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DESIGN OF AN IOT-BASED TEMPERATURE AND HUMIDITY MONITORING SYSTEM FOR EFFICIENT HVAC DATA COLLECTION IN AIRPORT

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Abstract

The Airport Authority enforces thermal comfort regulations under Government Regulation PM 41 of 2023, which requires room temperatures to be maintained below 25°C in check-in areas, departure lounges, and baggage claims. However, temperature and humidity are recorded manually at Juanda International Airport, Surabaya. This research aims to develop an IoT-based system for real-time environmental monitoring and automated server logging. Using a Level 3 R&D approach with the ADDIE model and Focus Group Discussion (FGD) validation, the system was tested. It achieved a standard temperature deviation of 0.3162°C and a humidity deviation of 0.733% relative humidity (RH), meeting the requirements of ISO/IEC 17025 standards. The system streams data to Google Sheets, Blynk, and a custom web interface. Expert evaluations gave the system an average feasibility score of 86.76%, categorizing it as "Very Feasible." These findings demonstrate the system's accuracy, reliability, and potential for efficient airport HVAC monitoring and control.

Keywords: *temperature, monitoring, datasheet, internet of thing*

Introduction

The dynamic operations at Juanda International Airport are shaped by fluctuations in passenger arrivals, departures, and transits, especially during holiday seasons and schedule changes. These fluctuations influence the effectiveness of service capacity planning, particularly the performance of Heating, Ventilation, and Air Conditioning (HVAC) systems. Maintaining optimal temperature and humidity is critical not only for passenger comfort but also for their health, as excessive humidity variations can lead to respiratory issues, fatigue, and irritation (Mushaithir & Muttaqi, 2019). Currently, HVAC technicians at Terminal 1 manually monitor environmental conditions across a 91,700 m² area three times daily. This approach is labor-intensive, lacks responsiveness to rapid thermal changes, and delays fault detection, such as duct leaks or reduced cooling performance due to aging infrastructure. Consequently, the existing protocol may delay fault detection and impair the overall efficacy of preventive maintenance.

Automated environmental sensing frameworks offer a robust template for enhancing both spatial coverage and temporal resolution of temperature and humidity surveillance (Arnas et al., 2023; Ridho'i et al., 2023; Silalahi et al., 2021). For example, a NodeMCU ESP8266–DHT11–Blynk system supplanted manual sampling at 25 discrete nodes every two hours, significantly reducing operational overhead without compromising measurement fidelity (Arnas et al., 2023). Similarly, LM35 and DHT22 sensors integrated with an Arduino web interface autonomously regulated a DC fan actuator when temperature thresholds were exceeded, thereby safeguarding pharmaceutical production integrity (Silalahi et al., 2021).

In agronomic applications, an ESP32–DHT22–Blynk platform maintained oyster mushroom cultivation chambers at 28 °C and 60 % RH through real-time remote monitoring and actuation of exhaust fans and pumps (Ridho'i et al., 2023). Collectively, these studies substantiate that low-cost IoT architectures underpinned by microcontroller-sensor arrays and real-time visualization can dramatically improve monitoring efficiency, anomaly responsiveness, and preventive maintenance protocols, capabilities that, if adapted to Juanda Airport's HVAC infrastructure, would markedly enhance system reliability and operational sustainability.

Previous studies have also developed IoT-based temperature and humidity monitoring systems that illustrate key hardware–software integrations. Yet, they fall short of meeting the stringent requirements of airport environments. For instance, Satria (2022) Implemented a NodeMCU ESP8266–DHT11 array interfaced with the Blynk application to deliver real-time environmental readings to smartphones, demonstrating reliable data transmission and user-friendly dashboards. Similarly, Akbar & Sugeng (2021) designed a WeMos D1 ESP8266–DHT11–MC-38 module for pharmaceutical storage monitoring, achieving continuous data logging via Blynk and rapid alerting capabilities. Meanwhile, Hidayat & Sari (2021) employed a NodeMCU ESP8266–DHT11 setup supplemented by an OLED display and buzzer alarm to maintain indoor comfort levels, with automatic notifications when predefined thresholds (40 °C) were exceeded. However, these solutions have not been validated under airport terminals' high-occupancy, regulatory-driven conditions, which demand integrated platforms, full compliance with service standards, and uninterrupted data capture.

