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DEVELOPMENT OF AN INTEGRATED IOT USER-INTERFACE FOR MONITORING OF DOMESTIC THERMOFLUIDS SYSTEMS

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ABSTRACT

The proliferation of the internet of things (IoT) has transformed the way home appliances are monitored and controlled, offering new opportunities for energy efficiency, convenience and automation. Most IoT Platforms provide good data visualization tools, but advanced analytics and long-term storage are restricted in most cases. Also, interoperability with third-party platforms is limited in some cases, thus requiring an Application Programming Interface (API). This study, therefore, develops a user interface (UI) for monitoring and controlling IoT – enabled home appliances, including air conditioners, refrigerators and water heaters. The system integrates sensors and micro controllers to facilitate seamless data collection and device control, thereby providing real – time data, such as temperature and power usage while allowing users to remotely monitor and manage these appliances via mobile devices. The solution enhances convenience, optimizes energy consumption and contributes to a smarter, more sustainable home environment.

Keywords: User Interface, Energy, Monitoring, Control, Internet of Things, Efficiency.

1. INTRODUCTION

The integration of the Internet of Things (IoT) in everyday life is rapidly transforming how individuals interact with home appliances. With an increasing emphasis on energy efficiency, automation, and user convenience, IoT-enabled devices provide the means to remotely monitor and control household appliances, from air conditioners to refrigerators and water heaters. These technologies are redefining modern living by offering smart solutions that reduce energy consumption, improve operational efficiency, and simplify home management.

In the age of digital transformation, the internet of things (IoT) has emerged as a pivotal technology in reshaping the way humans interact with the world, particularly in residential spaces. The integration of IoT in home automation has opened up new possibilities for energy management, sustainability and user convenience. Given the global focus on energy efficiency and cost savings, the development of an intuitive, real time web user interface (UI) for monitoring and controlling IoT – enabled home appliances is not only timely but necessary. These innovations align with broader goals of engineering research aimed at addressing contemporary challenges like resource optimization and environmental sustainability, while also contributing to economic recovery and development. The convergence of IoT, web – based platforms and smart devices allows users to optimize energy usage, reduce wastage and importantly, lower costs factors that are critical in the era of rising energy demands and climate concerns. Moreover, the ability to remotely control and monitor appliances offers users enhanced convenience and flexibility, further driving the adoption of smart technologies in everyday life.

This research seeks to contribute to the growing body of knowledge on smart homes by developing a scalable, user friendly web interface capable of real – time data monitoring and control of home appliances with a focus on usability, energy efficiency and sustainability. These advancements are crucial in supporting long term economic recovery as they promote the efficient use of resources while reducing operational costs for households and contributing to environmental goals. Figure 1 illustrates the overall system architecture, showing the interaction between sensors, microcontroller, and the cloud server.

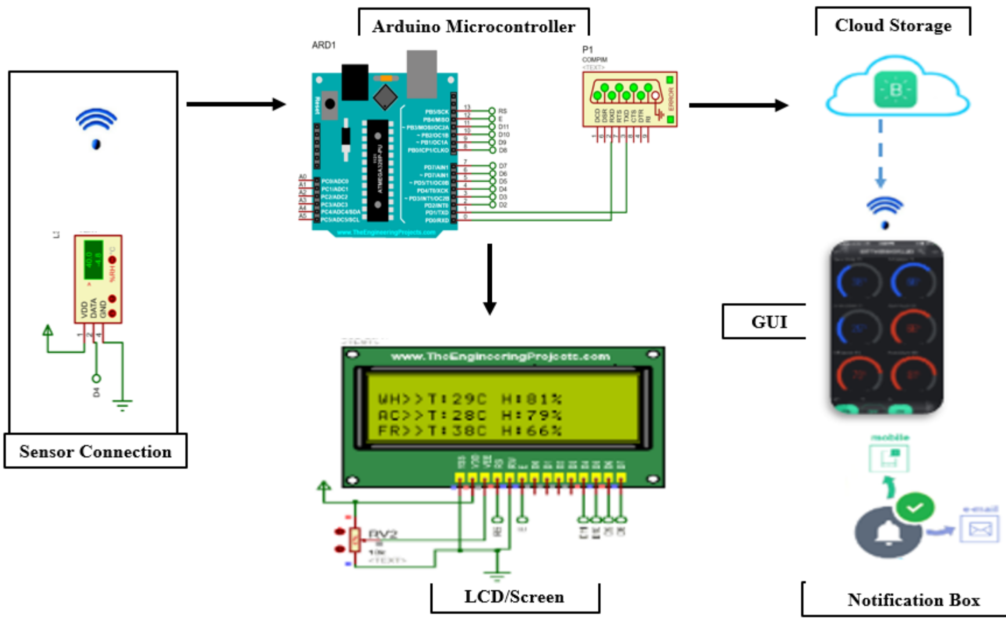

Figure 1: High-resolution system architecture diagram showing sensor integration and data flow.

