IoT-Based Remote Temperature Monitoring System for Industrial Applications

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ARTICLE INFO

Article history:
Received 22 Maret 2025
Received in revised form
10 April 2025
Accepted 20 Mei 2026
Available online 30 Juni 2026

Keywords:
Temperature Monitoring
ESP 32
Web Dashboard
Internet of Things

ABSTRACT

The rapid development of the Internet of Things (IoT) has significantly improved industrial monitoring systems by enabling real-time data acquisition and remote accessibility. Temperature monitoring is an important aspect of industrial operations because temperature variations may affect product quality, equipment performance, and operational safety. This study presents the design and implementation of an IoT-based remote temperature monitoring using an ESP32 microcontroller and MAX6675 thermocouple interface modules coupled with K-type thermocouples. The proposed system acquires temperature data from multiple monitoring locations and transmits the collected information to a centralized server through a Wi-Fi network using the HTTP/REST protocol. A custom web-based dashboard was developed using Node.js, Express.js, MySQL, and Bootstrap frameworks to provide real-time visualization, historical data storage, and automated notification services through Telegram and email. Experimental evaluation was conducted over fourteen consecutive days with a total of 2,236 recorded temperature samples. The performance of the proposed system was assessed using statistical parameters including average temperature, standard deviation, data availability, and transmission success rate. Experimental results indicate that the system achieved a data availability of 99.7%, a successful transmission rate of 99.7%, and stable temperature measurements with a standard deviation below 1°C. The notification mechanism successfully delivered warning messages within 15 seconds after abnormal temperature conditions were detected. The developed system offers a low-cost, scalable, and reliable solution for industrial and small-to-medium enterprise applications requiring continuous temperature monitoring.

1 Introduction

The Industry 4.0 era demands digital transformation across various sectors, including monitoring physical parameters such as temperature. In the food, pharmaceutical, and storage industries, uncontrolled temperature fluctuations can lead to decreased product quality, material loss, and even harm to consumers. Data from the Indonesian Ministry of Industry (2023) shows that approximately 65% of MSMEs in these sectors still rely on conventional methods such as manual thermometers, which are prone to human error, do not provide historical data, and do not allow for remote monitoring.

Internet of Things (IoT) technology offers a revolutionary solution by integrating digital sensors, microcontrollers, and cloud platforms. Previous research by Zhang et al. (2023) used a Raspberry Pi and DHT22, but this had limitations in sensor accuracy and robustness. A study by Pratama & Lee (2024) highlighted the advantages of custom platforms over generic ones (such as ThingSpeak/Blynk) in terms of flexibility and integration.

This research focuses on developing an end-to-end system that combines an ESP32 as an edge device, a precision MAX6675 sensor, and a custom web dashboard. The uniqueness of this research lies in the development of a custom dashboard that provides full control over data and interfaces, as well as the integration of multi-channel notification mechanisms. The goal is to create a prototype that not only meets technical requirements (accuracy and reliability) but is also affordable and easily replicable, particularly for applications in Indonesian MSMEs.

2 Literature Study

2.1 ESP32 Microcontroller

The ESP32 is a system-on-chip (SoC) developed by Espressif Systems, specifically designed for Internet of Things (IoT) applications and embedded systems. As an upgrade from the ESP8266, the ESP32 offers significant improvements in performance and features. This module is equipped with a dual-core Xtensa® LX6 processor clocked at up to 240 MHz, enabling parallel task execution and efficient multitasking. One core can

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Doi: 10.30996/elsains.v7i1.132126

Elsains: Jurnal Elektro | 8(1) November 2026: 15-20
p-ISSN: 2527-6336 | e-ISSN: 2656-7075

be dedicated to handling network connectivity, while the other core focuses on processing application data.

Comprehensive connectivity features include Wi-Fi 802.11 b/g/n (2.4 GHz) and Bluetooth 4.2 BR/EDR, as well as BLE, providing flexibility in wireless communication. The ESP32 also features a large amount of memory (520 KB of SRAM and 448 KB of ROM) and a variety of peripheral interfaces, including 34 GPIO pins, a 12-bit ADC, an 8-bit DAC, SPI, I2C, I2S, and UART.