This study aims to develop an IoT-based prototype using DHT22 and MQ-135 sensors for real-time temperature, humidity, and air quality monitoring, with automatic data transmission to cloud servers and local displays. The research employs a Level 3 R&D approach, utilizing the ADDIE model, and validates the system through Focus Group Discussions (FGDs) and statistical testing. Results demonstrate compliance with ISO/IEC 17025 (Muthmainnah et al., 2023; Muthmainnah & Tabriawan, 2022). Implementing this project is hoped to increase high power efficiency and practical feasibility, confirming the system's potential for improving preventive maintenance, enhancing operational efficiency, and advancing digital transformation in airport facilities.

Methods

This research employs the Level 3 Research and Development (R&D) method, focusing on the innovation of IoT-based temperature monitoring tool prototypes, enabling systematic product development and testing. The model used is ADDIE, consisting of five stages: analysis, design, development, implementation, and evaluation, with the advantages of evaluation at each stage to minimize errors in development. This model allows for continuous improvement based on feedback, making it ideal for the development of an automated temperature and humidity monitoring system to improve operational efficiency at Juanda International Airport Surabaya (Suandri & Hais., 2023).

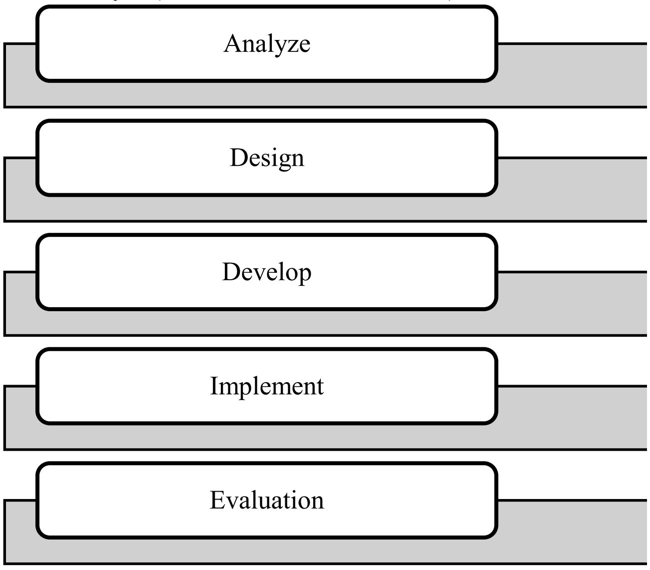

Figure 1. Steps of the ADDIE Model

This research was conducted in the dormitory of Palembang Aviation Polytechnic for one semester, or approximately 6 months. This research begins with the definition stage, which involves conducting a literature study to collect relevant theories and concepts from various sources, such as books and journals. This stage aims to identify problems in temperature and humidity monitoring within the airport environment, determine research objectives to address these issues with IoT-based temperature monitoring system innovations, and formulate the appropriate system design based on theoretical analysis, which serves as the basis for concept formulation.

The next stage is the Design stage, where the initial design of the product or prototype is developed. It involves creating a flowchart or framework that serves as a guide for product development and product design. The design stage focuses on aligning the product with the identified problems and research objectives to ensure its relevance and feasibility for further development. The assessment of expert validation analysis with quantitative methods uses the following table assessment:

$$P = \frac{N}{f} \text{ x } 100\%$$

Description:
P = Percentage
N = Score obtained
F = Maximum score

Table 1. Validation Criteria

Score (%)	Eligibility Category
<21 %	Very Unworthy
21 – 40 %	Not eligible
41 – 60 %	Quite Decent
61 – 80 %	Appropriate
81 – 100 %	Highly Worthy

After undergoing the validation process with experts, the input and suggestions received will serve as a reference for developing the next tool prototype. Furthermore, the prototype will be retested and evaluated upon completion of the prototype product.

