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Design and Implementation of an ESP32-Based IoT Smart Room System with Automated Temperature, Ventilation, and Lighting Control

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Abstract

This study develops a Smart Room System based on the Internet of Things (IoT) to enhance comfort and energy efficiency in boarding rooms by integrating automatic control of temperature, ventilation, and lighting. The system uses a DHT22 sensorr to monitor temperature and humidity, a PIR se to detect occupant and control lighting, a servo motor regulate ventilation, and a DC fan as the temperature controller. All components are managed by an ESP32 microcontroller connected to a web dashboard that enables real-time monitoring and remote control. The research methodology includes requiments analysis, system architecture design, web server develoment, hardware softwae integration, and functional testing. The test result indicate that the system operates automatically and reliably, the fan and servo active when the temperature exceeds the threshold, and the light turn on when the PIR sensor detects motion. Manual control via the web interface also functions effectively with low latency (0.5-1 s). In conclusion, the Smart Room System succesfully improves energi efficiency and provides convenient remote control, althrough it remains dependent on a stable Wi-Fi connection for monitoring and manual control features.

Keywords: Internet of Things (IoT), Smart Room, ESP32 Microcontroller, Room Automation, Boarding Room

1. Introduction

The application of technology in daily life is a form of creative innovation capable of increasing comfort and energy efficiency, including in boarding rooms widely used by students and migrant workers as their primary residence while studying and working outside their home region [1]. However, limitations in room size and varying environmental conditions often lead to problems such as increased room temperature due to suboptimal ventilation and residents forgetting to turn off the lights when leaving the room. To address these issues, utilizing natural ventilation, using energy-efficient fans [2] and implementing automatic lighting based on Passive Infrared (PIR) sensors can be effective solutions. This condition highlights the need for a smarter room management system, especially to prevent energy waste and improve comfort. As the need for more efficient living spaces grows, the Internet of Things (IoT)-based smart room concept becomes a relevant approach because it allows devices within the room to operate automatically, respond to environmental changes, and be monitored and controlled remotely.

The Internet of Things (IoT) is a technological paradigm that allows electronic devices to communicate and exchange data with each other over the internet. In the context of smart boarding rooms, IoT plays a crucial role in real-time monitoring, control, and automation of various electronic devices. This technology opens up opportunities to create systems that can adapt to environmental conditions while also providing greater comfort to users. Dorm rooms, which typically lack complex environmental management systems, can see an improvement in living quality with the implementation of IoT technology at a relatively affordable cost [3]. In this research the writer is going to use ESP32 for the main microcontroller. The ESP32 is a highly capable microcontroller developed by Espressif Systems Part of the ESP8266/ESP32 chip family, it is specifically designed for IoT applications. For monitoring Temperature and Humidity levels there are mainly three different types of sensors, which are DHT22, DHT11, and SHT71. Of that three sensors DHT22 is the best as it has good accuracy and low cost. Mainly it is an acceptable range than the other two. And it has low power consumption which we mainly focused on in the paper [4].

The use of the DHT22 sensor for an automatic temperature control system and actuators like DC fans can maintain room temperature on a small scale, such as in a boarding room [5]. Similarly, using motor sensors to automatically open and close air vents is effective in improving air circulation in small rooms [6][7]. Additionally, the use of Passive Infrared (PIR) sensors to detect human presence has been widely implemented in automatic lighting systems, thereby reducing energy consumption caused by inefficient use of lights [8]. However, most previously developed systems only focused on one or two aspects of automation, such as temperature control alone or automatic lights only, without comprehensive integration with a web platform for remote monitoring and control. Remote monitoring will allow boarding house owners to ensure that electronic equipment such as fans and lights is completely turned off remotely. Additionally, remote monitoring allows manual control systems to prevent automatic controls from working or being needed [9]. The ESP32 will play a big role into making the system remotely accessible. The ESP32 is a versatile and energy-efficient microcontroller featuring dual-core processing, integrated Wi-Fi and Bluetooth, and multiple GPIO ports. This networking capabilities of the ESP32 allow for centralized and remote management through cloud platforms or local servers, enabling adminitstrators to monitor and control all connected devices via a single interface accessible from computers or smartphones [10].