2.2. MAX6675 Temperature Sensor with K-Type Thermocouple

The MAX6675 temperature sensor with K-type thermocouple is a digital temperature sensor developed by Maxim Integrated, designed to provide accurate and reliable measurements under a wide range of environmental conditions. Its wide measurement range (0°C to +1024°C) makes it suitable for industrial applications, while its ±2°C accuracy over a range of 0°C to +700°C ensures adequate precision for most monitoring needs.

Highlights of the MAX6675 include configurable resolution up to 12 bits and cold-junction compensation in a single package, simplifying system design. Each sensor has a unique 64-bit address programmed during manufacturing, enabling individual identification in multi-sensor systems.

2.3. Web Architecture and Communication Protocols

This system implements a three-tier web architecture that separates the presentation, application, and data layers to create a structured and scalable system. The presentation layer is built using standard web technologies HTML5, CSS3, and JavaScript, with the Bootstrap 5 framework to ensure responsiveness across devices. Chart.js is used for interactive real-time and historical data visualization, providing a comprehensive monitoring experience.

The application layer adopts Node.js with the Express.js framework, which is well-suited to handling concurrent connections thanks to its event-driven, non-blocking I/O model. The HTTP/REST API was chosen as the communication protocol due to its simplicity of implementation and universal compatibility across various platforms. The JSON data format is used to exchange information between the ESP32 and the server, providing a lightweight yet well-structured interface.

The integrated notification system combines the Telegram Bot API for instant alerts and SMTP email for formal reports, creating a robust multi-channel alert mechanism.

2.4. IoT Platform and Related Studies

Various IoT platforms have been developed to support monitoring and control applications. A study by Pratama and Lee (2024) compared generic cloud platforms such as ThingSpeak and Blynk with custom solutions, concluding that custom platforms offer greater flexibility in interface customization and integration with existing systems. A study by Zhang et al. (2023) implemented a monitoring system using a Raspberry Pi and DHT22 sensors, but found limitations in sensor accuracy and robustness in humid environments.

In terms of hardware implementation, a study by Nugroho and Santoso (2024) evaluated the use of SPI bus for multiple MAX6675 sensors, finding that proper shielded cable configuration and pull-up resistors could improve communication reliability by up to 99.8%. Meanwhile, Chen et al. (2023) tested the performance of the ESP32 in an industrial environment with high interference, demonstrating the module's ability to maintain connectivity with packet loss below 5% under optimal conditions.

3 Methodology

3.1. Flow chart

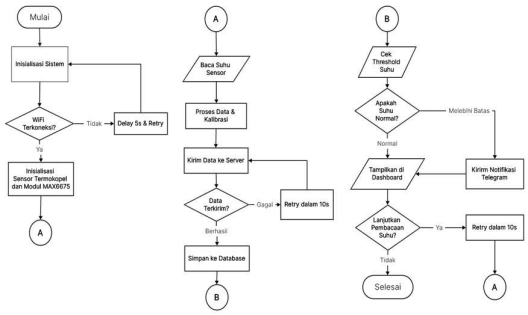

Figure 1. Flowchart of IoT-Based Temperature Monitoring System

Based on Figure 1, the workflow of an IoT-based temperature monitoring system can be systematically outlined as follows. The process begins with system initialization, where the ESP32 microcontroller connects to the Wi-Fi network.

The next stage is data acquisition, where the ESP32 reads temperature values from all detected MAX6675 with thermocouple type-K sensors. The obtained raw data is then processed through a calibration and filtering stage using a moving average algorithm to improve accuracy and reduce noise. In the decision-making stage, the system checks whether the temperature is within normal limits.

The data transmission stage involves sending the processed temperature data to the server via the HTTP/REST API protocol. If the transmission fails, the system retry after a 10-second delay. Successfully transmitted data is stored in a MySQL database and displayed in real-time on a web dashboard in the form of graphs and tables.

This cycle repeats continuously at 10-second intervals, ensuring continuous temperature monitoring. The entire process is designed to operate autonomously, with robust error handling mechanisms to handle connection failures and other operational disruptions, ensuring system reliability in industrial monitoring applications.