Results and Discussion

This automatic temperature and humidity monitoring system is designed to measure and monitor environmental conditions in the airport terminal area in real-time. This tool aims to ensure passenger comfort, maintain optimal facility conditions, and support airport operational standards in managing indoor air quality. The prototype has three main categories of indicators: smart monitoring system design, environmental data analysis, and application-based monitoring. In the design of smart monitoring systems, the indicators include sensor accuracy, energy efficiency, data storage, IoT integration, ease of use, and system reliability. Environmental data analysis focuses on recording temperature and humidity change patterns and providing early warnings in the event of extreme conditions that could affect comfort or safety. Meanwhile, application-based monitoring enables real-time data and notifications to airport operators, ensuring responsive actions in response to changing environmental conditions. In airport operations, unstable temperatures and humidity can impact various aspects, including passenger comfort, the condition of electronic equipment, and the efficiency of the HVAC conditioning system. Therefore, this system is designed to assist airport managers in optimizing temperature and humidity regulation according to aviation regulations and public convenience.

The sensors used in this study include DHT22 to detect temperature and humidity, ESP32 as the main controller, and a WiFi-based communication module to transmit data to the monitoring platform. The collected data will be displayed in real-time on the Blynk app, allowing operators to monitor environmental conditions in real time. If the temperature reaches 25°C or more, the system will automatically notify Blynk. In addition, temperature and humidity data is periodically recapped into Google Sheets as a basis for further recording and analysis. Through this innovation, the automatic temperature and humidity monitoring system is expected to support smarter, more efficient, and adaptive management of the airport terminal environment to the needs of flight operations.

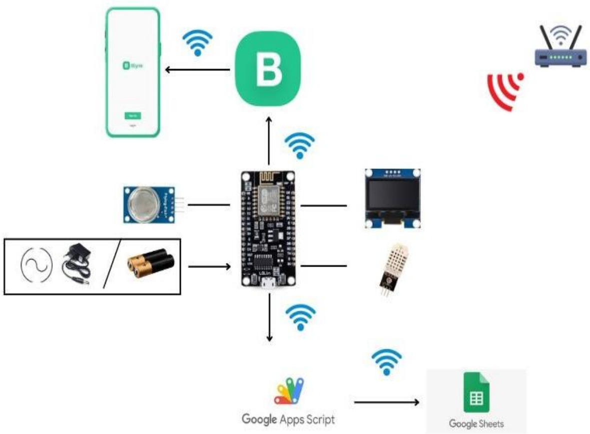

Figure 2. Illustration of Temperature Monitoring Prototype Work

The process begins with the initialization of the ESP32 to read data from the DHT22 sensor, which measures temperature and humidity, as well as the MQ135 sensor, which detects carbon levels in the air. The data from these sensors is immediately displayed on the OLED LCD screen. Next, the ESP32 will attempt to connect to the Wi-Fi network using its internal Wi-Fi module. If the connection fails, the ESP32 will repeat the process until it is successfully connected. Once successfully connected, the data is sent to Blynk's servers and Google Sheets for further processing. In Google Sheets, temperature and humidity data is stored with data capture settings at specific time intervals, while in Blynk's servers, data is sent every 2 seconds for real-time monitoring purposes, equipped with a chart feature to monitor sensor data fluctuations.

The servers support integration with multiple sensor devices, enabling monitoring across multiple locations and sectors. Alert notifications are sent to technicians when the temperature exceeds a specified threshold, allowing for a quick and effective response. This process ensures accurate and timely monitoring and provides valuable historical data for further analysis, improving operational efficiency and responsiveness in managing monitored environmental conditions.

