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IoT-Based Design of Automatic Home Lighting Using PIR Sensor and Manual Override

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ABSTRACT

Smart home automation systems are recognized as innovative methods to enhance comfort, efficiency, adaptability, and environmental connectivity. This study presented an IoT-based automatic home lighting system that combined occupancy sensing, ambient-light sensing, local override, scheduling, and remote control. The implemented prototype utilized an ESP32 microcontroller, an HC-SR501 Passive Infrared (PIR) sensor, a Light Dependent Resistor (LDR), a 5V relay, a physical push button, Network Time Protocol (NTP) synchronization, and an Android application. The control policy activated the lamp automatically only when motion was detected under low-light conditions, while local and remote modes allowed user intervention. Functional testing verified consistent PIR detection within a range of 1 to 5 m at an approximately 110° field of view and prevented automatic lamp activation when ambient illumination exceeded the configured 500-lux threshold. On a stable local Wi-Fi network, the application-to-relay response time ranged between 120 and 250 ms, while scheduled ON/OFF execution was within ±1 s. The manual override remained operational during Wi-Fi disconnections, and state changes were timestamped in the activity log. These results demonstrate reliable multimodal lighting control; however, direct electrical-energy savings were not quantified because the prototype did not include a power-metering module.

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1. INTRODUCTION

1.1 Background and Problem Identification

Energy consumption in the residential sector has seen a significant upward trend over the last decade. According to various energy reports, lighting and small electronic appliances account for a substantial portion of monthly electricity bills. However, a significant percentage of this energy is wasted due to human factors primarily negligence. Inhabitants often forget to deactivate switches when leaving a room or during daylight hours when natural illumination is sufficient [1]. Traditional electrical installations rely solely on manual intervention, which lacks the intelligence to adapt to environmental changes or human presence. This gap between manual control and energy efficiency goals necessitates a technological intervention that can minimize

human error. IoT-enabled home automation can address this problem by combining environmental sensing, local control, and networked monitoring. Recent systems have used PIR sensors for occupancy, LDR sensors for daylight availability, microcontrollers for rule execution, and mobile or web applications for remote control [2], [3]. However, automation based on only one sensing condition can still produce unnecessary switching. Occupancy-only lighting may turn on during adequate daylight, whereas light-only control cannot determine whether the room is occupied. A more appropriate control policy therefore combines occupancy and ambient-light conditions before energizing the lamp.

Furthermore, safety concerns arise when electrical devices are left active without supervision for extended periods. Overheating or short circuits in unattended appliances can lead to fire hazards. Therefore, a system that not only automates energy saving but also provides remote monitoring capabilities becomes essential for modern smart living.

1.2 The Role of IoT and ESP32 Technology

The emergence of the Internet of Things (IoT) has revolutionized home automation by enabling physical objects to communicate over the internet. At the heart of this technological shift is the ESP32 microcontroller, a powerful and cost-effective solution developed by Espressif Systems [4]. A microcontroller-also referred to as a microcontroller unit or MCU-is defined as a compact computer system contained within a single integrated circuit (IC). Unlike its predecessors, the ESP32 features a dual-core processor, integrated Wi-Fi, and dual-mode Bluetooth, making it an ideal candidate for complex IoT nodes. Its ability to handle multiple sensor inputs while maintaining a persistent connection to a cloud server or a mobile application allows for the development of highly responsive smart home systems.

1.3. Multi-Sensor Integration Strategy (PIR and LDR)

A common flaw in many existing automation systems is the reliance on a single trigger mechanism. For instance, a system using only a Passive Infrared (PIR) sensor defined as a device that detects changes in infrared radiation emitted by warm objects, such as the human body [5] will activate lights whenever motion is detected, regardless of the time of day, leading to energy waste during sunny periods. To solve this, this research integrates a light sensor, specifically a Light Dependent Resistor (LDR). A light sensor enables a system to distinguish between dark and bright environments, allowing it to determine whether it is day or night [6]. By implementing a logic-gate approach where the light only activates if (Motion = Detected) AND (Ambient Light < Threshold), the system achieves a higher level of "context-awareness." This dual-mode sensing ensures that the automation is truly efficient, operating only when both human presence and a lack of light are confirmed.

