succeeds at addressing a wide range of errors and disruptions, resulting in an ideal solution for the sectors that require precise monitoring to attain a wide range of operational objectives.

Keywords

IIoT, ESP8266, DHT22, Infinite loop prevention, MQTT

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Introduction

Microcontrollers and Internet of Things (IoT)-based systems have gained widespread popularity due to their low-cost and efficient system for remote monitoring and control (Karima et al., 2024; Talha et al., 2023; Bhuyan et al., 2023; Paul et al., 2023; Bhuyan et al., 2021). Over the past few years, Industrial Internet of Things (IIoT) has turned out to be a promising approach for monitoring and controlling diverse sectors that have heightened processing abilities within industrial environments (Hajlaoui et al., 2024). The conventional factory system depends on manual control that results in errors, delays, and higher costs, while uninterrupted operation on resource-constrained platforms offers a major challenge (Hailan et al., 2024). The ESP8266, a low-cost microcontroller highly sought after for environmental monitoring, features wireless capabilities on board, a compact size, and low cost. Disadvantages, such as single-core-based systems, are responsible for drawbacks in overall performance and disruption in functionality in case of failure of one subsystem (Kareem et al., 2021). Sensor malfunctions, transmission failures, or server loss of connectivity can lead to infinite program loops, resulting in complete system failure.

This paper illustrates the novel approach of a robust temperature and humidity monitoring system that can sustain operational performance even in the event of subsystem failure. The system integrates an ESP8266 microcontroller with DHT22 environmental sensors, an LCD module for local display, and the Message Queuing Telemetry Transport (MQTT) protocol for efficient transport of data to the Adafruit IO platform, which is a recommended cloud storage platform due to its user-friendly interface (Dinmohammadi et al., 2025). The structure of the article is planned as follows: Section II provides a background study review and related works. Section III provides the methodology and proposed system design in detail. Section IV presents experimental results and analysis. The overall cost analysis of the prototype has been described in Section V. Section V concludes the paper with the key findings and recommends possible paths for upcoming research and investigation.

Literature Review

Hendajani et al. (2022) designed an IoT-based system for the automatic monitoring of room temperature and humidity, incorporating fan control via a DHT22 sensor and NodeMCU ESP8266 microcontroller to run real-time monitoring regularly every 2 s and features manual fan control through a web interface, enabling an immediate response to environmental aberrations. Yet, the system comes with limitations, like dependence on a single sensor, the absence of a reconnection protocol in case of internet interruption and falling into an infinite loop in such a case. Riadi et al. (2021) established an IoT-based system for monitoring and controlling temperature and humidity to maintain soybean quality by utilizing the ESP8266 module and Arduino to ensure accurate environmental control. Nonetheless, the system faces challenges such as a lack of automatic reconnection if the system goes offline, the infinite loop interrupts operation, and displays inaccurate numbers, causing the system to be inefficient in unstable networks.

Ibrahima Toure et al. (2022) emphasized the importance of monitoring real-time temperature and humidity for efficient biogas production by using Arduino and DHT11 sensors, crucial for energy recovery from waste materials. Several limitations exist, such as significant sensor inaccuracies and a controlled experimental environment that may not represent real-world diversity. Medagedara and Liyanage (2024) developed a real-time IoT-based temperature and humidity monitoring system for factory electrical panel rooms to identify disparities and generate alerts during the manufacturing process. However, it comes with restrictions, such as reliance on a single sensor, a lack of internet reconnection alternatives, and infinite loops during internet outages. Yuan et al. (2020) implemented an IoT-based temperature and humidity detection system, where the chip uses an ESP8266 and a DHT11 sensor to achieve real-time data transmission on the Baidu cloud platform using MQTT for effective warehouse monitoring. Here, much emphasis is given to ESP8266 in developing high-performance temperature and humidity monitoring systems.