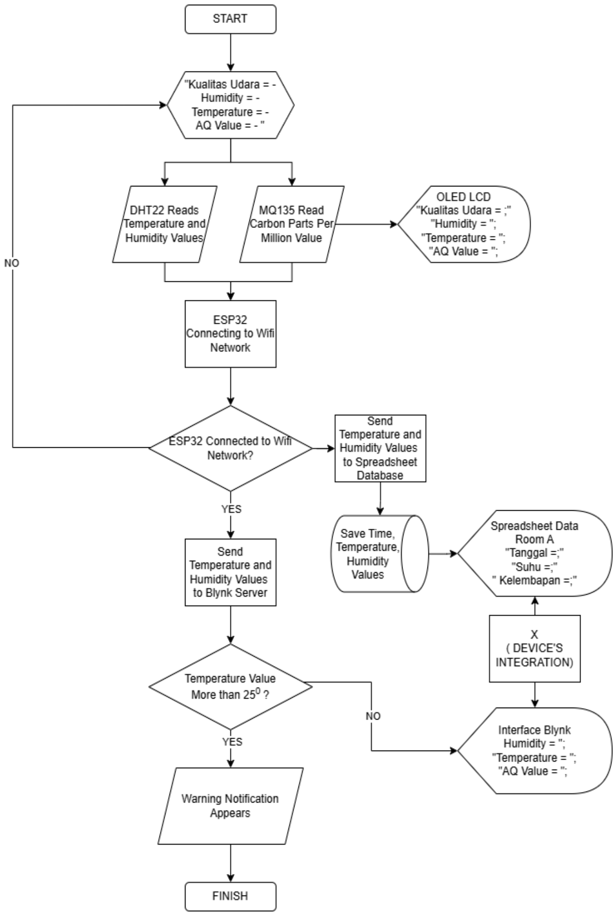

Figure 3. Workflow Diagram

Figures 2 and 3 show the prototype design of our proposed IoT-based temperature and humidity monitoring system for Juanda International Airport Surabaya. This system was developed to improve the efficiency of temperature monitoring in the check-in area, departure lounge, and baggage claim area to ensure comfort standards (< 25°C) following PM 41 of 2023. The technology implemented in this system includes temperature and humidity sensors connected to the ESP32 microcontroller, allowing for automatic measurement and data logging. The data is sent to Blynk cloud servers and Google Sheets, allowing HVAC technicians to access it in real-time. With this system, temperature and humidity monitoring can be carried out more accurately and efficiently than the manual methods.

In addition, this system allows periodic data recording with a neatly arranged format in Sheets, where sheets will automatically add every turn of the day to facilitate long-term data analysis. Integration with Blynk also alerts technicians if the temperature or humidity exceeds a set threshold. With the implementation of this system, it is hoped that temperature and humidity management in the terminal will be more structured, supporting passenger comfort and enabling the airport to meet service standards effectively and efficiently.

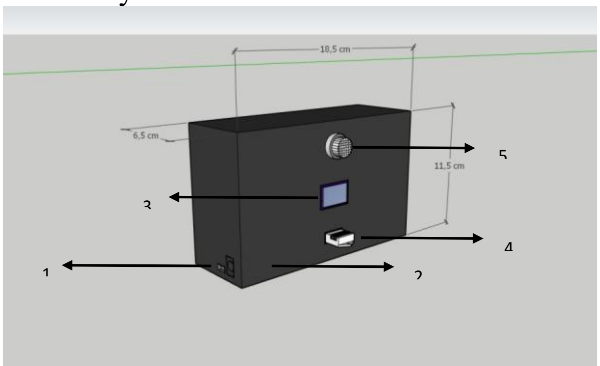

Figure 4. Front View Prototype

Figure 4 shows the prototype specifications: 1) ESP 32 ports, 2) microcontroller box with dimensions of 16.5 cm x 11.5 cm x 6.5 cm, 3) OLED LCD I2C, 4) DHT 22, and 5) MQ 135. It has a simple design for easier installation and maintenance, as shown in Figure 5.

