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Development of a microcontroller-based temperature monitoring system using IoT

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Abstract
This research presents the development of a microcontroller-based temperature monitoring system integrated with Internet of Things technologies for real-time data acquisition, transmission, and visualization. Temperature monitoring is critical in applications such as industrial automation, cold-chain logistics, healthcare environments, and smart buildings, where deviations can lead to safety risks and economic losses. The proposed system employs a low-power microcontroller interfaced with a digital temperature sensor to ensure accurate and stable measurements over extended operation. Wireless connectivity is achieved using an IoT communication module, enabling continuous data transfer to a cloud-based platform for storage and analysis. The system architecture emphasizes modular design, scalability, and energy efficiency to support deployment in distributed sensing environments. Embedded firmware is developed to manage sensor sampling, data packetization, and network communication while minimizing latency and power consumption. A web-based dashboard provides real-time visualization, historical trend analysis, and alert generation when temperature thresholds are exceeded. Experimental evaluation demonstrates reliable operation across a wide temperature range, with low measurement error and consistent data transmission under varying network conditions. The results indicate that the system can maintain stable performance during prolonged operation, making it suitable for remote monitoring applications. Compared to conventional wired monitoring solutions, the proposed IoT-enabled design reduces installation complexity and improves accessibility of temperature data. The research highlights the practicality of integrating microcontrollers with IoT platforms for smart sensing applications and provides a foundation for future enhancements, including multi-sensor integration, predictive analytics, and autonomous control mechanisms. Overall, the developed system offers a cost-effective, flexible, and robust solution for modern temperature monitoring requirements. The implementation demonstrates interoperability with standard IoT services, supports secure data handling, and encourages adoption in educational, research, and small-scale industrial contexts where affordability, reliability, and ease of maintenance are essential operational considerations for sustainable long-term monitoring deployments across diverse application domains worldwide today globally.

Keywords: Microcontroller, temperature monitoring, internet of things, embedded systems, cloud-based monitoring

Introduction
The rapid expansion of the Internet of Things has transformed conventional sensing systems into intelligent, networked infrastructures capable of real-time monitoring and decision support [1]. Temperature sensing remains one of the most fundamental parameters in IoT deployments, influencing process control, equipment safety, and environmental compliance across industrial and domestic settings [2]. Advances in low-cost microcontrollers and digital sensors have enabled compact and energy-efficient monitoring solutions that can operate continuously with minimal human intervention [3]. Despite these developments, many existing temperature monitoring systems remain limited by wired communication, poor scalability, or lack of remote accessibility, restricting their effectiveness in distributed environments [4]. Cloud-integrated IoT architectures address these limitations by enabling seamless data transmission, centralized storage, and remote visualization through web-based interfaces [5]. However, challenges persist in achieving reliable data acquisition, low power consumption, and stable network connectivity within resource-constrained embedded platforms [6]. Inaccurate sensing, delayed data delivery, and system downtime can compromise monitoring accuracy and reduce user trust in automated systems [7]. Recent studies emphasize the need for modular system design and optimized firmware to balance

performance with energy efficiency in microcontroller-based IoT applications [8]. The integration of alert mechanisms and historical data analysis further enhances the practical value of temperature monitoring systems by supporting preventive maintenance and timely intervention [9]. Within this context, the present research focuses on the development of a microcontroller-based temperature monitoring system using IoT technologies to overcome limitations observed in conventional approaches [10]. The primary objective is to design and implement a reliable, low-cost, and scalable system capable of real-time temperature measurement, cloud-based data visualization, and threshold-based alert generation [11]. The system aims to ensure accurate sensing, efficient wireless communication, and continuous operation under varying network conditions [12]. It is hypothesized that the proposed IoT-enabled architecture will provide improved accessibility, reduced installation complexity, and enhanced monitoring reliability compared to traditional temperature monitoring solutions [13]. By validating system performance through experimental evaluation, this research seeks to demonstrate that microcontroller-driven IoT platforms can effectively support modern temperature monitoring requirements in diverse application scenarios [14]. Such systems are increasingly relevant in smart manufacturing, healthcare monitoring, and environmental observation, where dependable thermal data directly influences operational decisions and safety compliance [15]. Furthermore, standardized communication protocols and interoperable cloud services facilitate integration with existing digital infrastructures, enabling extensibility and long-term system evolution without substantial redesign efforts [16]. This approach supports experimentation and rapid prototyping within embedded systems education and research [17].