Huang et al. (2021) presented a PID algorithm-based temperature and humidity control system based on the ARM11 platform, featuring a DHT21 sensor, an STC11F48 microcontroller, and Wi-Fi for remote monitoring, to have improved precision and effective performance. Nonetheless, constraints exist, such as scaling concerns caused by dependence on a single-chip microcontroller and a lack of additional functions, such as data storage. Zuo et al. (2021) describe a temperature and humidity measurement system that collects data via a single-chip microprocessor and a DHT11 sensor, which is then processed by a C-programmed microcontroller. However, constraints include a narrow measurement range (0-50°C, 20-90% RH), potential accuracy gaps for sensitive applications, dependency on steady power, and the use of a single sensor, which may impede scalability and redundancy.

Wang et al. (2020) conducted research that focused on sensitive environmental management to preserve stored items such as food and archives. Review the literature available on newly integrated technologies, such as the STC89C52 microcomputer, which has programmable Flash memory with low power consumption for monitoring and real-time control of the process. Although some progress is being made, many systems remain highly expensive and unintelligent, which demands much better solutions to utilize sensor technology along with digital processing. Huang et al. (2023) developed an indoor temperature and humidity monitoring system model that features a Kalman filter method to increase the accuracy of measurement. The system includes a DHT11 sensor, an STM32 microcontroller, and a mobile app-controlled monitoring system. The restrictions include relying on the accuracy of the DHT11 sensor and a reliable power supply.Mubaraka and Iddha (2022) proposed an ESP32-based system for indoor air quality improvement, adopting IoT technology to solve the problems arising because of increased time spent indoors during the pandemic. It allows remote monitoring and control using the Blynk application, ultrasonic mist maker, and infrared remote module for effective regulation of the humidity of the system. The limitations include dependence on surrounding environmental elements and no humidity regulation mechanism in low-budget air conditioners.

Methodology

The system has been designed for monitoring environmental conditions using four DHT22 sensors connected to an ESP8266 microprocessor. Data is transmitted over a Wi-Fi connection using the MQTT server protocol and is displayed in real time on two LCD monitors, one for data display and another for system status display. The block diagram for the system and an overall overview of the hardware scheme are shown in Figures 1 and 2, respectively.

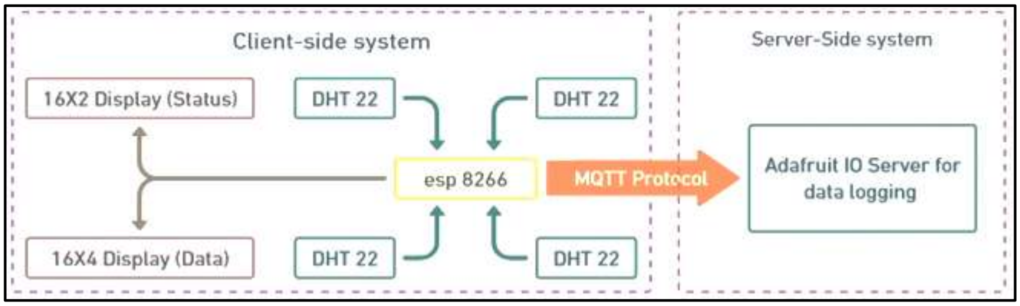


Figure 1. Block diagram of the overall scheme

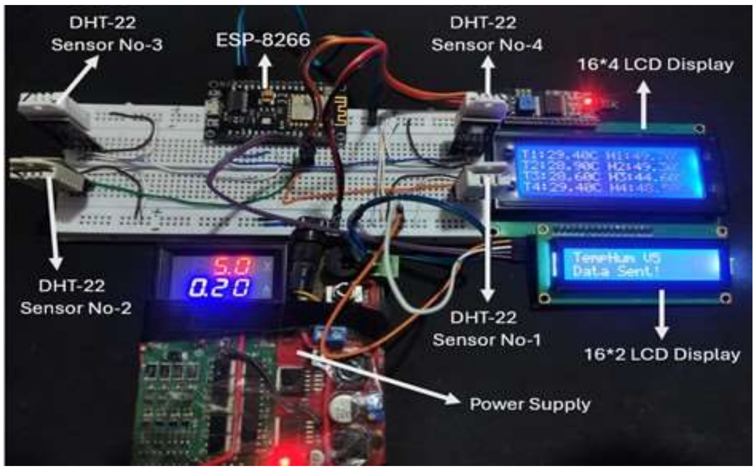


Figure 2. Overview of the overall hardware scheme

- **System Initialization**

At startup, the ESP8266 configures all required peripherals, such as 4 DHT22 sensors, 1 MQTT client, the Wi-Fi interface, and the LCD monitors. The system initialization messages shown on the status display (16×2 LCD) indicate the startup procedure of the system, as shown in Figure 3.