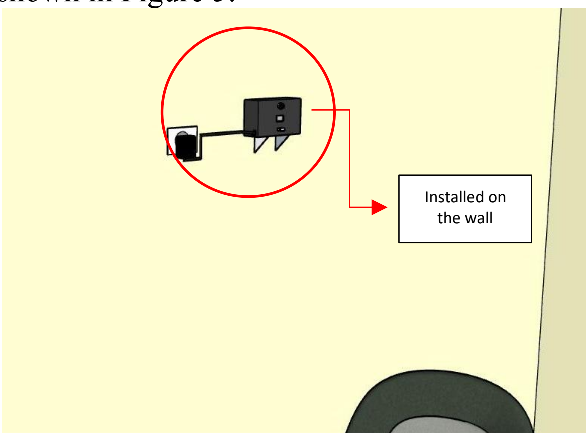

Figure 5. Prototype Installation Display

Table 2 presents the components used in the design of the IoT-based temperature and humidity monitoring tool model, along with the functions of each component. The ESP32 serves as the primary controller, regulating the sensors and motors within the system. The power source of this appliance is a 9 VDC power supply adapter, ensuring a stable energy supply. To expand the capacity of the input/output pins and increase flexibility in component installation, the Expansion ESP32

Shield and ESP32 Doit V1 30P Base Plate Extension are used.

The DHT22 sensor is used to accurately obtain temperature and humidity values, while the MQ-135 sensor detects carbon concentrations in the air, providing information related to air quality in the monitoring environment. The measurement results of these sensors are displayed via an I2C OLED LCD, which serves as a visual interface for the user. In addition to the local display, temperature and humidity data is automatically sent and saved to the Spreadsheet Server, which serves as a database and a medium for further data processing. The system is connected to the Blynk Server for remote monitoring, allowing users to access and monitor sensor data in real-time from a specific location. Integrating all these components creates an efficient temperature and humidity monitoring system, supports more accurate data analysis, and increases effectiveness in HVAC system management.

Table 2. Components of IoT-based

Component	Function
ESP32	Sensor and motor controllers
Power Supply Adaptor 9 VDC	Electrical energy source
Expansion ESP32Shield ESP32 Doit V1 30P Base Plate Extension	Expanding input/output pins and control mounting frames
DHT 22 (Temperature and Humidity Sensor)	Obtaining temperature and humidity values
MQ – 135 (Quality/airborne particle sensor)	Obtaining the concentration of carbon in the air (air quality)
OLED LCD I2C	Displaying variable interfaces of acquired sensors
Spreadsheet Server	As a database of temperature and humidity values and data processing
Blynk Server	Function of monitoring the variable values of sensors from a certain distance

At the validation test stage, validators assess various aspects to ensure that this IoT-based temperature monitoring system is feasible to use (Ramadhani et al., 2024). This assessment includes technical, functional, and system integration aspects to evaluate the tool's accuracy, reliability, and ease of use. The testing process involves validators with IoT, sensors, and information systems expertise. Each validator provides an assessment based on their competencies to ensure that this temperature monitoring system meets the required standards in measurement accuracy, data transmission reliability, and ease of integration with platforms such as Blynk and Google Sheets.

Table 3. Design Validation (Expert Validators)

No	Assessment Aspects	Percentage	Criterion
1	System Performance and Reliability	90%	Highly Worthy
2	Ease of Use and Management	87.91%	Highly Worthy
3	Implementation and Potential Use at Airports	78.89%	Appropriate
Average		85.60%	Highly Worthy

The results of the validation test show that this IoT-based temperature monitoring system received a score of 85.60% (highly worth).

Table 4. Design Validation (Engineering Experts)

No	Assessment Aspects	Percentage	Criterion
1	System Performance and Reliability	88%	Highly Worthy
2	Ease of Use and Management	89.07%	Highly Worthy
3	Implementation and Potential Use at Airports	86.67%	Highly Worthy
		87.91%	Highly Worthy

The results of the validation test indicate that this IoT-based temperature monitoring system achieved scores of 85.60% from IoT Expert validators and 87.91% from Information System validators (Amalia et al., 2024; Ulfa, 2021). Thus, an average score of 86.76% was obtained. Based on these results, this temperature monitoring system is categorized as "Very Feasible" for use in temperature and humidity monitoring within the airport environment. It has the potential to enhance the efficiency of HVAC system management.

