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Original Research

Implementation of An IoT-Based Temperature and Humidity Monitoring System with Data Logging Features in the Calibration Laboratory

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ABSTRACT

ISO/IEC 17025:2017 accredited calibration laboratory, holds an absolute obligation to monitor, control, and record environmental conditions (temperature and humidity) to maintain the validity of measurement results and support budget uncertainty calculations. However, the current monitoring system is still conventional and manual (three times a day), making it vulnerable to human errors, data duplication, and an inability to record fluctuations between intervals. This study aims to design and build an automatic temperature and humidity monitoring system based on the Internet of Things (IoT) featuring a dual-logging system to ensure continuous technical records. The system design utilizes an ESP32 microcontroller as the central processing unit, a DHT11 sensor to detect ambient temperature and relative humidity, a Micro SD Card module as a local backup media (offline backup), and the ThingSpeak platform as a cloud database for remote monitoring. The sensor data is saved to the SD Card in CSV format every 5 minutes, while data transmission to ThingSpeak is scheduled every 1 minute. System testing involved functionality tests (Black Box Testing), local storage capability tests, connectivity tests, data validity tests, and stability/durability tests. The results indicate that the IoT-based monitoring device was successfully functionality test success rate. The implementation of the dual-logging feature effectively preserves the integrity and continuity of records; ThingSpeak simplifies real-time data visualization, while the Micro SD Card operates as a reliable local failsafe during network fluctuations. This system minimizes human error, increases operational oversight efficiency, and supports regulatory compliance with Clauses 6.3 and 7.5 of ISO/IEC 17025:2017.

KEYWORDS

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1. INTRODUCTION

Companies providing services in the field of instrumentation and calibration are required to commit to providing quality assurance to their customers. Product quality assurance has become one of the main factors to consider in today's highly competitive industrial activities [1]. To ensure global standardization of laboratory competence, the company is committed to referring to the ISO/IEC 17025:2017 standard. Based on ISO/IEC 17025:2017 Clause 6.3, laboratory environmental conditions such as temperature and humidity are critical variables that must be strictly controlled, monitored, and recorded because they directly affect the validity of measurement results and the calculation of uncertainty evaluation (budget uncertainty) in accordance with Clause 7.6 [2]. However, the process of monitoring environmental parameters one of the companies in Indonesia still relies on a conventional system. Daily measurements are manually performed by laboratory personnel by reading an analog thermo-hygrometer three times a day and subsequently recording the results in a paper logbook. This manual system has significant limitations in providing continuous technical records for detecting fluctuation trends occurring between recording intervals. In addition, the periodic physical intervention of operators entering and leaving the room has the potential to affect the stability of environmental parameter values [3]. Manual recording is also susceptible to human error, incorrect numerical transcription, data duplication, and the loss of administrative records due to poorly organized physical archiving systems [4–6]. In previous research in the field of clinical laboratories, it was revealed that 14.2% of total manual transcription errors resulted in extreme numerical deviations above 20% of the original value [7]. The application of IoT-based data logger technology is present as an integrative solution to increase the effectiveness of fulfilling these two clauses. IoT technology has proven effective in supporting the efficient and reliable digitalization of laboratory environmental monitoring systems [8]. The implementation of this technology is also an effective solution to overcome conventional manual monitoring methods which are considered to have limitations, such as non-integrated systems [9].

Previous studies have attempted to address the problem of temperature and humidity monitoring. Syahputra et al. (2023) developed a room monitoring system based on the NodeMCU ESP8266 and DHT11 sensor; however, the system only displayed instantaneous (real-time) data on smartphone screens without providing historical data records (data logging) [10]. Rangan et al. (2020) implemented a chemical laboratory monitoring system using a local MySQL database; however, this architecture was highly dependent on a local PC server that had to remain continuously powered and was not equipped with an offline backup storage medium [11]. Gozal et al. (2026) implemented DHT11 on smart agriculture, but only using cloud storage without backup offline [12]. Similar limitations have also been identified in systems based on local web servers or single wireless platforms, where the risk of data loss remains high in the event of internet network fluctuations or sudden power interruptions.