Figure 3. Hardware initialization of the system

- **Network Connection**

The system attempts to connect to a predefined network. If the connection is successful, a status message is displayed in Figure 4 (a), and the Wi-Fi status flag (isWiFiConnected) is set to true. If the connection fails, a maximum of five (5) reconnection attempts are made before the Wi-Fi status flag is updated accordingly, and a status message is shown in Figure 4 (b). The flowchart for this connection process is shown in Figure 4 (c).

(a) (b) (c)

Figure 4. Wi-Fi connection-related issues: (a) successful Wi-Fi connection confirmation; (b) connection couldn't be established, connection failure; (c) connection process flowchart

- **Server Connection**

After the network connection stage is completed, the system starts connecting to the server via the MQTT protocol. This step follows the same connection logic whereby a status flag keeps track of the connection status, and connection success or failure messages are displayed on the LCD screen, as in Figures 5 (a) and (b), one-to-one. The flowchart for this stage is shown in Figure 5 (c).

(a) (b) (c)

Figure 5. Server connection-related issues: (a) successful MQTT server connection confirmation; (b) unsuccessful connection message, connection failure; (c) connection process flowchart

- **Data Acquisition**

The system begins acquiring temperature and humidity values from four sensors, preferably placed at four corners of a room, regardless of the connection status of the Wi-Fi or the MQTT. The sensor data is first temporarily stored on the system RAM and displayed on the LCD, then sent to the server. If one sensor or multiple sensors fail to provide valid data, an error message identifying the faulty sensor is displayed on the LCD screen, and the data from the remaining sensors is displayed without interruption. This is further illustrated in Figure 6 using a flowchart of the process.

Otherwise, the collected data is displayed on the data display (16×4 LCD monitor), giving the user a real-time view of the environmental conditions. It is noted that ‘NaN’ stands for ‘not a number’.

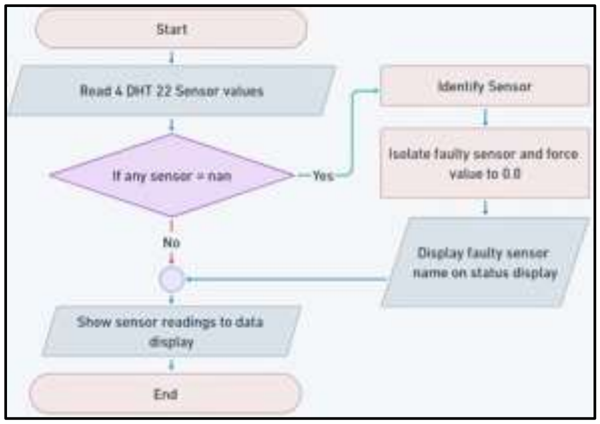


Figure 6. Flowchart of the data acquisition step

- **Data Publishing**

When both the MQTT and Wi-Fi connection flags are set to true, i.e., connection to the server is successful, the sensor data is sent to the Adafruit IO server via the MQTT protocol, and a confirmation message is shown on the status display, Figure 7 (a). In case any of the status flags are set to false, the system displays a specific error message on the status display and operates locally according to Figure 7 (b). If a sensor fault occurs, while connection to the server is available, that specific sensor value is sent as zero to the server, while the readings from the other sensors remain intact and are successfully sent to the server, in Figure 7 (c).