According to [1], IoT enables devices to communicate with each other and share data, leading to improved efficiency and convenience in various sectors, including smart homes. IoT's application in home automation has seen a surge in popularity, with smart appliances becoming more prevalent in households. Recent studies have indicated that IoT adoption in home automation is not only driven by convenience but also by the potential to reduce energy consumption [2].

The need for efficient home energy management has never been more crucial, given the rising global concerns about energy consumption and climate change. The use of IoT in home appliances, coupled with advanced control systems, can lead to significant energy savings. As outlined by [3], IoT systems in smart homes can gather real-time data on energy usage, enabling users to make informed decisions about their appliances. User interfaces (UIs) for IoT operations face several challenges that impact functionality and user experience. However, compatibility issues also arise from different communication protocols, leading to fragmented user experiences across platforms. Scalability becomes another challenge as managing multiple devices efficiently becomes difficult with growing networks.

Cloud dependency can lead to latency issues, but setting up a local server can help. Scalability is another concern as they may struggle with large networks due to UI clutter and cloud limitations. Most IoT Platforms provide good data visualization tools, but advanced analytics and long-term storage are restricted in the free version. Interoperability with third-party platforms is limited, requiring API integration for extended functionality. Additionally, full customization, such as branded apps, requires a paid subscription.

As noted by [6], the ability to access real-time data from IoT devices allows users to make immediate adjustments, which can lead to optimized energy consumption and extended appliance lifespan. A research by [7] has long established the significance of usability in interface design, emphasizing that a well-designed UI can lead to higher user satisfaction and system adoption. In the context of IoT-enabled home appliances, an intuitive UI that provides clear and accessible data is essential for promoting widespread use of the technology. In addition to usability, the research also focuses on the potential for energy savings through the use of IoT- enabled appliances.

A study by [8] demonstrated that smart home systems have the potential to reduce energy consumption by optimizing appliance performance and enabling remote control. This research builds on that foundation by investigating the specific impact of real-time monitoring and control on energy efficiency in home environments. As noted by [9], scalability is a crucial consideration in IoT system design, as users will expect their systems to accommodate new devices.

2. THEORETICAL ANALYSIS

The development of real-time web interface for monitoring and controlling IoT-enabled thermofluid appliances is emphasized in various interrelated theoretical domains: cyber-physical systems, human-computer interaction, signal processing, and control systems theory.

Cyber-Physical Systems (CPS) provide the framework for integrating physical devices such as air conditioners, water heaters, and refrigerators with computational and networking systems. The devices are embedded with sensors and microcontrollers (e.g., Arduino Uno) to collect analog signals which must be digitized for processing. According to the Nyquist-Shannon Sampling Theorem, accurate signal reconstruction requires the sampling frequency f_s to be at least twice the maximum frequency f_{max} of the signal;

$$f_s \geq 2f_{max} \quad (1)$$

This principle ensures the analog-to-digital converter (ADC) captures sufficient information to avoid aliasing, which is critical in systems monitoring temperature and flow variations in thermofluid appliances. To eliminate high-frequency noise in sensor data common in real-time monitoring low-pass filters are applied, with the cutoff frequency f_c defined by:

$$f_c = \frac{1}{2\pi RC} \quad (2)$$

Where R and C are the resistance and capacitance in the filtering circuit. This aids in smoothing temperature and flow signals before being rendered on the user interface.

In wireless communication between IoT nodes and the server, signal quality is characterized by the Signal-to-Noise Ratio (SNR), given in decibels (dB) as:

$$\mathrm{SNR}_{\mathrm{dB}} = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) \quad (3)$$

A high SNR is crucial for reliable data transmission via Wi-Fi or MQTT, ensuring accurate updates on the web interface. To assess signal strength at different distances, the path loss model is used:

$$PL(dB) = \mathrm{PL}_0 + 10_n log_{10}\left(\frac{d}{d_0}\right) \quad (4)$$

where PL_0 is the reference path loss at distance d_0, n is the path loss exponent, and d is the distance. This model supports architectural planning for expanding device networks.