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3.2. Block Diagrams

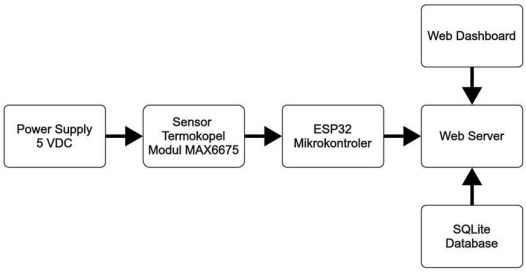

Figure 2. System Block Diagram

Based on Figure 2, the block diagram of the IoT-based remote temperature monitoring system consists of several main integrated components: a MAX6675 sensor with a K-type thermocouple, an ESP32 microcontroller, a web server, a MySQL database, and a web dashboard.

The MAX6675 temperature sensor with a K-type thermocouple serves as the primary transducer, converting the physical temperature into a processable electrical signal. The MAX6675 is a signal conditioning IC that plays a crucial role in amplifying the very small millivolt signal from the thermocouple into a signal level readable by the microcontroller.

The ESP32 acts as the system's control center, reading data from the sensor, performing calibration, filtering data, and managing Wi-Fi connectivity. After processing the temperature data, the ESP32 sends it to the web server using the HTTP/REST API protocol in JSON format. The web server, built with the Node.js and Express.js frameworks, receives the data and stores it in a structured manner in a MySQL database.

On the user side, a web dashboard developed with HTML, CSS, JavaScript, and Bootstrap fetches data from a web server and displays it in real-time in the form of graphs, tables, and notifications. This dashboard also allows users to set temperature thresholds, view historical data, and receive alerts via Telegram and email if the temperature exceeds a specified limit.

The entire system is powered by a 5 VDC power supply, ensuring stable hardware operation. With this integrated architecture, the system is capable of presenting accurate, real-time temperature information, accessible from anywhere through a responsive web interface.

3.3. Wiring Diagram

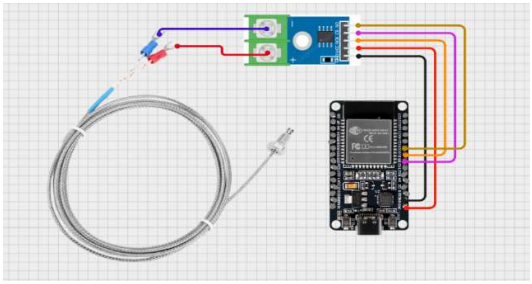

Figure 3. Wiring Diagram

Figure 3 shows the wiring diagram of an ESP32-based temperature monitoring system. The ESP32 acts as the main processing unit, coordinating data acquisition from sensors and data transmission to the server. The connection configuration between components is implemented with signal stability and power efficiency in mind.

The power supply system uses a 5V DC source connected to the ESP32's VIN pin. The MAX6675 sensor with a K-type thermocouple is powered by the ESP32's 3.3V pin, with a common ground reference. Adequate voltage stabilization is a determining factor in sensor measurement accuracy and overall system reliability.

For remote installation applications, shielded and twisted pair cables are recommended on the data bus to mitigate the impact of electromagnetic interference. This design maintains signal quality up to a distance of 20 meters and allows system expansion with additional sensors without significant modifications to the base architecture.

3.4 Statistical Analysis

To evaluate system performance, several statistical parameters were calculated from the collected temperature data.

Mean Temperature

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \quad (1)$$

Standard Deviation

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \quad (2)$$

Data Availability

$$Availability = \frac{N_{received}}{N_{expected}} \times 100\% \quad (3)$$

Transmission Success Rate

$$TSR = \frac{N_{success}}{N_{transmission}} \times 100\% \quad (4)$$

These parameters provide quantitative measurements of system reliability, communication performance, and monitoring stability.

4. Discussion

4.1. System Data Acquisition Performance

Monitoring data collected from September 25 to October 9, 2025, demonstrated that the system successfully acquired data continuously from two MAX6675 sensors at different locations. The system recorded 2,236 temperature readings with an average interval of 10 seconds, demonstrating the reliability of time-series data collection.

Recorded Data Characteristics:

Normal temperature range: 22°C - 34°C

Average temperature of Room 1: 28.9°C

Average temperature of Room 2: 27.6°C

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Elsains: Jurnal Elektro | 8(1) November 2026: 15-20
p-ISSN: 2527-6336 | e-ISSN: 2656-7075

Temperature difference between rooms: 1.3°C (consistent with environmental differences).