(a) (b) (c)

Figure 7. Data transmission-related issues: (a) successful data transmission; (b) MQTT Failure, system operating in offline mode; (c) Data transmission with a single sensor failure

- **Continuous Operation**

The system is designed to operate continuously. It is achieved by having the system operate in a continuous loop every 5 s, as can be seen in Figure 8, from connector C1 to C3. A 5-second interval was chosen to avoid server thrashing or overloading at Adafruit IO. If either the Wi-Fi or the MQTT or both connection flags are set to FALSE, i.e., failure in connecting to the server, the system automatically tries to reconnect at the beginning of the following cycle. Local data acquisition and display remain uninterrupted during such connection interruptions, and only error messages are displayed, but the code executes onward. In the case of a single sensor failure, if the sensor is fixed or a new sensor is placed and connected, the system can start reading data from that sensor at the next cycle. This approach eliminates the infinite loop stalling of code execution that was faced in the previous systems and ensures persistent motoring even under partial failures.

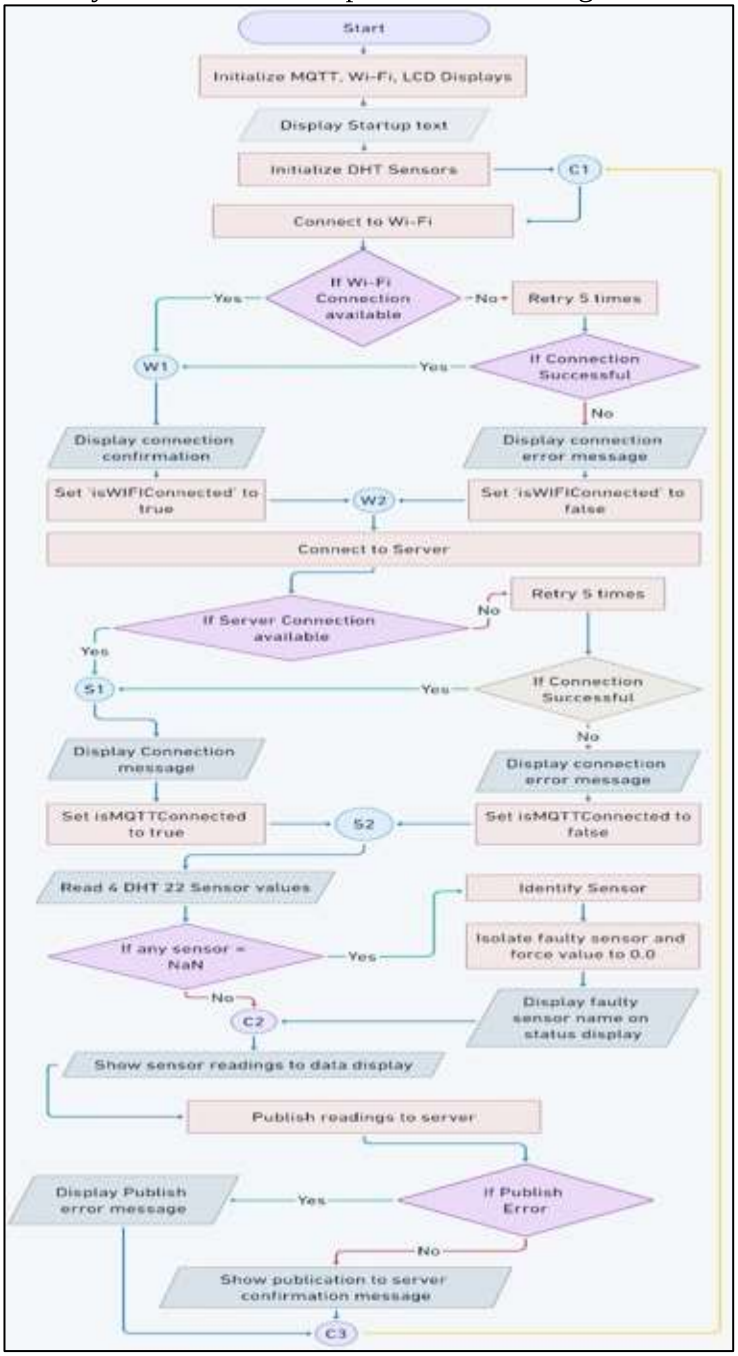
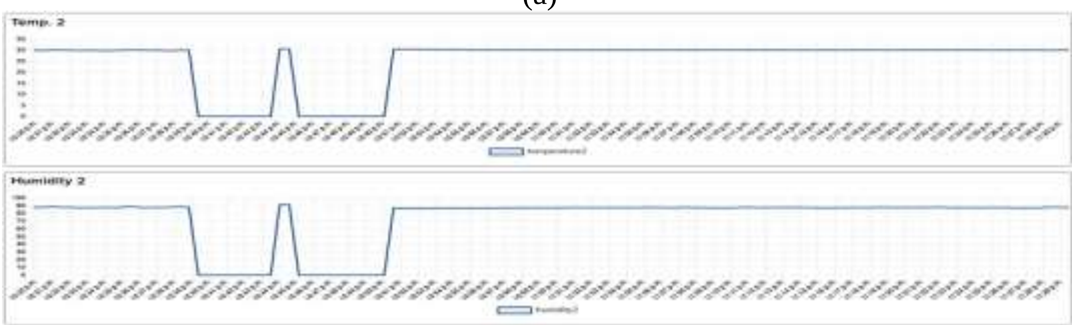