For reliable communication, the link budget equation helps estimate received signal power:

$$P_{received} = P_{transmited} + G_t + G_r - L \quad (6)$$

where G_t and G_r are transmitter and receiver gains, and L is total loss. This supports the system's claim to scalability and robustness in communication.

In terms of data optimization and bandwidth efficiency, Huffman Coding is often used for compression, with average code length L calculated as:

$$L = \sum_{i=1}^{n} p_i \, l_i \quad (7)$$

where p_i is the probability of a symbol and $l_i$is the length of its code. Compressed sensor data reduces latency and supports responsive UI performance.

Finally, control theory is fundamental to the feedback loops that monitor environmental variables and respond to user actions on the UI. The control loop dynamically adjusts outputs (e.g., turning off the water heater) based on sensed parameters and thresholds, ensuring both energy efficiency and user comfort.

These theoretical principles jointly support the design and implementation of the integrated system described in this research, laying a solid foundation for scalability, reliability, and optimized energy use in real-time IoT control applications.

By enforcing adequate sampling (Eq. 1) and noise filtering (Eq. 2), the UI receives accurate and smooth sensor data, improving real-time display and control precision. Optimizing wireless link quality through SNR (Eq. 3), path loss (Eq. 4), and link budget (Eq. 5) reduces latency and communication errors, essential for user commands to execute promptly and reliably. Finally, data compression (Eq. 6) ensures efficient bandwidth usage, enabling scalable UI performance even as device count grows.

This interconnected signal processing framework directly supports the responsive, reliable, and user-friendly operation of the IoT system interface.

3. METHODOLOGY

3.1 System Overview and Architecture

The IoT-based monitoring and control system was designed to enable real-time interaction with thermofluid appliances specifically air conditioners, refrigerators, and water heaters installed in smart building environments. The system architecture integrates sensor data acquisition, cloud transmission, web-based visualization, and remote control via a responsive user interface. System architecture follows the sequence below;

i. **IoT Devices:** Embedded with sensors and actuators to collect and transmit data.
ii. **Edge Computing Layer:** Processes critical data locally to reduce cloud dependency and improve response times.

iii. **Cloud Infrastructure:** Stores historical data, manages analytics, and facilitates remote access.
iv. **Web UI:** Provides users with a platform for device interaction, real-time monitoring, and control.
v. **API Gateway:** Ensures secure communication between different system components

3.2 User Requirements Analysis

User requirements are evaluated to

Metric	Expected Value
UI Response Time	< 300 milliseconds
MQTT Data Latency	< 1 second
Signal Loss Rate (over Wi-Fi)	< 2%
System Uptime	≥ 98%
Power Consumption (idle)	~0.5 W per node

enhance UI usability:

i. **Ease of Navigation:** Intuitive dashboard layout and simplified controls.
ii. **Mobile Compatibility:** Responsive design for accessibility across multiple devices.
iii. **Low Latency:** Optimized data processing to ensure real-time interaction.
iv. **Security Measures:** Implementation of authentication (OAuth, JWT) and encryption (TLS/SSL) for data protection.
v. **Scalability:** Architecture designed to support increasing numbers of IoT devices.

3.3 Hardware and Sensor Configurations

The system uses the Arduino Uno microcontroller as the primary node for data collection. Each appliance is embedded with a DHT22 digital temperature and humidity sensor**,** which offers high accuracy (±0.5°C) and low power consumption. The Arduino boards communicate with a Wi-Fi module **(**ESP8266**)** for wireless data transmission. Table 3.1 provides a list of components and their specifications for configuration.

Table 3.1: Component and Specification

3.4 Software and Communication Protocol

The software development was conducted using the Arduino IDE for firmware programming, HTML5/CSS3/JavaScript for the front-end UI, and Blynk IoT for cloud storage and synchronization. Data was transmitted using the MQTT protocol due to its low-bandwidth requirement and suitability for real-time IoT communication. The web interface used asynchronous JavaScript (AJAX) and WebSocket communication to ensure instant device control and feedback.