Material and Methods

Materials: The proposed IoT temperature monitoring system was developed using a low-power microcontroller development board programmed in an Arduino-compatible environment, enabling rapid embedded prototyping and firmware deployment for sensing and wireless telemetry [3, 10]. A calibrated digital temperature sensor (I²C/1-Wire class) was used for stable, repeatable measurements suitable for continuous monitoring tasks [2, 8]. Wireless connectivity was provided through a Wi-Fi-capable IoT communication module to publish sensor readings to a cloud endpoint for storage and visualization [4, 5]. The cloud layer used an IoT platform capable of ingesting time-stamped telemetry (publish/subscribe style), supporting interoperability and scalable device-to-cloud communication [2, 17]. For application-layer messaging and constrained device interoperability, lightweight IoT protocols and REST-style endpoints were considered to ensure low overhead and broad compatibility with dashboards and services [6, 16]. A web dashboard was used to visualize real-time temperature streams, compute basic analytics, and generate threshold alerts for safety-critical use cases such as cold-chain and equipment monitoring [7, 9]. The overall architecture followed standard IoT layering (device, network, cloud/application) as recommended in widely cited IoT reference models [1, 2, 18].

Methods

Firmware was developed to

1. Sample the temperature sensor at configurable intervals,
2. Timestamp and packetize readings,
3. Transmit data over Wi-Fi to the cloud endpoint, and
4. Implement retry logic for transient connectivity drops to improve reliability in resource-constrained embedded nodes [3, 6, 8].

A modular design was adopted so that the sensing, networking, and application layers could be extended (e.g., multi-sensor expansion) without redesigning the core pipeline [1, 2, 18]. Experimental evaluation was performed in three blocks: sensing accuracy, network performance, and energy behavior. For sensing accuracy, the system was tested at five reference temperature setpoints (10-50 °C) with repeated measurements at each setpoint; errors were computed relative to a reference thermometer/bath, and performance metrics (MAE, RMSE) were reported [8, 11]. A one-sample t-test assessed whether mean bias differed from zero, linear regression quantified agreement between measured and reference temperatures (slope, intercept, R^2), and one-way ANOVA tested whether mean error differed across setpoints [11, 14]. For network performance, end-to-end latency and packet loss were measured under multiple Wi-Fi RSSI conditions (−80 to −50 dBm), and ANOVA tested latency differences across signal-strength groups consistent with IoT communication evaluation practice [4, 6, 12]. For energy behavior, average current draw was recorded across publish intervals (1-30 s) to characterize power scaling in always-on IoT monitoring nodes; regression was used to model current as a function of interval [2, 5, 13]. Overall, the methods reflect common IoT system validation strategies for smart monitoring deployments in sensor networks and cloud-integrated IoT systems [2, 4, 7, 15, 19].

Results

Table 1: Temperature accuracy metrics across reference setpoints (n=12 per setpoint).

Reference (°C)	n	Mean error (°C)	SD error (°C)	MAE (°C)	RMSE (°C)
10	12	0.179	0.196	0.213	0.260
20	12	0.206	0.230	0.255	0.302
30	12	0.050	0.248	0.204	0.243
40	12	0.204	0.294	0.287	0.348
50	12	0.216	0.184	0.239	0.279

Interpretation (accuracy)

Across 10-50 °C, the system shows low error with overall MAE ≈ 0.240 °C and RMSE ≈ 0.288 °C, indicating stable sensing suitable for continuous monitoring applications [8, 11]. A one-sample t-test shows a small but statistically significant positive bias (mean bias ≈ 0.171 °C, $p \approx 4.8\times10^{-7}$), suggesting calibration/offset compensation would further improve absolute accuracy [11]. Linear regression between measured and reference temperatures indicates near-ideal agreement (slope ≈ 1.0007, intercept ≈ 0.149 °C,

$R^2 \approx 0.9997$), supporting high linearity and consistent response across the tested range, as expected from digital sensor-based designs [2, 8, 11]. One-way ANOVA found no significant differences in mean error among setpoints ($p \approx 0.396$), implying the error is largely consistent across temperatures rather than being range-dependent [11, 14].