Figure 8. Flow chart of the connection process in case of active sensors or any failure

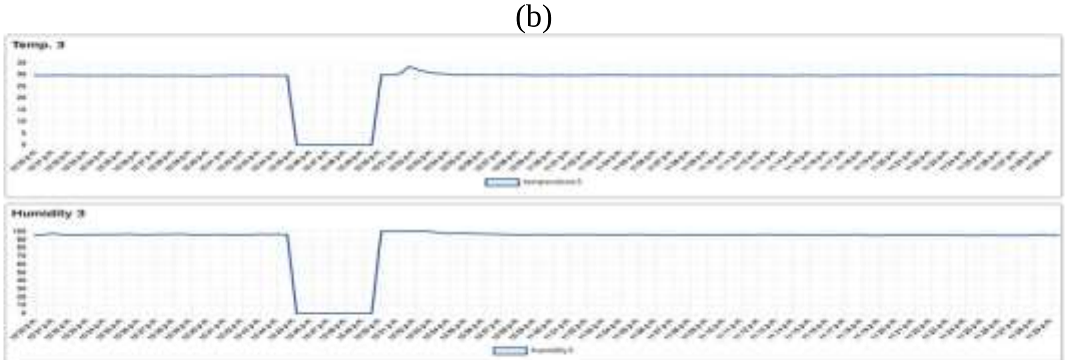
Results and Discussion

To demonstrate the reliability and robustness of the system, data was taken over an hour, and several types of faults were simulated by disconnecting and reconnecting several components of the system, as shown in Figures 9 (a)-(d). The results from these failure simulations are discussed. The time taken by the system to detect disconnection of system components and the time for the system to detect reconnection and automatic data collection upon recovery are discussed, too. For data management and visualization, the Adafruit IO platform is used to provide real-time monitoring and graphical depiction of sensor readings.

(a)



(b)