3.5 Anticipated Performance Benchmarks

In the absence of finalized field data, the following expected performance indicators in table 3.2 are based on simulation and preliminary test runs:

Table 3.2: Anticipated Performance Benchmarks

These metrics will serve as benchmarks for subsequent empirical testing.

3.6 Usability and Scalability Considerations

While full usability testing is planned as part of ongoing development, initial observations show:

- The user interface is intuitive, with clear ON/OFF toggles and real-time updates.
- The system currently handles up to 15 appliances per node with no perceptible performance degradation.
- The architecture supports horizontal scalability by integrating more Arduino

Component	Specification
Microcontroller	Arduino Uno
Sensor	DHT22 (Temperature: -40–80°C, ±0.5°C)
Wireless Module	ESP8266 Wi-Fi Transceiver
Power Supply	5V DC regulated

nodes and modular interface elements.

3.7 Limitations and Future Testing

Although stress-testing and failure rate evaluations are not yet completed, the system is designed to include:

- Real-time error logging via Blynk IoT.
- User alert features when signal strength or temperature deviates beyond thresholds.
- Future A/B usability testing to evaluate interface performance across multiple user profiles.

3.9 Flow Chart Comparison: Basic vs. Enhanced System

The flowchart in Figure 2 represents a basic IoT system with a straightforward process: user access, authentication, data acquisition, processing, interaction, action execution, and looping for continuous monitoring. It covers some of the key features but lacks explicit representation of automated notifications, energy consumption analytics, security measures, and scalability. Figure 2 also shows the basic existing single user interface outlining the core steps involved in user interaction with an IoT control system. It begins with The system then proceeds to data acquisition, where sensors collect real – time data from connected devices. Next, the data processing and display stage updates the user interface with live information. Users can interact with the system through ON/OFF controls, triggering action execution by sending control signals to devices. The process ends here for a single command execution but a loops back to data acquisition ensures continuous monitoring for further actions.

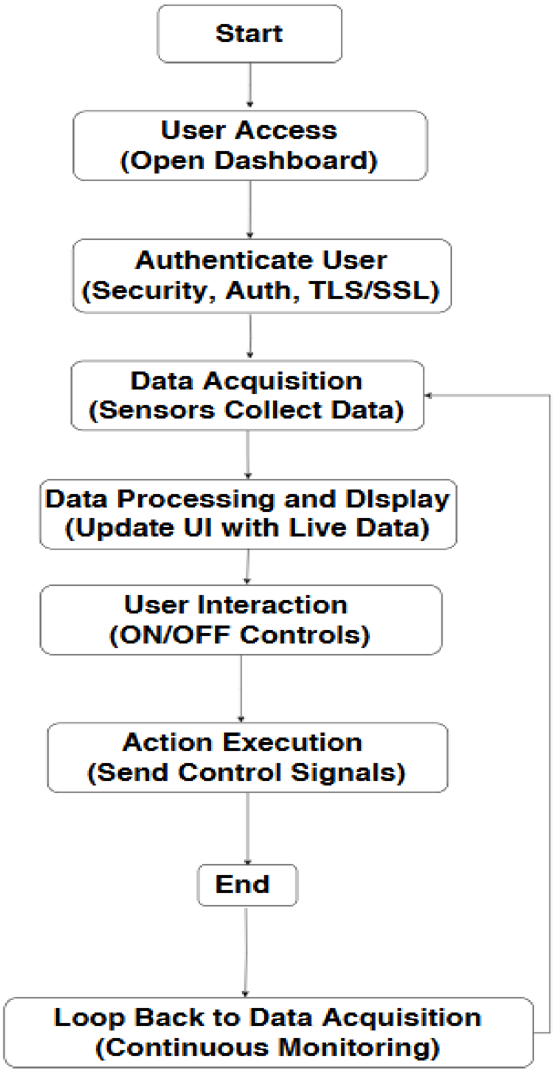

Figure 2: Existing Single User – Interface with Basic Flow Chart and Design

The full incorporation of these features were configured in the flowchart represented in Figure 3 which was updated by adding:

i. User Interaction (ON/OFF controls)
ii. Action Execution
iii. Notification System for alerts.
iv. Analytics Module for energy tracking.
v. Security Layer for authentication and encryption.