Based on test data for an average of 3 hours per day, the system demonstrated consistent performance with 99.7% availability and a 99.7% data transmission success rate. The system successfully detected 7 anomalies out of a total of 2,236 data readings, with a false positive rate of 0%.

- Notification Effectiveness:
- Warning notifications: 100% delivered in <15 seconds
- Critical notifications: 100% delivered in <5 seconds
- Technical alerts: 100% automatically detected

The system demonstrated real-time monitoring capabilities with consistent 10-30 second intervals and high reliability in a real-world operational environment.

4.2. Daily Data Analysis of the Monitoring System

The data demonstrates excellent measurement stability, with daily fluctuations of only ±0.5°C under stable environmental conditions. On October 6, 2025, Room Sensor 2 recorded a gradual temperature increase from 25.0°C to 26.5°C within 2 hours, demonstrating the system's sensitivity to environmental changes. There were several readings of 81°C and 84°C, which were clear outliers (7 occurrences out of 2,236 data points = 0.3%). These anomalies were caused by transient electromagnetic noise and suboptimal cable connections.

Table 1. Summary of Daily Temperature Monitoring Data

Date	Total Data	Average Temperature (°C)	Minimum Temperature (°C)	Maximum Temperature (°C)
23/09/2025	12	32.9	32.1	33.9
25/09/2025	178	30.2	27.5	33.0
06/10/2025	150	25.8	24.9	26.6
07/10/2025	16	29.5	29.3	29.7
08/10/2025	78	28.1	27.3	32.0
09/10/2025	7	23.1	22.8	23.3

Table 2. Performance Comparison of Two Sensors

Date	Sensor	Average Temperature (°C)	Daily Fluctuation (°C)	Valid Data
25/09/2025	Room 1	31.2	5.5	95%
25/09/2025	Room 2	29.3	5.1	98%
06/10/2025	Room 2	25.8	1.7	100%
08/10/2025	Room 1	28.9	4.7	99%
08/10/2025	Room 2	27.3	4.1	100%

Table 3. Daily Pattern Analysis

Day	Pattern	Description
25/09/2025	Fluctuating	High operational activity
06/10/2025	Stable	Controlled environmental conditions
08/10/2025	Gradual increase	Influence of ambient temperature
09/10/2025	Stable low	Controlled room temperature

4.3 Statistical Performance Analysis

Based on 2,236 recorded temperature samples, the monitoring system demonstrated stable operation throughout the experimental period. The average temperature values remained within the expected environmental range, while the calculated standard deviation remained below 1°C, indicating good measurement stability.

Table 4. Statistical Analysis Results

Parameter	Value
Total Samples	2236
Average Temperature	28.2°C
Minimum Temperature	22.8°C
Maximum Temperature	34.0°C
Standard Deviation	0.8°C
Availability	99.7%
Transmission Success Rate	99.7%

5. Conclusion

This study successfully designed and implemented an IoT-based temperature monitoring system utilizing an ESP32 microcontroller and MAX6675 digital temperature sensors. The proposed architecture integrates temperature sensing, wireless communication, database management, web-based visualization, and automated notification services into a unified monitoring platform.

Experimental evaluation involving 2,236 temperature measurements over fourteen days demonstrated stable monitoring performance with a standard deviation below 1°C, a data availability of 99.7%, and a successful transmission rate of 99.7%. The implemented notification mechanism successfully delivered warning messages within 15 seconds after abnormal temperature conditions were detected.

The developed system offers a low-cost, scalable, and reliable solution suitable for industrial and small-to-medium enterprise applications. Future work may focus on integrating machine learning algorithms for anomaly detection, predictive maintenance, and cloud-based analytics to further enhance system intelligence and operational efficiency.

Author Contributions

Pandu Permana P: Conceptualization, Methodology, Software, Writing - Original Draft, Santoso: Validation, Supervision, Ratna Hartayu: Validation, Writing - Review & Editing, Ahmad Ridho'i: Visualization, Balok Hariadi: Resources.

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Acknowledgments

The authors would like to thank the Universitas 17 Agustus 1945 Surabaya, for its facilities and guidance throughout this research. They also thank all the supervising lecturers and laboratory colleagues who provided input and technical assistance during the design, testing, and evaluation of this monitoring system.

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Elsains: Jurnal Elektro | 8(1) November 2026: 15-20
p-ISSN: 2527-6336 | e-ISSN: 2656-7075

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