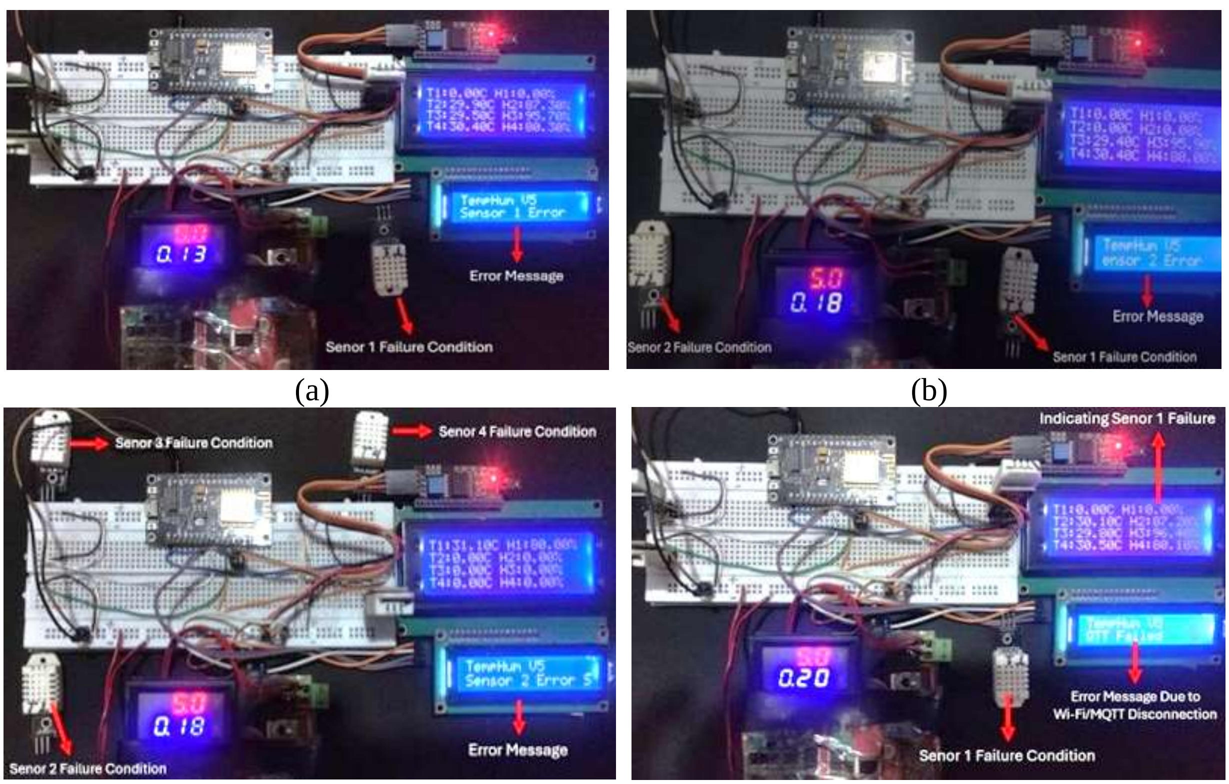


(c)

(d)

Figure 9. Time-series plots of temperature and humidity from (a) Sensor 1, (b) Sensor 2, (c) Sensor 3, and (d) Sensor 4, generated on the Adafruit IO platform

Conditions such as single and multiple sensor failures, as well as server interruptions, have been tested to analyze the performance. The data for the sensor at fault shows zero in both the display and the server. From 10:30 pm to 10:33 pm, the system operates under normal conditions with all four sensors actively reporting eight (8) data parameters, as shown in Figure 10 (a). During this interval, the system performed without any flaw. As is evident in Figure 11, the system took 25 s to initialize. It is noted that the system executes each loop after 5 s of completing the last loop.



(a) (b)

(c) (d)

Figure 10. System performance under different fault conditions: (a) single sensor fault, (b) dual sensor fault, (c) triple sensor fault, and (d) sensor fault with MQTT and Wi-Fi disconnection

Between 10:33 pm to 10:38 pm, a single sensor fault was created by removing Sensor 1 according to Figure 10 (a). The system accurately identified the fault, while the remaining three sensors continued to transmit data according to Figures 10 (b), (c), and (d). The system took 25 s to detect the error and update the error display, while it took another 14 s for the system to detect the reconnection and display the updated data automatically, according to Figure 10 (b).

Between 10:40 to 10:44 pm, the two-sensor fault condition was met by the removal of sensors 1 and 2, as shown in Figure 10 (b). The system identified the removal of these two sensors successfully within 20 s, as shown in Figure 10 (b), while sensors 3 and 4 continuously sent and displayed temperature and humidity data, as shown in Figure 10 (c) and (d). After reconnection, the system took 6 s to update data.