The system test is carried out through simulation and thorough testing using basic statistical methods. Measurements were taken five times using the prototype tool and compared with those from the reference tool (DHT22). The mean value ($\bar{x}$) is used to determine the middle value of the data, while the standard deviation and standard deviation (SD) describes the data distribution and variability of the measurement (Muthmainnah et al., 2023; Muthmainnah & Tabriawan, 2022). The error percentage is calculated to assess the relative differences between the prototype results and the reference tool, thereby indicating the tool's accuracy. This method has been widely used in scientific research and engineering to ensure the reliability and validity of measuring instruments (Yazid et al., 2023). This process involves measuring the temperature of the prototype and comparing it with a reference measuring instrument. In this test, the HTC-2 Hygrometer Thermometer serves as a reference measuring tool to ensure the accuracy and reliability of the temperature measurement results.

Table 5. Temperature Testing

Trial No.	Tool Prototype Temperature (^{0C})	HTC-2 Temperature Thermometer Hygrometer (^{0C})	Difference
1	24,9	24,7	0,2
2	24,7	24,7	0
3	24,5	25,0	0,5
4	24,3	24,6	0,3
5	25,1	25,2	0,1

Subsequently, the percentage error provides a measure of the relative deviation between two measurements. It indicates the extent to which the prototype's measurement deviates from the reference instrument, expressed as a percentage of the reference instrument's measurement. The formula used to calculate the percentage error for each trial is as follows:

Percentage Error = $\left|\frac{T_p - T_r}{T_r}\right| x\ 100\%$

Table 6. Error Percentage of Temperature for Each Trial between the Prototype and Reference Instrument

Trial No.	Percentage Error
1	0,43%
2	1,71%
3	2,00%
4	1,22%
5	0,40%
Average Error	1,15%

The mean is the middle value of a group of data. To calculate the average, add up all the values and divide by the amount of data.

For Tool Prototype Temperature (T_p):

$\overline{T}_p = \frac{24{,}9 + 24{,}7 + 24{,}5 + 24{,}3 + 25{,}1}{5} = \frac{123{,}5}{5} =$ 24,7 ^{0C}

For HTC-2 Temperature Thermometer Hygrometer (T_r):

$\overline{T}_r = \frac{24{,}7 + 24{,}7 + 25{,}0 + 24{,}6 + 25{,}2}{5} = \frac{124{,}2}{5} =$ 24,84 ^{0}C

Furthermore, the Deviation shows how far each value is from the average. To calculate this, subtract the average from each data value.

Here is a formula to find the deviation from the average Temperature of the Prototype of the Tool and the temperature of the HTC-2 Thermometer Hygrometer:

Prototype Junction = $T_p - \overline{T}_p$

Reference Deviation = $T_r - \overline{T}_r$

Table 7. Deviation Table between the Prototype and Reference Instrument Temperature

Trial No.	Prototype Deviation ($T_p - \overline{T}_p$)	Reference Deviation ($T_r - \overline{T}_r$)
1	24,9 - 24,7 = 0,2	24,7 - 24,84 = -0,14
2	24,7 - 24,7 = 0	24,7 - 24,84 = -0,14
3	24,5 - 24,7 = -0,2	25,0 - 24,84 = 0,16
4	24,3 - 24,7 = -0,4	24,6 - 24,84 = -0,24
5	25,1 - 24,7 = 0,4	25,2 - 24,84 = 0,36

Next, the Standard deviation calculation is a measure of how scattered the data is from the mean. Smaller values indicate more consistent data, while larger values indicate more variation.