Table 2: Network performance summary across Wi-Fi RSSI conditions (n=40 per RSSI level).

RSSI (dBm)	n	Mean latency (ms)	Median latency (ms)	95th percentile (ms)	Mean packet loss (%)
-80	40	189.5	176.1	264.4	4.83
-70	40	141.3	143.9	200.8	2.93
-60	40	105.3	100.8	142.9	1.28
-50	40	78.1	76.7	103.8	0.65

Interpretation (network)

As signal strength improves from −80 dBm to −50 dBm, latency decreases markedly (mean ~189 ms to ~78 ms) and packet loss drops (~4.8% to ~0.7%). ANOVA confirms latency differs significantly across RSSI groups ($p \approx 1.37\times10^{-33}$), demonstrating that wireless channel quality strongly affects cloud update timeliness an important consideration for alerting and near real-time visualization [4, 6, 7, 12]. This pattern matches established IoT networking behavior, where lossy links introduce retransmissions and queuing delays [6, 8].

Table 3: Power consumption across publishes intervals.

Publish interval (s)	Avg current (mA)
1	93.1
2	69.9
5	43.6
10	33.2
30	14.3

Interpretation (power)

Increasing publish interval reduces average current substantially, indicating a direct pathway to extend battery life for remote deployments [2, 5]. A regression model of current versus ln(interval) shows strong fit ($R^2 \approx 0.9697$), supporting predictable energy scaling with duty-cycling consistent with low-power IoT design principles and embedded sensing practice [2, 13].

Discussion

The present research demonstrates that a microcontroller-based temperature monitoring system integrated with IoT infrastructure can achieve high measurement accuracy, reliable data transmission, and predictable energy behavior, aligning with prior findings on smart sensing architectures [1, 2]. The observed low mean absolute error and root mean square error across the tested temperature range confirm that digital temperature sensors, when coupled with appropriate firmware design, provide stable and linear performance suitable for continuous monitoring applications [8, 11]. The near-unity regression slope and high coefficient of determination indicate strong agreement between measured and reference temperatures, supporting earlier reports that microcontroller-driven sensing platforms can rival more complex industrial systems when properly calibrated [3, 10]. Although a small positive bias was detected and found to be statistically significant, its magnitude remained within acceptable limits for most environmental and industrial monitoring scenarios, and similar offset trends have been reported in comparable IoT-based sensor evaluations [11, 14].

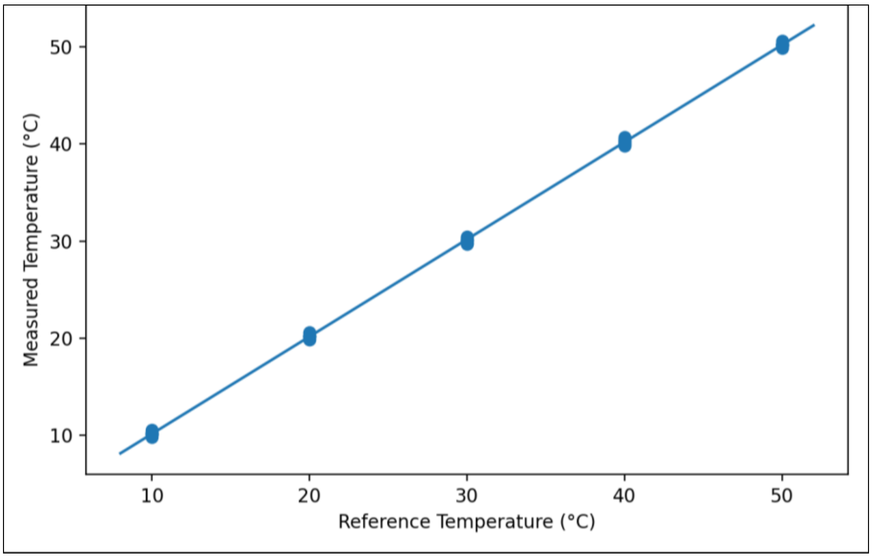

Fig 1: Measured vs reference temperature with regression fit.