1.4 Manual Override and User Transparency

One of the critical challenges in IoT development is system reliability during network failures. Many smart switches become unusable if the Wi-Fi connection drops. This study addresses this by implementing a physical push-button manual override, ensuring that the system remains functional as a conventional switch in emergencies. While cloud computing offers scalability and the capacity to handle large volumes of data for real-time monitoring, such integration often creates a heavy reliance on internet connectivity [3].

To overcome this limitation, the system developed in this study prioritizes local reliability while maintaining user transparency through an Android-based application. In this context, the interface acts as more than just a remote control; it serves as a data visualization tool. By utilizing NTP synchronization and a comprehensive logging system, the application provides real-time status updates and scheduling without sacrificing the system's autonomy during network outages. These logs allow users to audit their energy usage patterns, fostering a more conscious approach to electricity consumption.

1.5 Research Objectives

This study contributes a compact IoT smart-lighting prototype with four integrated functions: (1) context-aware automatic switching using PIR and LDR inputs; (2) a physical manual override that preserves local operation when Wi-Fi is unavailable; (3) remote control and NTP-based scheduling through an Android interface; and (4) timestamped state logging for operational transparency. The research objective is to design, implement, and experimentally evaluate the functional reliability and response characteristics of this multimodal lighting controller. Claims of electrical-energy savings are intentionally limited to reduced unnecessary operating opportunities because direct watt-hour consumption was not measured in the current prototype.

2. METHOD

The methodology of this research follows a structured engineering approach, consisting of hardware integration, software development, and system testing. The system is designed to operate as a smart node within a local wireless network. Figure 1 summarizes the sequence used to move from system requirements to evaluation.

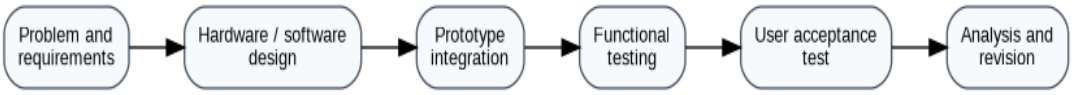


Figure 1. Research workflow from requirements analysis to system evaluation.

A. System Architecture

The architecture consists of three main layers: the perception layer (sensors), the network layer (Wi-Fi), and the application layer (Android App). The ESP32 acts as the core controller, receiving inputs from the PIR sensor (motion), LDR sensor (light intensity), and a physical push button. Data is processed to trigger a 5V Relay module, which switches the 220V AC load.

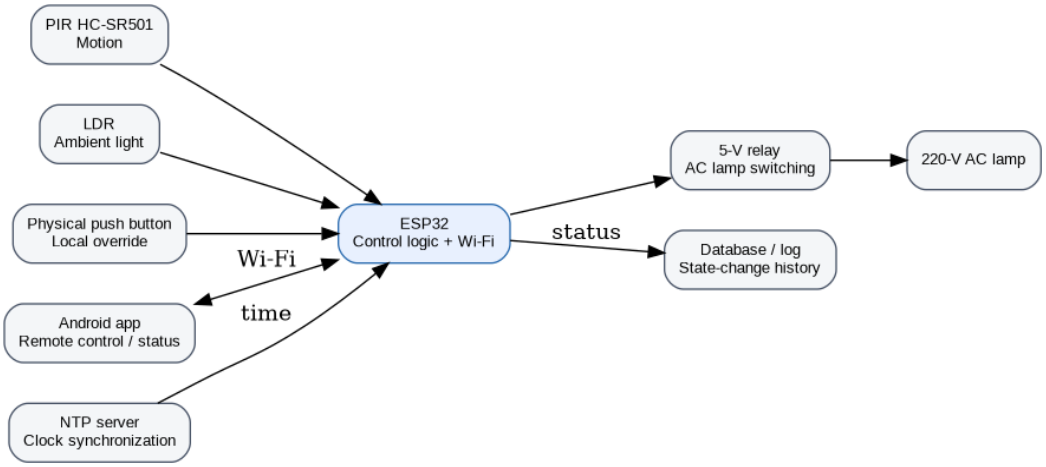


Figure 2. Integrated architecture of the ESP32-based smart-lighting prototype.

B. Hardware Implementation

The hardware components were selected based on their reliability and low power consumption:

1. **ESP32 Microcontroller:** At the core of a hub-based system is the hub itself, that is, a tangible piece of hardware that acts as the central unit coordinating all connected devices. Implementing this concept, the ESP32 was chosen as the primary controller due to its dual-core processor and integrated Wi-Fi/Bluetooth modules. Furthermore, the ESP32 provides NTP synchronization to support the scheduler functionality, allowing the device to maintain accurate timing for all automated tasks within the system.