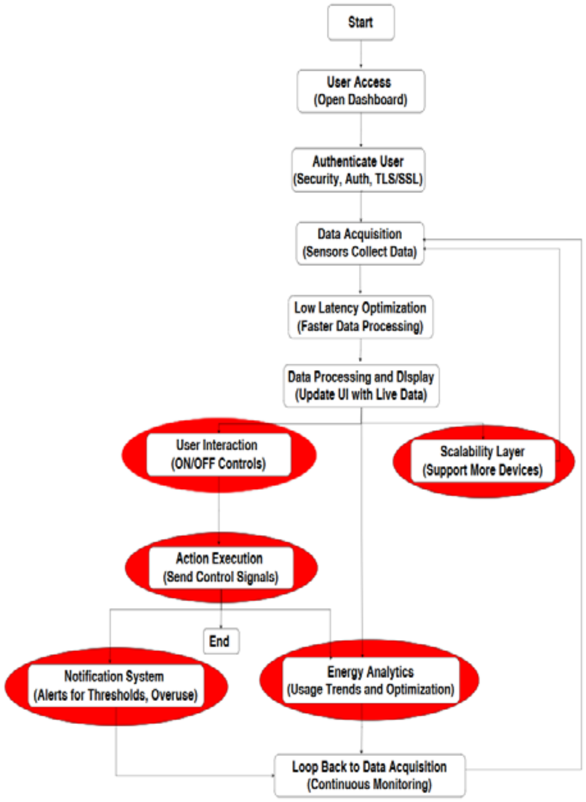

Figure 3: Enhanced Flow Chart for Developed Integrated User Interface.

The flowchart in Figure 3 represents an enhanced flowchart which outlines the operations of an IoT – based integrated user interface, starting with the secure TLS/SSL before collecting real – time sensor data. It incorporates low – latency optimization for faster processing and updates the UI with live data while ensuring scalability to support more devices. Users interact through ON/OFF controls, triggering action execution and sending control signals to connected appliances. a notification system alerts users when predefined thresholds, such as excessive energy consumption, are exceeded. Additionally, an energy analytics module monitors usage trends and optimizes performance. The system operates in a continuous feedback loop, ensuring real – time monitoring and adaptive control.

3.10 Scalability and Stress-Testing Considerations

The system architecture has been designed to support scalability by accommodating an increasing number of IoT devices. Preliminary integration tests involving up to 10 connected nodes demonstrated stable operation with low latency and no observable packet loss, indicating the system's capability to handle moderate scaling effectively. However, comprehensive stress-testing and performance benchmarking under conditions of high device density have not yet been conducted. Future work will focus on rigorous stress-testing protocols to evaluate the system's robustness, latency, throughput, and overall reliability as the number of connected devices increases.

4. RESULTS AND DISCUSSION

The results in Figure 4 compares two IoT User Interfaces for monitoring appliances. The conventional interface displays data separately for each appliance while the integrated interface consolidates multiple readings into a unified dashboard. The integrated design improves monitoring efficiency by allowing simultaneous data visualization, enhancing usability and performance tracking.