This research develops an IoT-based Smart Room System that integrates several control functions simultaneously, mainly room temperature control using DHT22 sensors and DC fans, servo motors for ventilation adjustment, and PIR sensors for automatic lighting based on motion detection using PIR sensors. The system is also equipped with a web platform that displays real-time room condition information and allows users to remotely control fans, ventilation, and lights. With web-based control and monitoring features, users can manage their rooms from anywhere and anytime they are connected to the internet [11][12].

This research aims to design and implement a Smart Room System to enhance boarding house occupant comfort while optimizing energy usage. The system includes automatic temperature control responsive to room conditions, automated ventilation operation, presence-based lighting control, and an integrated web platform for remote monitoring and control [13].

This research is expected to contribute to the development of simple, effective, and widely applicable smart housing solutions, particularly in boarding houses with limited resources. In addition, this research also provides insights into the potential application of Internet of Things technology in creating more efficient, comfortable, and energy-friendly room management systems. Thus, this research not only offers practical value but can also serve as a reference for further innovation development in the fields of automation and IoT-based systems.

2. Methodology

This section will explain the methodology used in designing an Internet of Things-based Smart Room System for Automatic Temperature, Ventilation, and Lighting Control, as well as Web-based Monitoring and Control for Dorm Rooms. This is based on the system block diagram that was compiled in Figure 1 below. The block diagram below serves as the foundation for the research workflow, starting with user input thru the web dashboard, data from the DHT22 and PIR sensors, then proceeding to the processing block where the microcontroller will process all data from each sensor. After the data is processed, it will continue to the output process where actuators such as servos, fans, and lights will be activated. All stages of the methodology, from needs analysis, architecture design, to implementation.

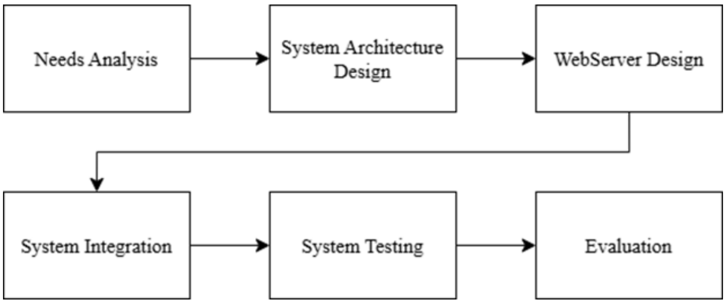

Figure 1. Workflow Block Diagram

2.1 Needs Analysis

Needs analysis was conducted to ensure that the Smart Room automation system designed will work as intended, which is to provide device control both manually and automatically via the web. Based on observations made in several students' boarding rooms, there is a need for the ability to turn lights or fans on and off remotely, adjust the fan speed according to the room temperature, and monitor device status in real-time. The developed system will also be able to open ventilation channels from the room using a servo as an actuator if the temperature value exceeds the threshold. Therefore, the system will require a web-based dashboard as the user interface, an ESP32 module as the main controller, and relays as actuators/switches for electrical devices such as lights. The system will also require a Wi-Fi connection for data communication, data storage to retain data after a restart, and a WebSocket mechanism for rapid status updates. All these needs are designed to make the system simple to operate, easy to use, and capable of reducing energy waste in the lecture hall [14]-[16].