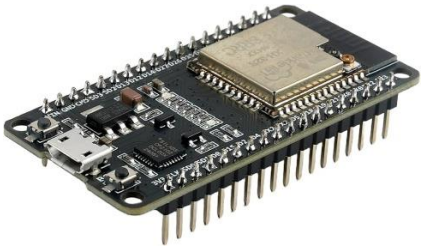


Figure 3. ESP32

2. **PIR Sensor (HC-SR501):** Utilized to detect infrared radiation from human movement within a 7meter range.



Figure 4. PIR Motion Sensor

3. **LDR Sensor:** Used to measure ambient light levels to prevent the lights from turning on during daylight hours.



Figure 5. LDR Sensor

4. **Network Time Protocol:** Time synchronization has a significant contribution in distributed systems and plays a crucial part in any infrastructure [7]. In this system, Network Time Protocol provides highly accurate time synchronization from internet servers to ensure that the lighting schedules are executed precisely at the programmed intervals. By leveraging its built-in Wi-Fi connectivity, the ESP32 retrieves real-time data from these servers to maintain consistent operation and timing accuracy even after a system reset.

5. **Relay Module:** Acts as an electromagnetic switch to control high-voltage appliances.



Figure 6. Relay Module

C. Software Development

The software was developed using the Arduino IDE for the firmware and a mobile framework for the Android application. Arduino IDE is an official software introduced by Arduino.cc, that is mainly used for editing, compiling and uploading the code in the Arduino Device [8]. In this project, this environment was utilized to program the ESP32 controller, ensuring that the source code is efficiently compiled and deployed. Following the successful upload of the firmware, the control logic follows a multi-conditional algorithm to process inputs from the PIR and LDR sensors simultaneously.:

1. Automatic Mode: The relay activates only if the PIR sensor detects motion and the LDR sensor value is below a specific darkness threshold.
2. Manual & Scheduling Mode: Users can override the sensors via the Android App or set specific time intervals using the NTP (Network Time Protocol) for accurate synchronization.

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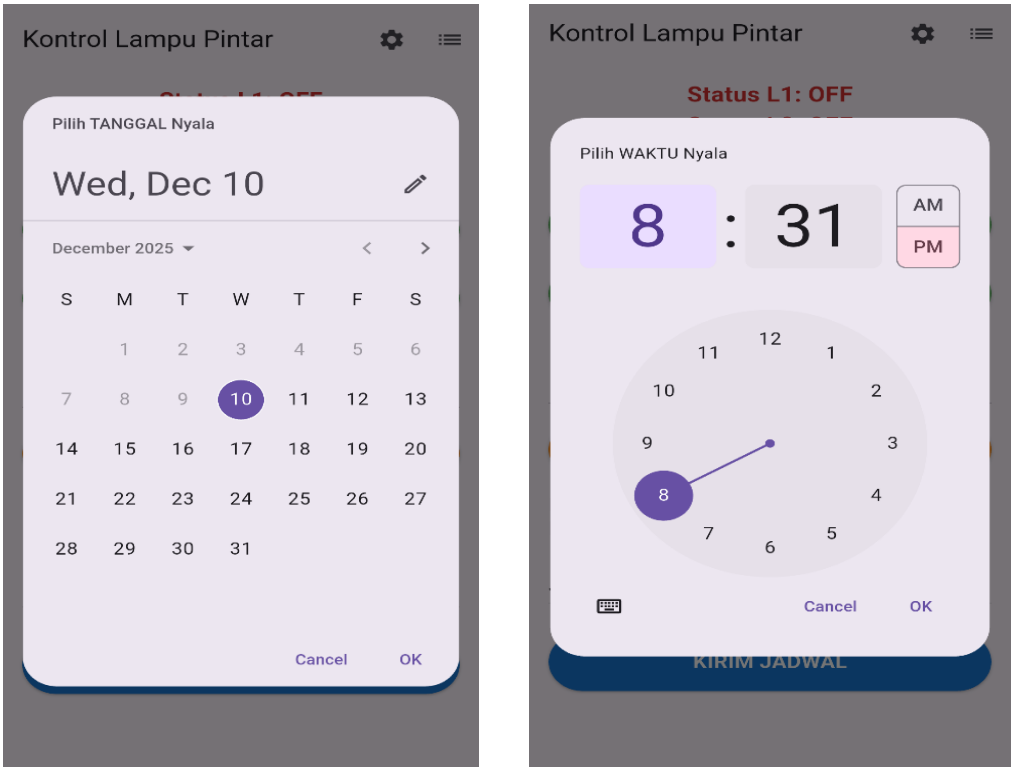