To address the gaps identified in previous studies, this manuscript proposes a novel integrated monitoring system featuring a dual-logging mechanism based on the ESP32 microcontroller. System reliability is enhanced through the addition of a Micro SD Card module as a local data storage medium (offline backup) in CSV format. Utilizing a memory card (SD card) can be an effective local storage solution to anticipate wireless connection instability [13]. This CSV file is automatically equipped with timestamps generated by an external RTC module and operates in parallel with instant (snapshot) data transmission to the ThingSpeak cloud database. Format CSV has the advantage of a neat data structure and automatic time stamping and this makes it easier for users to open and process the data on a computer using Microsoft Excel [14]. Through a wireless microcontroller, sensor reading data can be transmitted automatically and stored in a structured manner into a database server, so that environmental parameter history can be detected remotely in real-time [15]. In the event of a Wi-Fi connection failure, the local storage mechanism functions as a failsafe to ensure the continuity of 24-hour data recording. The objective of this study is to design, develop, and evaluate the reliability of this IoT-based automatic monitoring system on calibration laboratory. Through the implementation of this technology, the laboratory is expected to provide continuous and valid technical records of environmental conditions to fulfill the causal relationship between Clause 6.3 and Clause 7.5 of the ISO/IEC 17025:2017 standard.

2. RESEARCH METHODS

2.1. Research Framework

The research employed an engineering experimental approach. The stages of the study consisted of preparation and literature review, hardware and data architecture design, physical assembly of components, system programming using the Arduino IDE, configuration of the ThingSpeak cloud platform, and a series of system performance tests. This experimental workflow was systematically designed to validate the performance of the monitoring device before its full implementation in the laboratory.

2.2. Hardware Architecture and Wiring

Cloud based infrastructures are created with various information areas in mind, such as web applications, remote access, remote console, homogeneity strategic planning, data warehousing, statistics, implementation, surveillance, visualizing, and ultimately scientific studies [16]. The hardware architecture of this system is based on a single main microcontroller, namely the ESP32, which processes input from the DHT11 sensor and simultaneously distributes the data to three output components. The interconnection mapping of pins among the main components was designed efficiently to avoid signal noise, as presented in Table 1 [17].

Table 1: ESP32 Pin Mapping with System Components

Component	Component Type	Pin ESP32	Communication Type
Sensor DHT11	VCC, Data, GND	3.3V, GPIO 4, GND	Single-Bus
OLED 0.96"	VCC, GND, SCL, SDA	3.3V, GND, GPIO 22, GPIO 21	I2C
MicroSD Adapter	MISO, MOSI, SCK, CS	GPIO 19, GPIO 23, GPIO 18, GPIO 5	SPI
RTC Module	SDA, SCL	GPIO 21, GPIO 22	I2C Shared

The system receives its primary power supply from a minimum 5 VDC, 1 A adapter connected directly to the ESP32 micro-USB port to maintain long-term operational stability.

2.3. Proposed Dual-Logging Logic

Data processing in the software is managed using a non-blocking system so that the failure of one function does not interfere with other functions. The microcontroller acquires data from the DHT11 sensor and subsequently processes timestamps obtained from the external RTC module.

a. Local Storage

Data are written to the Micro SD Card in a structured CSV format (Columns: Date, Time, Temperature, Temperature Status, Humidity, Humidity Status) with a sampling interval of every five minutes. The program ensures that the file is opened, written, and immediately closed during each cycle to prevent file corruption. SD Card is able to support monitoring system effectively [18].

b. Cloud Storage

In this research cloud storage using ThingSpeak, this platform can be used as an open source which functions to run applications and API [19]. Wireless transmission to the ThingSpeak server is scheduled at one-minute intervals. The transmitted data consist of instantaneous (snapshot) data corresponding to the current minute. Access to the cloud database is secured using a private mode through Write API Key authentication. The ThingSpeak interface is capable of displaying the most recent sensor reading data and presents a graphical sensor reading complete with information on the reading time [20].

2.4. Experimental Setup and Evaluation Metrics

System reliability testing was continuously conducted for a period of seven (7) days directly inside the Calibration Laboratory one of the companies in Indonesia. System performance was evaluated through five primary metrics: Electrical functionality testing (Black Box Testing); Local storage capability testing (offline logging); Wireless connectivity testing (latency and packet loss); Multi-interface data synchronization validity testing; and Twenty-four-hour operational endurance testing (stress test).