2.2 System Architecture Design

In the system design phase, a simulation of the system to be created will be conducted. In this phase, components will be arranged in such a way that they can be used as a reference when creating the system prototype later. Below is the circuit diagram and wiring connections from the simulation that has been performed:

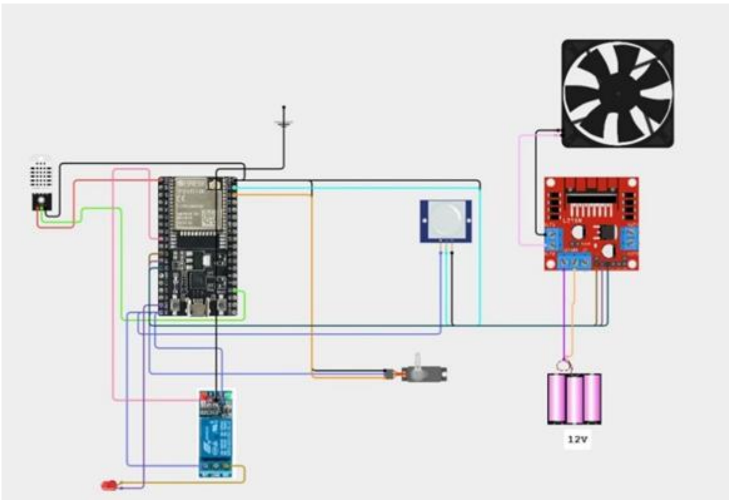

Figure 2. Circuit Simulation

The diagram above shows all the components that will be used. In the simulation created, the ESP32 will function as the main controller. The DHT22 will determine the action of the fan and servo. If the temperature detected by the DHT22 is greater than the specified temperature, the fan and servo will run. The speed of the fan can be adjusted by the motor driver depending on the temperature value [17]; if the temperature value increases, the fan speed increases. Next, there's a PIR sensor and an LED; if the PIR sensor detects an object, the LED will turn on.

2.3 WebServer Design

In this WebServer design stage, a design or mock-up of the webserver interface that will be created and integrated into the system later has been made. Here is the designed mock-up.

Figure 3. Mock Up Interface

The image above is the design for the control page that will be used as the monitoring and manual control page for the system. The communication protocol that will be used is the HTTP/HTTPS protocol. On this control panel page, users will be able to view the sensor readings from each integrated sensor, namely the DHT22 Sensor and the PIR Sensor. In addition, users can also choose to manually control the system from the control page and change the temperature threshold value. With this manual control feature, users will be able to control lights, fans, and ventilation remotely.

2.4 System Integration

At this stage, the system that has been created will be integrated with the webserver that has been built. This will be possible because the microcontroller used, the ESP32, is already equipped with a Wi-Fi module that allows connection between the system and the webserver. Users only need to add the SSID and password of the Wi-Fi they will be using to the program code.

```
// WiFi Configuration
const char* ssid = "pp";            // ⚠ GANTI dengan nama WiFi Anda
const char* password = "amanlah22";  // ⚠ GANTI dengan password WiFi Anda
const char* serverURL = "http://10.206.253.178:3000"; // ⚠ GANTI dengan IP Laptop Server

WebServer server(80);
```

Figure 4. Wi-Fi Configuration

After the connection is successful, the user can then open the IP address of the laptop or device used as the server. In this case, the address is http://10.206.253.178:3000, with port 3000 being the port for the web application running locally. Once the page is open, the user can then directly view the running web interface and monitor data and perform manual control. Here is the finished WebServer interface.