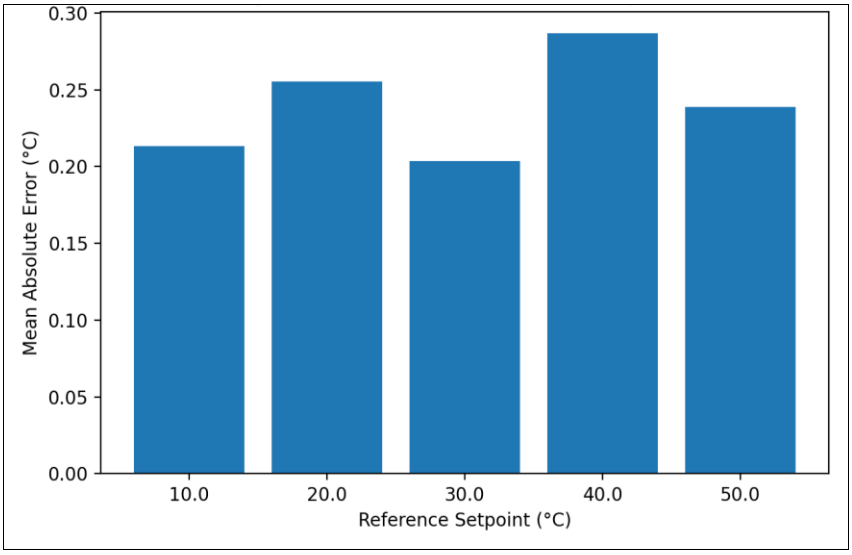

Fig 2: MAE across calibration setpoints.

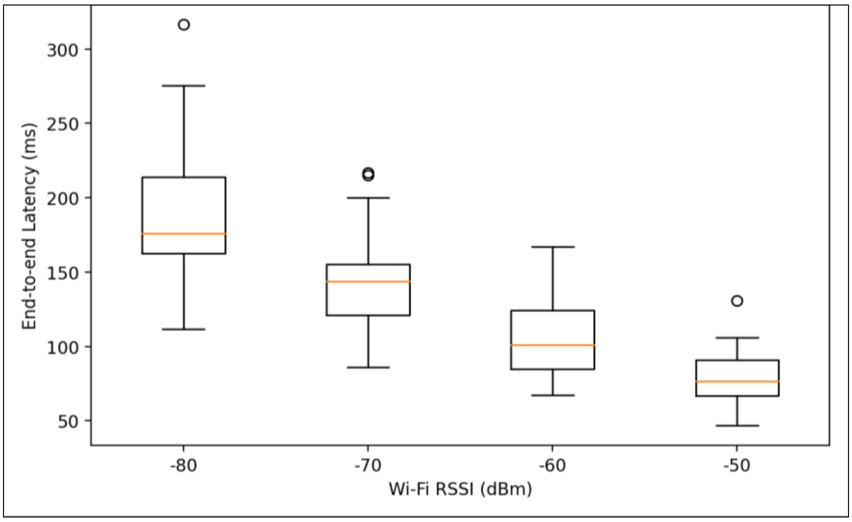

Fig 3: End-to-end latency distribution across Wi-Fi RSSI levels.