Figure7. Schedule Date and Clock ON

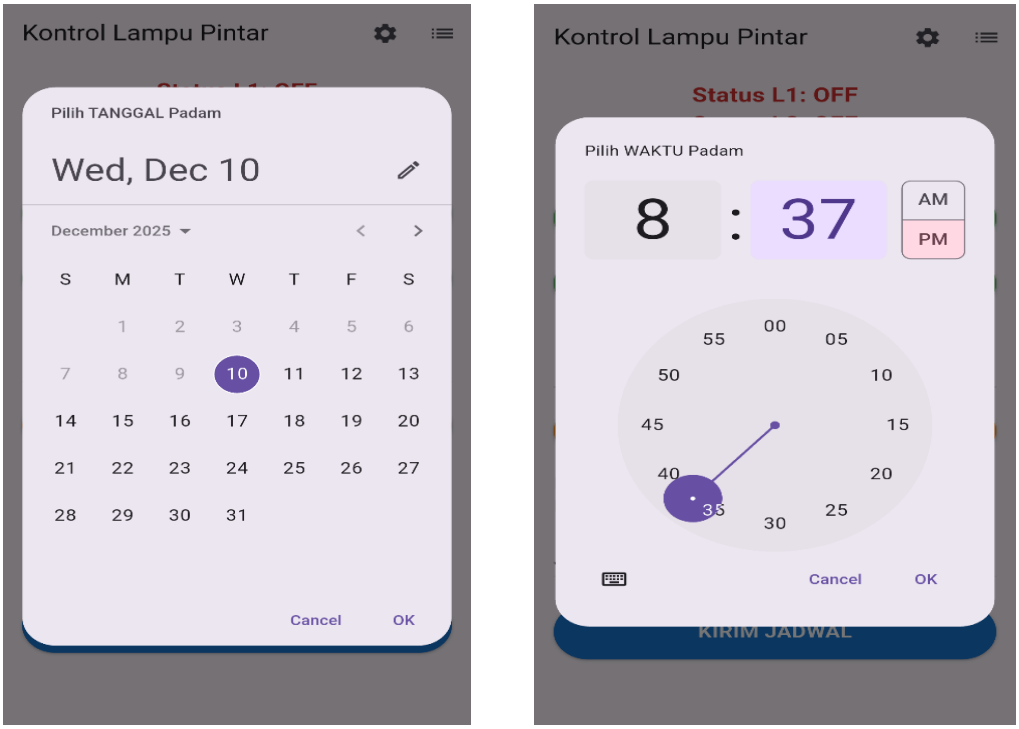


Figure 8. Schedule Date and Clock OFF

3. **Data Logging:** Every state change is recorded and sent to a database, allowing users to monitor historical usage through the mobile interface.



Figure 9: Logging

D. Testing Procedure

The evaluation of the developed system was carried out through a systematic two-stage testing process to ensure both technical reliability and user satisfaction. This structured approach allowed for the identification of potential hardware limitations and software usability issues.

1. Technical Functional Testing

The first phase focused on the operational integrity of the hardware components and the accuracy of the control logic. This phase was divided into several specific test scenarios:

a. Sensor Sensitivity Analysis: The PIR sensor was tested by simulating human movement at various distances (1m to 7m) and angles to determine the maximum detection perimeter. Simultaneously, the LDR sensor was tested under different lighting levels (measured in Lux) to define the optimal threshold for the "Dark" and "Light" conditions.

b. Response Latency Measurement: This test measured the time interval between a user triggering a command on the Android Application and the physical activation of the Relay. Testing was performed across different network conditions to evaluate the impact of signal strength on system responsiveness.

c. Reliability of Manual Override: A critical test was conducted to ensure the physical push button could override the automated sensor logic and the mobile application commands, especially during simulated Wi-Fi disconnection.