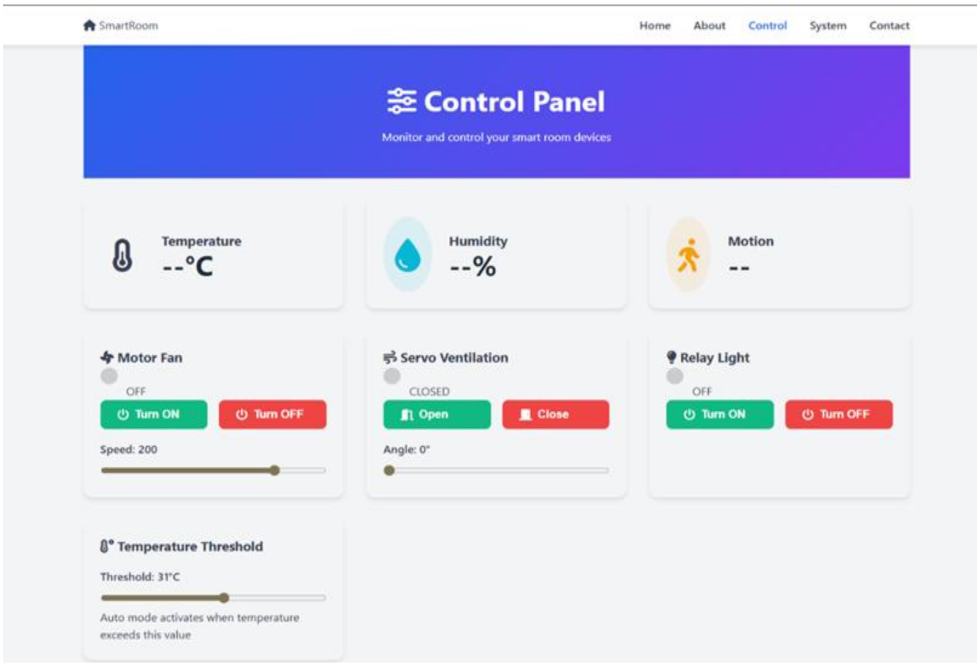

Figure 5. Web Server UI Display

2.5 System Testing

System testing is performed to ensure that all system functions work well, either directly from the webserver or offline. Here, testing will be conducted for each part of the features that have been designed.

1. Temperature and Fan Testing
   - The temperature is raised above the threshold.
   - The DC fan automatically activates and its speed adjusts according to the temperature value. When the temperature drops, the fan will turn off.
2. Ventilation Testing (Servo)
   - The temperature is raised above the threshold.
   - The servo moves to open the ventilation (0-90°) responsively according to the DHT22 reading, and the servo also closes the ventilation when the temperature has dropped back down.
3. Lamp Testing (PIR)
   - An object is detected by the PIR sensor.
   - The light turns on. When no more objects are detected by the PIR, the light will turn off to save energy.
4. Testing via WebServer (Manual Control)
   - The fan speed button, light switch, and vent opening are pressed on the web.
   - The system responds and begins to activate the devices related to the pressed buttons with a latency of approximately 0.5 – 1 s.

2.6 Evaluation

Evaluation is conducted to determine whether the system successfully meets all previously implemented scenarios. Here, the system has proven successful in increasing energy efficiency (automatic lights/fans off) and providing remote control convenience as per the initial goal. Reliance on a stable internet/Wi-Fi connection has become extremely important. If the internet goes down, the manual monitoring and control features from the web will not be able to function. However, the system will continue to run automatically without web monitoring.

3. Results and Discussion

The results and discussion section of this study presents the main findings from the implementation of an Internet of Things-based Smart Room System for automatic temperature, ventilation, and lighting control, as well as web-based monitoring and control. The test results are accompanied by explanations and analyzes that link the researcher's findings to the research objectives and related theories. Testing includes performance analysis of DHT22 and PIR sensors, servo and DC fan actuators, and system integration with a web platform. The results obtained not only demonstrate the system's functionality but can also be understood thru its impact on the effectiveness of indoor automation.

Testing of the DHT22 sensor showed that the device is capable of reading temperature and humidity stably and quickly, making it suitable for use in small rooms like boarding houses. The DC fan activity automatically runs when the temperature exceeds the set threshold and will return to inactive when normal conditions are detected. This finding indicates that the temperature control system is functioning in accordance with previous research that implemented the DHT22 as a sensor capable of reading room temperature conditions, which were used as the control condition. In the ventilation mechanism, the servo motor can adjust the ventilation opening based on environmental conditions. The servo works responsively and according to the readings from the DHT22 sensor.

Next, testing of the PIR sensor showed a high detection success rate for automatic lighting. The light turns on when the sensor detects movement from the room's occupant and will turn off again when it no longer detects any activity, thus reducing unnecessary energy consumption. This behavior is consistent with the literature stating that PIRs are highly reliable sensors for detecting user presence in small rooms. System integration with the web platform is also working effectively. Users can monitor temperature, humidity, fan status, indoor movement, and lighting conditions in real-time. The manual control feature via the web works with a latency of between 0.5-1 s, indicating a system response that is fast enough for smart home applications.