Between 10:45 pm to 10:50 pm, three-sensor failure condition was simulated when sensors 2, 3, and 4 were removed, while sensor 1 continued to function without any interruption, according to Figure 10 (c). It took the system 6 s to detect the fault, as shown in Figure 10. The system properly detected the failures and continued operation with only one sensor's data, illustrated in Figure 9. Upon reconnection, the data was automatically updated after 25 s.

The final fault condition of MQTT/Wi-Fi disconnection, along with a single sensor malfunction, was conducted in the period between 10:54 pm and 10:59 pm, as shown in Figure 10 (d). At this stage, the system provided appropriate error messages after 5 s, as shown in Figure 10 (d), and continued operational activities in local mode. After reconnection, data transmission to the server resumed automatically after 8 s, while other sensors remained unaffected and continued to report normally throughout the interruption, as shown in Figure 11.

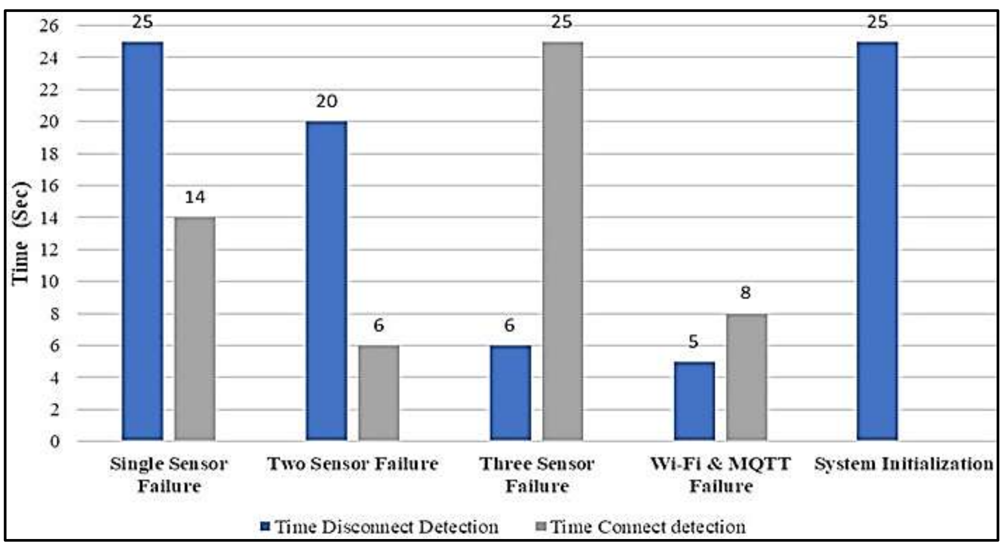


Figure 11. Detection and reconnection times of sensors and server fault conditions

- **Cost Analysis:**

The cost analysis for the prototype of the system illustrates a total expense of US$23.37 (US Dollars twenty-three point three six), including components, such as a microcontroller unit, various sensors, a power supply unit, and a few other supporting parts.

Table 1. Breakdown of the cost analysis of the system

SL	Components	Quantity	Unit Price ($)	Total Price ($)
1	ESP-8266	1	2.87	2.87
2	DHT-22	4	2.13	8.52
3	16×4 LCD Monitor	1	3.68	3.68
4	16×2 LCD Monitor	1	2.79	2.79
5	Power Supply	1	4.27	4.27
6	Breadboard	1	1.23	1.23
			Total Price	**23.36**

Conclusion

The study successfully demonstrates an advanced IIoT-based temperature and humidity monitoring system that can overcome the infinite loop and failure limitations typically encountered in single-core microcontrollers such as the ESP8266. By the integration of four DHT22 sensors, the MQTT protocol, and fault-tolerant mechanisms, the system offers constant local monitoring and automatic recovery from sensor faults, network, and server issues. Experimental results confirm that the system tolerates up to three simultaneous sensor failures and maintains continuous operation with recovery of connections and data transfer immediately upon fault recovery. Compared to existing solutions, the study provides a noble approach of enhanced reliability, scalability, and operational robustness at a low cost, making it suitable for industrial and smart infrastructure applications where precise and robust environmental monitoring is important.

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