2. User Acceptance Test (UAT)

The second phase involved human-centric evaluation to assess the practical utility of the system. A group of participants was selected to interact with the device and the mobile interface.

a. Participant Interaction: Users were given a set of tasks, such as manually toggling the lamp via the app, setting a specific schedule, and reviewing the activity logs.

b. Measurement Scale: Feedback was collected using a structured questionnaire based on the Likert Scale (1-5). The evaluation criteria included:

1. Ease of Use: How intuitive the Android interface is for first-time users.
2. Information Clarity: The readability of the activity logs and status indicators.
3. Automation Trust: The perceived reliability of the PIR and LDR sensors in managing the lights without manual intervention.

3. Data Analysis Method

Data collected from the functional tests were tabulated and compared against the initial design specifications. For the UAT, the mean score for each criterion was calculated to determine the overall system performance. A system is considered successful if it achieves an average score of "Good" (4.0) or higher across all parameters, indicating that it is ready for real-world residential deployment.

3. RESULT AND DISCUSSION

This section presents the experimental results of the implemented system, including functional evaluations of the sensors, the performance of the wireless control, and the feedback from the user acceptance tests.

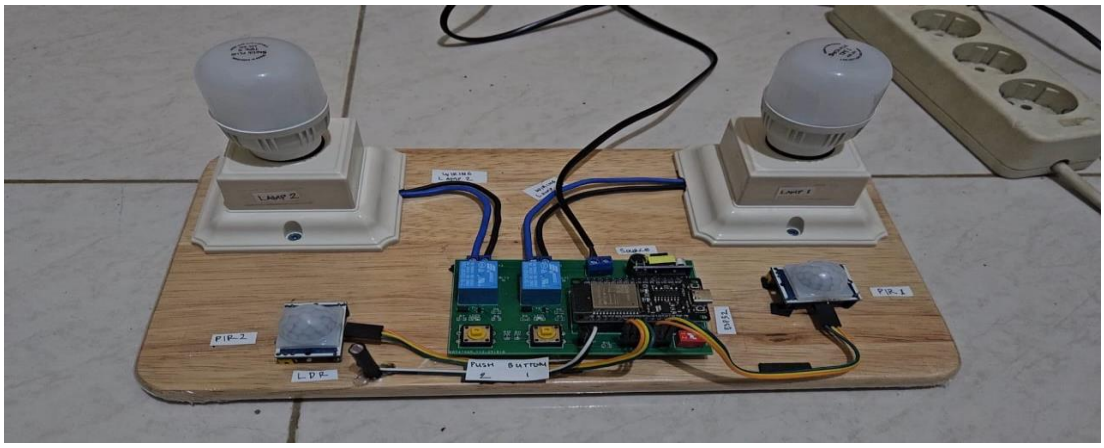


Figure 10: ESP32 system prototype

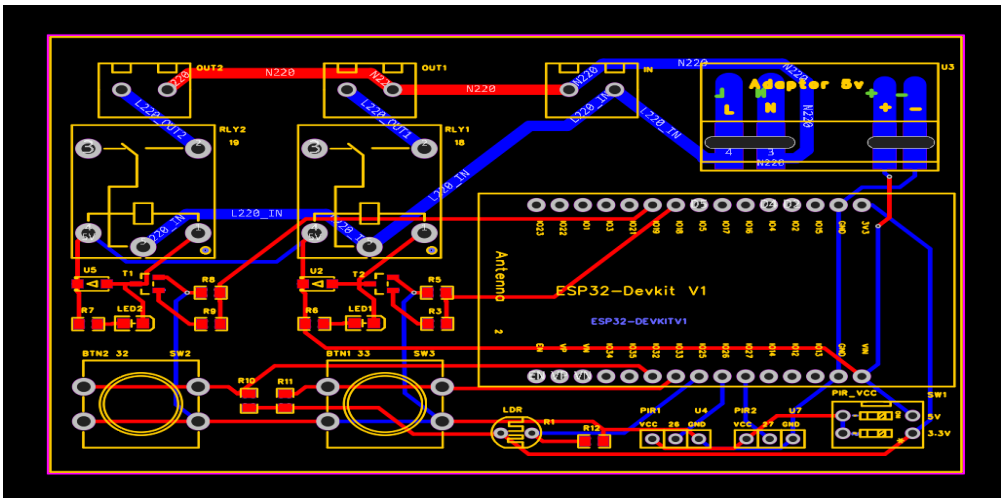


Figure 11: PCB Scheme

3.1 Functional Testing of Sensors and Actuators

The primary objective was to ensure that each hardware component responded accurately to environmental stimuli. The PIR sensor and LDR sensor were tested under various conditions to determine their reliability.