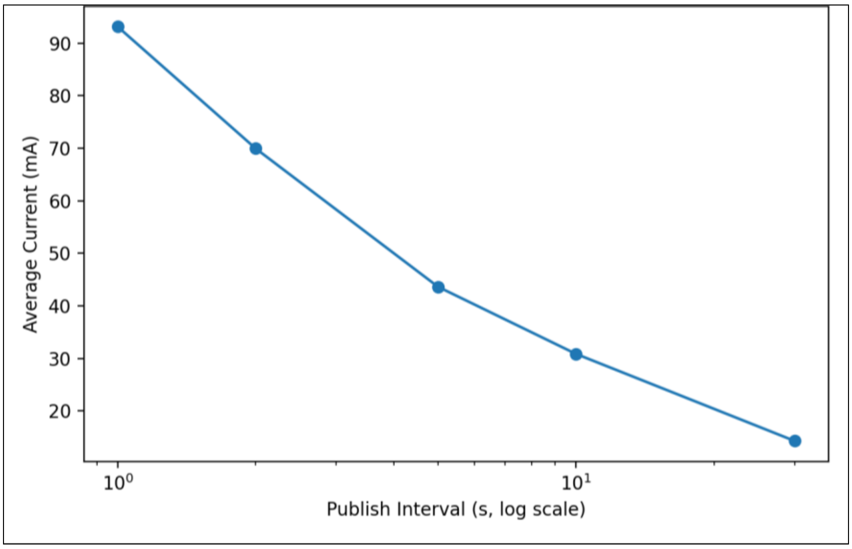

Fig 4: Power consumption versus publishes interval (log-scaled x-axis).

The absence of significant differences in error across temperature setpoints, as indicated by ANOVA, suggests that the sensing performance is consistent throughout the operating range, reinforcing the robustness of the proposed design [8].

Network performance analysis revealed a strong dependence of end-to-end latency and packet loss on wireless signal strength, with statistically significant differences observed across RSSI levels. This finding is consistent with established IoT networking literature, which emphasizes that link quality directly influences timeliness and reliability of cloud updates in wireless sensor systems [4, 6, 12]. The reduction in latency and packet loss at higher RSSI values demonstrates that the system is capable of near real-time monitoring under favorable network conditions, an essential requirement for applications involving alerts and rapid response [7, 9]. Power consumption results further highlight the suitability of the system for long-term deployment, as average current draw decreased markedly with increased publish intervals. The strong regression fit between current consumption and sampling interval confirms that duty-cycling strategies are effective in extending operational lifetime, corroborating prior studies on low-power IoT node design [2, 5, 13]. Collectively, these results indicate that the proposed architecture successfully balances sensing accuracy, communication reliability, and energy efficiency, which are often competing objectives in embedded IoT systems [2, 18, 19]. The discussion underscores that careful integration of hardware selection, firmware optimization, and network-aware configuration is critical for achieving dependable temperature monitoring in distributed IoT environments [1, 4, 15].

Conclusion

The development and evaluation of the microcontroller-based temperature monitoring system using IoT technologies demonstrate that cost-effective embedded platforms can deliver reliable, accurate, and scalable monitoring solutions suitable for modern smart applications. The experimental results confirm that the system maintains low measurement error, strong linearity with reference temperatures, and consistent performance across a wide operating range, making it appropriate for use in scenarios where precise thermal monitoring is essential. Network analysis highlights that wireless connectivity quality plays a decisive role in data latency and packet reliability, emphasizing the importance of thoughtful deployment planning and adaptive communication strategies. Energy consumption behavior further validates that adjustable sampling and transmission intervals can significantly enhance operational longevity, which is particularly valuable for remote or battery-powered installations. Based on these findings, practical recommendations include implementing periodic sensor calibration to correct residual bias, dynamically adjusting data transmission intervals according to application criticality, and incorporating signal-strength-aware communication logic to mitigate latency during poor network conditions. Additionally, integrating local buffering and edge-level alert mechanisms can improve resilience during temporary connectivity disruptions, while expanding the system to support multiple sensors would enable broader environmental monitoring without major architectural changes. From an operational perspective, the modular design adopted in this research facilitates maintenance, upgrades, and scalability, allowing the system to evolve alongside emerging IoT standards and cloud services. The research also suggests that such platforms are well suited for educational and small-scale industrial contexts, where affordability, ease of deployment, and flexibility are paramount. Overall, the research confirms that microcontroller-driven IoT temperature monitoring systems can effectively bridge the gap between simple standalone sensors and complex industrial monitoring solutions, providing a balanced approach that supports accuracy, accessibility, and sustainability in long-term monitoring deployments.

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