3. RESULTS AND DISCUSSION

3.1. System Realization and Functionality Test

The physical implementation of the IoT-based temperature and humidity monitoring system was successfully realized as an integrated standalone device. Functionality testing using the Black Box Testing method was conducted to ensure the reliability of the electrical interactions among all constituent components. Based on the functionality testing checklist, all circuit blocks, including DHT11 sensor reading, Micro SD SPI initialization, OLED I2C communication, and Wi-Fi data transmission, demonstrated a 100% success rate with normal operational status.

3.2. Data Logging Capability Analysis (Local Storage)

The local data logging feature was tested to validate the performance of the Micro SD Card module as a backup storage medium during offline conditions. The recorded data samples were successfully organized in a neat and structured CSV format. An example of the recorded log data is presented in Table 2.

Table 2: Sample Data Logging Results in Local Micro SD Storage

Date	Time	Temperature (°C)	Temperature Status	Humidity (%)	Humidity Status
07/05/2026	01:00:50	26.6	Good	74	Wet
07/05/2026	01:05:51	26.6	Good	74	Wet
07/05/2026	01:10:52	26.6	Good	74	Wet

Throughout the seven-day testing period, the system successfully performed continuous writing operations without experiencing memory failure issues. The program logic, which immediately closes the file after the writing process, proved effective in maintaining the integrity of textual data against the risk of data loss caused by power supply fluctuations.

3.3. IoT Connectivity and Cloud Transmission Test

Wireless connectivity testing was conducted to evaluate the stability of snapshot data transmission to the ThingSpeak dashboard. The performance of the laboratory Wi-Fi network was analyzed based on latency (response time) and packet loss (the percentage of data packets lost during transmission).

Table 3: Sample Data Logging Results on ThingSpeak Storage

Timestamp	Temperature	Humidity
2026-05-07 23:53:07	23,0	58
2026-05-07 23:54:11	22,9	58
2026-05-07 23:55:20	23,0	58

The transmission data calculations indicated an average update latency of 68.96 seconds to reach the cloud server. Meanwhile, packet loss testing recorded an average value of 12.39%, confirming that the wireless infrastructure in the laboratory area was capable of consistently supporting periodic data transmission every one minute.

3.4. Data Validity and Multi-Interface Consistency

The validity metric was evaluated by comparing parameter values simultaneously displayed across three visualization interfaces: the physical OLED display, the local storage file (.CSV), and the online ThingSpeak dashboard graphs. The comparison results demonstrated perfect data synchronization.

Table 4: Sample Results of the Multi-Interface Validity Test

No.	Testing Time	Sensor Parameter	Value Reading OLED (D_{Acuan})	Value SD Card (D_{Uji})	% Validity (V_d)	Status
1	02/06/2026 19:18	Temperature (°C)	27.5	27.5	100.0	Valid
		Humidity (%RH)	80.0	81.0	98.8	Valid
2	02/06/2026 19:23	Temperature (°C)	27.5	27.5	100.0	Valid
		Humidity (%RH)	78.0	78.0	100.0	Valid
3	02/06/2026 19:28	Temperature (°C)	27.5	27.5	100.0	Valid
		Humidity (%RH)	78.0	78.0	100.0	Valid

The numerical values of temperature and humidity displayed on the OLED were proven to be identical to the raw data stored on the Micro SD Card. Likewise, the snapshot data appearing in the ThingSpeak time-series charts showed precise correspondence with the current-minute data stored locally. This synchronization ensures that there are no numerical deviations or information distortions within the internal system.

3.5. Durability and Stability Analysis (Stress Test)

The system was operated in a fully active mode (continuous active/standby) without sleep mode for a continuous period of 24 hours to evaluate the thermal endurance and logical stability of the microcontroller under constant workloads. The 24-hour monitoring results indicated that the system was capable of maintaining stable data acquisition without experiencing hanging or crashing phenomena. The physical temperature measurements on the ESP32 chip surface after continuous operation showed that the device temperature remained within the normal operating range. These results demonstrate that the 5 V power supply scheme through the micro-USB interface was capable of providing a constant current supply without triggering excessive heat (overheating).