$$\mathrm{SD} = \sqrt{\frac{\sum_{i=1}^{n}(\mathrm{Tp.i} - \bar{\mathrm{T}}_{\mathrm{p}})^2}{n-1}}$$

$$\mathrm{SD} = \sqrt{\frac{(0{,}2)^2+(0)^2+(-0{,}2)^2+(-0{,}4)^2+(0{,}4)^2}{5-1}}$$

$$\mathrm{SD} = \sqrt{\frac{0{,}04+0+0{,}04+0{,}16+0{,}16}{4}}$$

$$\mathrm{SD} = \sqrt{\frac{0{,}4}{4}}$$

$$\mathrm{SD} = \sqrt{0.1}$$

$$\mathrm{SD} = 0.3162 \ ^{\circ}\mathrm{C}$$

Humidity testing aims to determine the level of conformity of humidity to the desired standard. This process involves measuring the humidity on the prototype and comparing it to a reference measurement instrument. In this test, the HTC-2 Hygrometer Thermometer serves as a reference measuring tool to ensure the accuracy and reliability of the humidity measurement results.

Table 8. Humidity Testing Table for the Prototype and Reference Instrument

Trial No.	Equipment Prototype Humidity (%)	Humidity HTC-2 Thermometer Hygrometer (%)	Difference
1	51,7	50	1,7
2	50,4	50	0,4
3	49,9	51	1,1
4	50,1	51	0,9
5	51,0	50	1,0

Subsequently, the percentage error provides a measure of the relative deviation between two measurements. It indicates the extent to which the prototype's measurement deviates from the reference instrument, expressed as a percentage of the reference instrument's measurement. The formula used to calculate the percentage error for each trial is as follows:

Percentage Error = $\left|\frac{H_p - H_r}{H_r}\right| \ x \ 100\%$

Table 9. Error Percentage of Humidity for Each Trial between the Prototype and Reference Instrument

Trial No.	Percentage Error
1	3,4 %
2	0,8 %
3	2,16 %
4	1,76 %
5	2,0 %
Average Error	2,02 %.

The mean is the middle value of a group of data. To calculate the average, add up all the values and divide by the number of data points. For the Moisture Prototype Tool (H_p):

$\bar{H}_p = \frac{51{,}7+50{,}4+49{,}9+50{,}1+51{,}0}{5} = \frac{253{,}1}{5} = 50{,}62$ %

For HTC-2 Temperature Thermometer Hygrometer (H_r):

$\bar{H}_r = \frac{50+50+51+51+50}{5} = \frac{252}{5} = 50{,}4$ %

Furthermore, the Deviation shows how far each value is from the average. To calculate this, subtract the average from each data value. Here is a formula to find the deviation from the average Temperature of the Prototype of the Tool and the temperature of the HTC-2 Thermometer Hygrometer:

Prototype Junction = $H_p - \bar{H}_p$

Reference Deviation = $H_r - \bar{H}_r$

Table 10. Deviation Table between the Prototype and Reference Instrument Humidity

Measurement to-	Prototype Deviation $(\mathbf{H_p - \bar{H}_p})$	Reference Deviation $(\mathbf{H_r - \bar{H}_r})$
1	51,7 – 50,62 = 1,08	50 – 50,4 = -0,4
2	50,4 – 50,62 = -0,22	50 – 50,4 = -0,4
3	49,9 – 50,62 = -0,72	51 – 50,4 = 0,6
4	50,1 – 50,62 = -0,52	51 – 50,4 = 0,6
5	51,0 – 50,62 = 0,38	50 – 50,4 = -0,4

Next, the standard deviation calculation measures how scattered the data is from the mean. Smaller values indicate more consistent data, while larger values indicate more variation.

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(Hp.i - \bar{H}_p)^2}{n-1}}$$

$$SD = \sqrt{\frac{(1{,}08)^2+(-0{,}22)^2+(0{,}72)^2+(-0{,}52)^2+(0{,}38)^2}{5-1}}$$

$$SD = \sqrt{\frac{1{,}17+0{,}05+0{,}52+0{,}27+0{,}14}{4}}$$

$$SD = \sqrt{\frac{2{,}15}{4}}$$

$$SD = \sqrt{0{,}5375}$$
$$SD = 0{,}733\ \%$$

In initial testing, our prototype demonstrated a temperature measurement standard deviation of 0.3162 °C, well below the 1 °C threshold, and a humidity measurement standard deviation of 0.733 % RH, well below the 5 % RH threshold, indicating that its DHT22 sensor not only meets but exceeds recommended accuracy specifications. Across five independent trials, the system achieved mean percentage errors of 1.15% for temperature and 2.02% for humidity. Furthermore, IoT expert validators awarded the prototype an average feasibility score of 86.76%, classifying it as "Very Feasible." These results collectively substantiate the precision, reliability, and practical viability of the system for real-time environmental monitoring.