1. PIR Sensor Evaluation: Testing showed that the HC-SR501 sensor could consistently detect human movement within a range of 1 to 5 meters with a detection angle of approximately 110°.
2. LDR Sensor Calibration: The LDR was calibrated to define a "dark" threshold. The system successfully prevented the light from turning on when the ambient light exceeded 500 lux, even if motion was detected.
3. Manual Push Button: The physical button demonstrated a 100% response rate, acting as an interrupt to toggle the relay state regardless of the current sensor or app status.

3.2 Wireless Control and Connectivity Performance

Wireless networking allows you to connect several computers or smart devices in your home without the need for a physical cable, providing significant flexibility for IoT deployments [9]. In this research, the integration between the ESP32 and the Android application was tested to measure latency and connection stability within this wireless environment. This evaluation ensures that the system can maintain a reliable exchange of data between the controller and the user interface without the constraints of a wired infrastructure [10].

1. Latency: The average time between sending a command from the Android app and the relay activation was measured at approximately 120ms to 250ms on a stable local WiFi network.
2. Time Scheduling: Utilizing the Network Time Protocol (NTP), the system executed scheduled ON/OFF commands with a precision of ± 1 second.
3. Logging System: Every state change triggered by sensors or the app was successfully recorded in the database with an accurate timestamp, providing a reliable audit trail for energy usage.

3.3 User Acceptance Test (UAT) Analysis

To evaluate the system from a user's perspective, participants were involved in a controlled trial. They were asked to operate the system through the mobile app and observe the automation features. The results were quantified using a Likert scale (1 to 5).

Table 1: UAT Test Result

No.	Parameter	Category
1	Ease of Use (App Navigation)	Very Good
2	System Responsiveness	Good
3	Automation Accuracy (PIR/LDR)	Very Good
4	Features (Logging & Scheduling)	Good
	Average Total	**Very Good**

3.4 Discussion

The results align with the broader literature showing that occupancy and ambient-light information are complementary inputs for adaptive lighting [11]. Rabbani and Foo [12] also used PIR and LDR sensing but included a PZEM-004T module and consequently could report electrical consumption; this distinction is important because the present study cannot substantiate a numerical energy-saving percentage. Mustofa et al. [5] and Addow et al. [3] demonstrate broader ESP32-based smart-home platforms with multiple sensors and network services, whereas the present prototype focuses on a simpler lighting-specific controller with a physical fail-safe override, NTP scheduling, and timestamped logging. Recent MQTT-based ESP32-node architectures [6] provide a more scalable publish/subscribe communication model than the current prototype and therefore represent a logical direction for multi-room expansion.

The measured 120-250 ms local-network switching latency is substantially below one second and is adequate for interactive lighting control. Nevertheless, it should not be generalized to wide-area Internet conditions because the experiment did not report received-signal-strength indicator (RSSI), packet loss, or latency distributions under weak Wi-Fi. Similarly, the PIR result should be interpreted as a validated operating range of 1-5 m for the present setup rather than the maximum capability of the HC-SR501 device.

4. CONCLUSION

The design and development of the IoT-based smart lighting system using the ESP32 microcontroller have been successfully implemented. The integration of PIR and LDR sensors provide a highly efficient automation logic, ensuring that lights are only activated when a room is occupied and ambient light is insufficient. Experimental results demonstrate that the system is reliable, with a high accuracy rate in motion detection and a responsive wireless control interface via the Android application.

The inclusion of multiple control modes: automatic (sensors), manual (physical push button), and remote (mobile app) enhances the system's flexibility and ensures functionality even during network outages. Furthermore, the real-time logging and scheduling features provide users with better transparency and control over their energy consumption. The User Acceptance Test (UAT) score of 4.5 out of 5.0 confirms that the system is intuitive and meets the practical needs of a smart home environment.

For future work, the system could be enhanced by integrating a power monitoring module (e.g., PZEM-004T) to provide real-time data on actual electricity savings in Watts. Additionally, implementing the MQTT protocol would improve scalability and communication efficiency for larger multi-node installations, and integration with voice-controlled assistants like Google Assistant or Alexa could further improve user accessibility.

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