3.6. Discussion

The implementation of this IoT-based temperature and humidity monitoring system effectively addresses the fundamental limitations of the conventional methods previously employed in the calibration laboratory. The system's success in achieving a 100% functionality rate and maintaining synchronized data validity across three interfaces (the physical OLED display, local storage, and the cloud dashboard) demonstrates that the ESP32 and DHT11 architecture is highly reliable for continuous environmental data acquisition. These findings directly respond to the challenges of complying with Clauses 6.3 and 7.5 of the ISO/IEC 17025:2017 standard, where the need for continuous, human-intervention-free technical records is critical. By eliminating the manual thrice-daily recording process, this system not only minimizes the risk of transcription errors and data duplication but also captures environmental parameter fluctuations between intervals that were previously unrecorded, thereby providing actual, high-resolution data that is highly valuable for measurement uncertainty budget calculations.
The primary advantage of this research lies in the application of a dual-logging mechanism, which serves as a robust risk mitigation strategy. Unlike previous studies that relied heavily on continuous internet connectivity or a single local server, the integration of a Micro SD Card module as a local backup (offline storage) recording data in CSV format every 5 minutes, running parallel to the 1-minute transmission to the ThingSpeak cloud, creates a system resilient to infrastructure disruptions. The connectivity test results, which recorded an average packet loss of 12.39%, actually underscore the urgency of this local storage feature; without the Micro SD Card, this percentage of data loss would create significant gaps in the laboratory's technical records. Furthermore, the generated CSV format offers high practical value, allowing laboratory personnel to easily process historical data using standard spreadsheet software without requiring specialized programming skills, while simultaneously guaranteeing data integrity through precise timestamps provided by an external RTC module.
Although the system has proven its stability and endurance during a 24-hour operational stress test without experiencing overheating or logical failures, there are inherent limitations that must be considered for future development. The use of the DHT11 sensor, while highly cost-effective and easy to integrate, possesses lower accuracy and resolution compared to industrial-grade sensors such as the DHT22 or SHT31. Given the context of its application in a calibration laboratory that demands high precision, upgrading the sensor specifications in future iterations is highly recommended to meet stricter metrological tolerances. Nevertheless, overall, this prototype has successfully demonstrated that the digitalization of environmental monitoring through an IoT approach with a dual-storage architecture is a scalable, efficient, and highly relevant solution for enhancing quality assurance standards in modern calibration facilities.

4. CONCLUSION

The design and implementation of an automatic, IoT-based temperature and humidity monitoring system have been successfully realized and validated within a calibration laboratory environment. Utilizing an ESP32 microcontroller and a DHT11 sensor, the standalone system demonstrated high reliability and performance, effectively replacing error-prone manual recording methods with continuous, automated environmental data acquisition. A key achievement of this study is the successful implementation of a dual-logging mechanism that guarantees the integrity and continuity of technical records. The ThingSpeak cloud platform provides efficient, real-time remote visualization of environmental trends, while the Micro SD Card module serves as a highly reliable local failsafe. This offline logging capability prevents data loss during network fluctuations, ensuring uninterrupted monitoring. Furthermore, the generation of structured CSV data files offers significant practical value for laboratory management, directly facilitating regulatory compliance with Clauses 6.3 and 7.5 of the ISO/IEC 17025:2017 standard by providing accurate, historical fluctuation data essential for measurement uncertainty evaluations. Ultimately, this system proves to be a scalable, cost-effective, and robust solution for modernizing laboratory environmental monitoring. It significantly enhances operational oversight, minimizes the risk of human error, and strengthens overall quality assurance protocols in calibration facilities.

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Author Contributions:
Ryan Franki Risdianto: Conceptualization, Methodology, Software, Writing – Original Draft.
Jendra Sesoca: Primary Supervisor.
Bayu Firmanto: Co-Supervisor.

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AI Use Statement:
During the preparation of this manuscript, the authors used Gemini solely for language refinement and readability improvement and used ChatGPT as an assistant for programming support in the Arduino IDE, including code suggestions, debugging assistance, and code optimization. All scientific content, analysis, interpretations, conclusions, and final program implementations were developed, verified, and validated by the authors. Following the use of these tools, the authors carefully reviewed and edited the manuscript and assume full responsibility for the content of the published article.

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