The present IoT-based temperature and humidity monitoring system builds upon a lineage of environmental sensing prototypes (Pujianto & Fadlilah, 2023) and demonstrates clear advantages over specific prior implementations. For instance, the Wemos D1 R1/DHT11-based module, which employed IR-controlled air-conditioning and local LCD/Android logging (Deswar & Pradana, 2021), and the ESP32 platform integrating DHT22, DS18B20, and soil moisture sensors with SD-card backup (Thoriq et al., 2022)Both required substantial hardware complexity and manual data offloading. Likewise, the DHT22-driven device used in oyster mushroom cultivation achieved temperature errors as low as 0.33 °C and humidity errors within ±2 % RH (Wibowo et al., 2021) but lacked cloud-native reporting. In contrast, our system utilizes the Blynk platform and Google Sheets to deliver continuous, remote, and serverless data streaming, thereby minimizing points of failure and human intervention while maintaining measurement accuracy (mean errors of 1.15% for temperature and 2.02% for humidity).

Arnas et al., (2023) demonstrated that an IoT-driven solution using NodeMCU and DHT11 sensors greatly enhanced monitoring efficiency and spatial coverage in airport terminals. Ridho'i et al., (2023) designed an ESP32-based system that maintained 28 °C and 60 % RH via DHT22 sensing and Blynk-controlled exhaust and pump operations for oyster mushroom cultivation, illustrating reliable remote climate management. Silalahi et al., (2021) Implemented an Arduino-ESP8266 web-based IoT network with LM35 and DHT22 sensors, plus automatic fan activation to regulate environmental conditions in non-sterile pharmaceutical production rooms precisely. Kusumah et al., (2023) deployed a DHT11-based IoT device—augmented with a water-level sensor and OLED interface—in data centers, achieving minimal error rates of 1.7 % for temperature and 2.1 % for humidity. Collectively, these studies confirm the feasibility and advantages of IoT-based environmental monitoring (Amalia et al., 2022; Arnas et al., 2023; Kusumah et al., 2023; Ridho'i et al., 2023; Silalahi et al., 2021), directly informing our development of a real-time temperature and humidity monitoring prototype tailored to airport HVAC management.

Conclusion

This study successfully developed and implemented a prototype of an IoT-based automatic temperature and humidity monitoring system at Terminal 1 of Juanda International Airport Surabaya. Designed to enhance environmental control and operational efficiency, the system integrates the DHT22 sensor and ESP32 microcontroller for real-time data acquisition and transmission. Data is automatically logged to Google Sheets and visualized through the Blynk mobile platform, enabling continuous remote monitoring. Employing the ADDIE-based R&D methodology, the system underwent full-cycle development—from analysis to evaluation. Test results indicate high accuracy and reliability in detecting environmental fluctuations, offering significant improvements over the manual monitoring process, which is labor-intensive, infrequent, and vulnerable to delayed fault detection. Despite its advantages, the current single-node architecture presents limitations in scalability and resilience, particularly under network disruptions. Furthermore, the reliance on third-party cloud services raises concerns about data privacy, and the system's energy efficiency has not yet been optimized for long-term, off-grid use. Future research should focus on deploying multi-node systems across larger terminal areas, supported by centralized dashboards for predictive maintenance and climate control. Integrating renewable energy sources, such as photovoltaic modules, can improve operational autonomy, while edge computing for on-device anomaly detection may reduce system latency and network dependency. These enhancements are crucial for establishing a scalable, secure, and robust IoT ecosystem for smart airport environmental management.

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