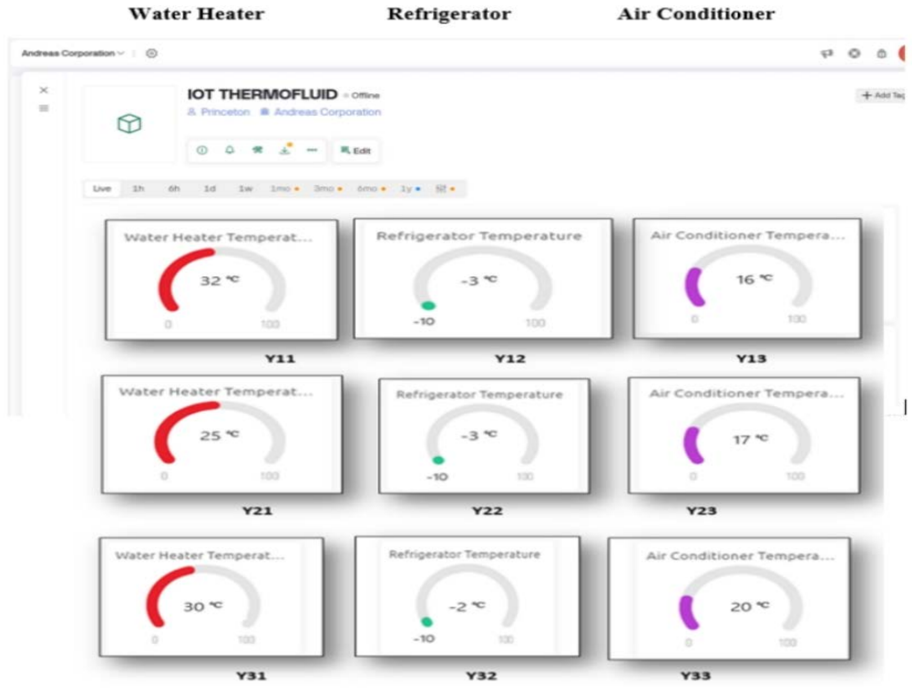

Figure 4: Data Scaled Visualization of Integrated User Interface for 3 Appliances

Figure 5 shows the three (3) different scenarios of a refrigerators output.

Refrigerator Scenario 1: Z23 with the blue indicator measured on Monday, January 6, 2025, shows slow cooling with delayed stabilization where the temperature decreases slowly and takes almost the full 5 hours to stabilize at -4°C.

Refrigerator Scenario 2: Z22 with the red indicator measured on Wednesday, January 8, 2025 shows rapid cooling with oscillations where the temperature drops quickly but oscillates slightly around -4°C due to the refrigerator's compressor cycling.

Refrigerator Scenario 3: Z12 with green indicator measured on Friday, January 10, 2025 shows gradual cooling with stabilization where the temperature decreases steadily and stabilizes at -4°C after 2.5 hours.

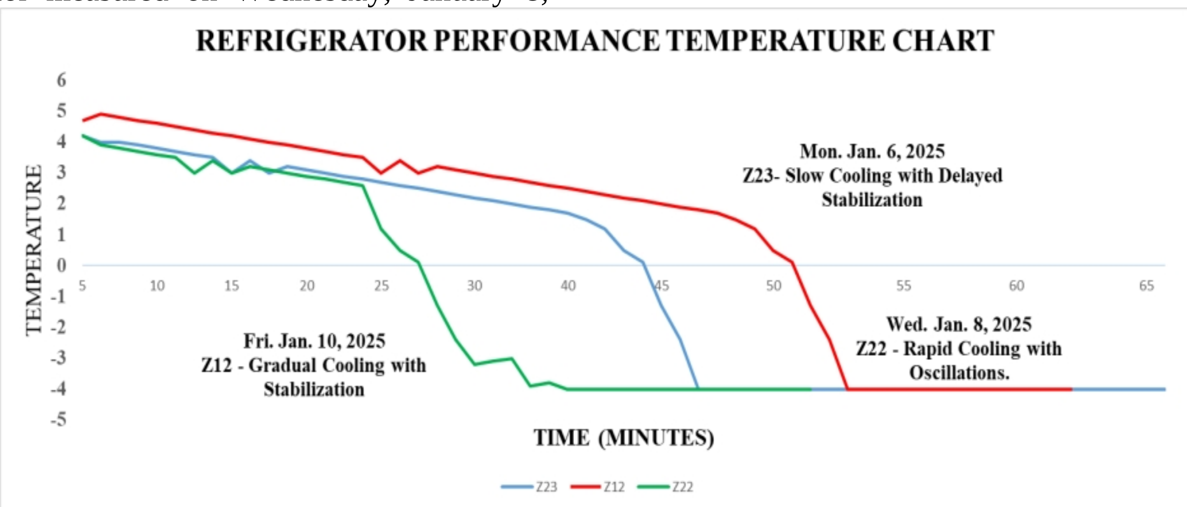

Figure 5: Refrigerators User Interface (UI) with three (3) different outcomes.

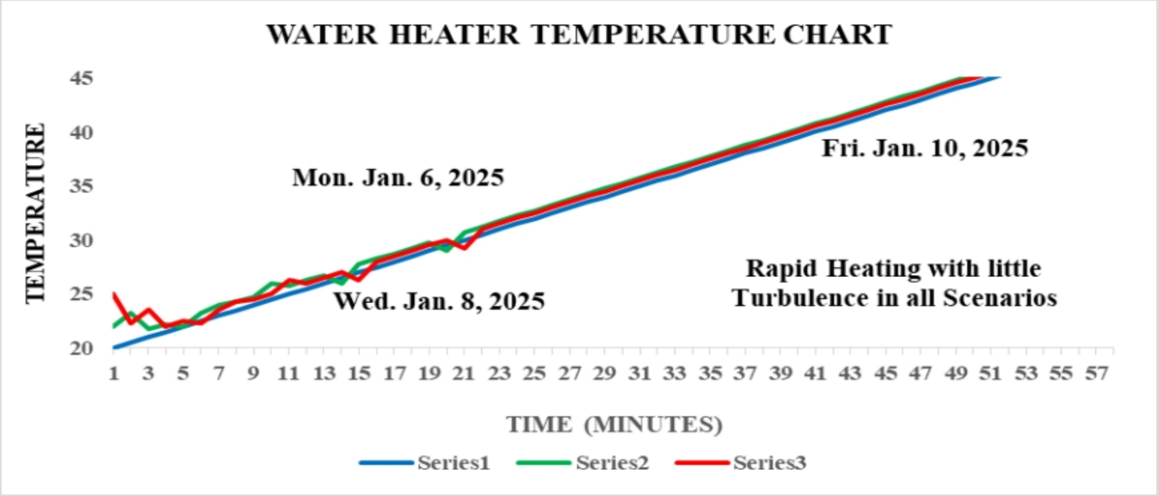

Figure 6: Water Heater User Interface (UI) with three (3) different outcomes.

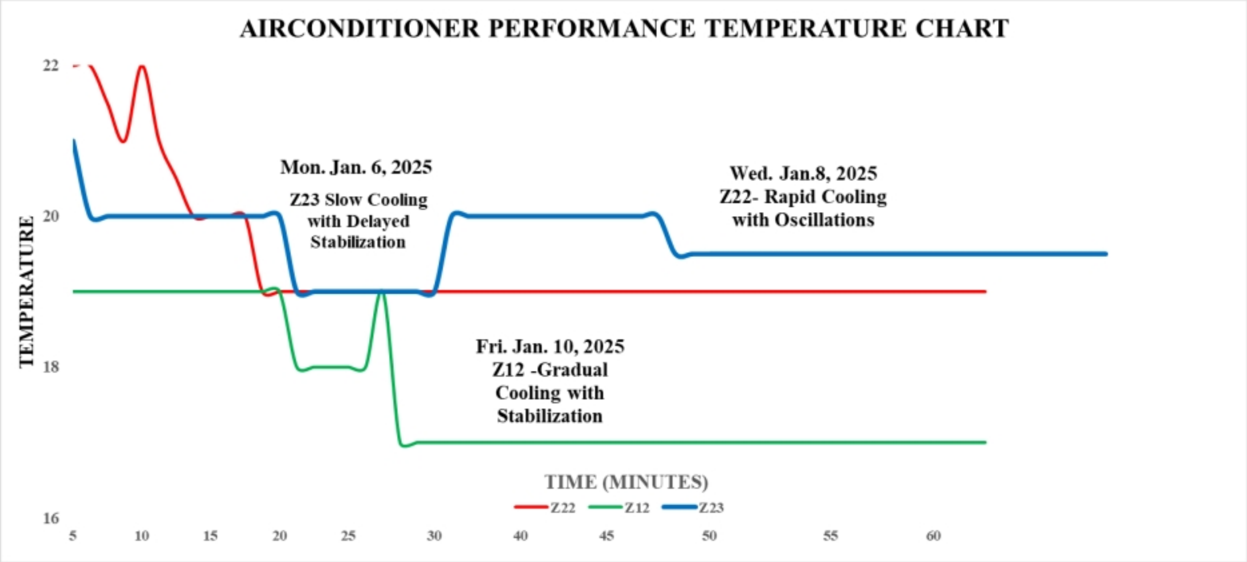

Figure 7: Air conditioner User Interface (UI) with three (3) different outcomes.

4.2 Discussion of Findings

The user interface and the centralized dashboard in Figure 4 revealed a highly intuitive design that allows users to monitor the operational status and environmental parameters (e.g., temperature) of connected devices. Users were able to:

i. Set and adjust device parameters remotely,
ii. Monitor current room or device-specific temperatures,
iii. View the status (ON/OFF) of multiple devices across different rooms,
iv. Receive real-time feedback on energy consumption and device activity.

The centralized dashboard also facilitated large-scale device management, displaying up-to-date sensor readings for multiple devices (e.g., Y11 to Y33 units) across different categories. This highlights the scalability of the proposed system for larger facilities like hotels, hospitals, and corporate offices.

Refrigerator Performance and Efficiency

Figures 5, 6 and 7 show the temperature output of the refrigerator (REF), water heater (W.H), and air conditioner (A.C) over extended time periods. The trends highlight important operational characteristics and areas for optimization. The refrigerator temperature (black line) exhibits frequent oscillations between 5’C and – 5’C, suggesting:

i. Regular compressor cycling, necessary for maintaining stable internal cooling but also contributing to high energy demand [11].
ii. Sudden temperature spikes and drops, potentially linked to fluctuations in ambient conditions, compressor inefficiencies, or door openings [12].
iii. A need for predicting cooling algorithms that reduce unnecessary compressor

activity, thereby enhancing energy savings [13].

Water Heater Heating Profile

Water heater temperature (green line) shows a gradual increase over time reaching 20'C to 45'C, indicating:

i. A stable and progressive heating cycle, suggesting optimal operation within the expected range [14].
ii. Fluctuations in temperature, which might be influences by irregular power supply or variations in external thermal load [15].
iii. The potential for smart heating control where AI algorithms predict peak usage times and adjust heating cycles for better energy efficiency [16].

Air conditioner Cooling Patterns

The air conditioner (red line) maintains a relatively consistent temperature range between 20'C and 27'C with key observations including:

i. Stable cooling performance suggesting and efficient regulatory mechanism [17].
ii. Variability in cooling patterns, likely caused by changing room occupancy and heat load.
iii. Potential energy optimization strategies such as adaptive cooling algorithms that adjust setpoints based on real – time occupancy and external weather conditions.

Implication of Findings

The results have significant implications for personal convenience and cost savings to users. By providing granular control over home appliances and delivering real-time consumption analytics, users can make more informed decisions about their energy usage. The ability to adjust device settings remotely also enhances user comfort, particularly in regions with extreme weather variations.

The results also show that stakeholders can also leverage on the system's ability to monitor, analyze, and control multiple devices translates into direct operational benefits for facility managers, hotel operators, and utility service providers. Stakeholders can:

i. Reduce maintenance costs through predictive maintenance alerts,
ii. Improve customer satisfaction by offering tailored room temperature settings,
iii. Optimize energy usage across multiple devices and locations, ultimately reducing operational expenditures.

The deployment can also provide researchers with a real-world platform for data collection on energy usage patterns, device performance, and user interaction behaviors. This data can be invaluable in:

i. Building machine learning models to predict energy needs,
ii. Designing more efficient IoT communication protocols,
iii. Developing user-centered smart home interfaces.

This research aligns with the global pursuit of sustainable development goals (SDGs), especially those targeting affordable and clean energy (SDG 7) and climate action (SDG 13). By enabling more conscious energy consumption behaviors and optimizing appliance operation, the system contributes to:

i. Reducing carbon footprints,
ii. Promoting energy conservation,
iii. Improving overall environmental health.

Moreover, democratizing access to smart control systems fosters technological inclusivity, offering individuals across various socio-economic backgrounds the tools needed to manage their resources more effectively.

5. CONCLUSION

The findings of this research highlight the importance of intuitive UI design, secure communication protocols, and seamless interoperability in IoT systems. Addressing challenges such as latency, cloud dependency, and data security will further enhance the reliability and scalability of smart home automation.

Building on the current system, future work can focus on integrating artificial intelligence (AI) to enhance the system's predictive and adaptive functionalities. This includes the development of machine learning models for anomaly detection to enable proactive identification of device malfunctions and inefficiencies. Furthermore, reinforcement learning approaches can be explored to dynamically optimize energy consumption by learning from user behavior and environmental changes. To improve accessibility, natural language processing (NLP) techniques can be incorporated to support voice-command interfaces, facilitating more intuitive user interactions. These AI-driven enhancements are expected to increase the overall intelligence, efficiency, and usability of the IoT monitoring and control system

Ultimately, this study contributes to the growing field of IoT-driven home automation by providing a framework that balances energy management, user interaction, and technological scalability. The adoption of such systems can play a crucial role in reducing household energy consumption, lowering costs, and supporting global sustainability initiatives.

6. ACKNOWLEDGEMENT

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