3.1 System Implementation Results

This Smart Room system has been successfully integrated into the web using the ESP32 module as the main controller, relays for controlling the ON/OFF of the lights, a Motor Driver for controlling the speed of the fan's rotation, and a Servo for opening the ventilation. There is also a web dashboard as a user interface. Dashboard control is also divided into three parts: monitoring, manual control, and automatic scheduling.

The monitoring interface will allow users to view the reading data from each sensor that is running. Users can also see the status of each actuator that is working, whether it is active or inactive.

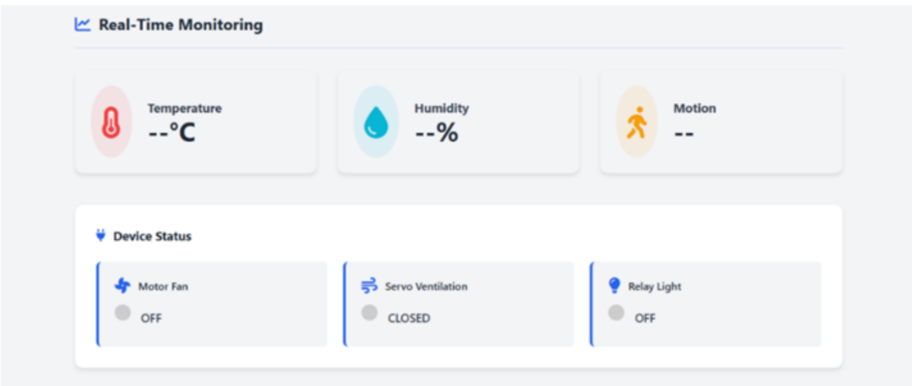

Figure 6. Web Monitoring

The manual control interface will allow users to activate/deactivate the actuators without having to view the sensor's read data conditions. Users can also change the threshold values of the DHT22 sensor and the fan's rotational speed through this page.

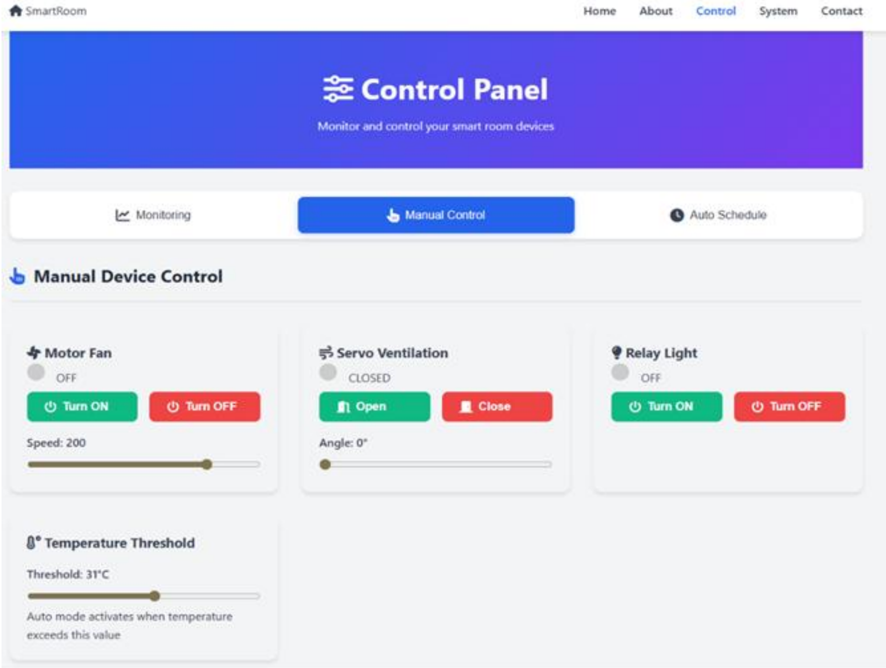

Figure 7. Manual Control Page

The automatic scheduling interface will allow users to add schedules for fan or light activation and automatic ventilation opening.

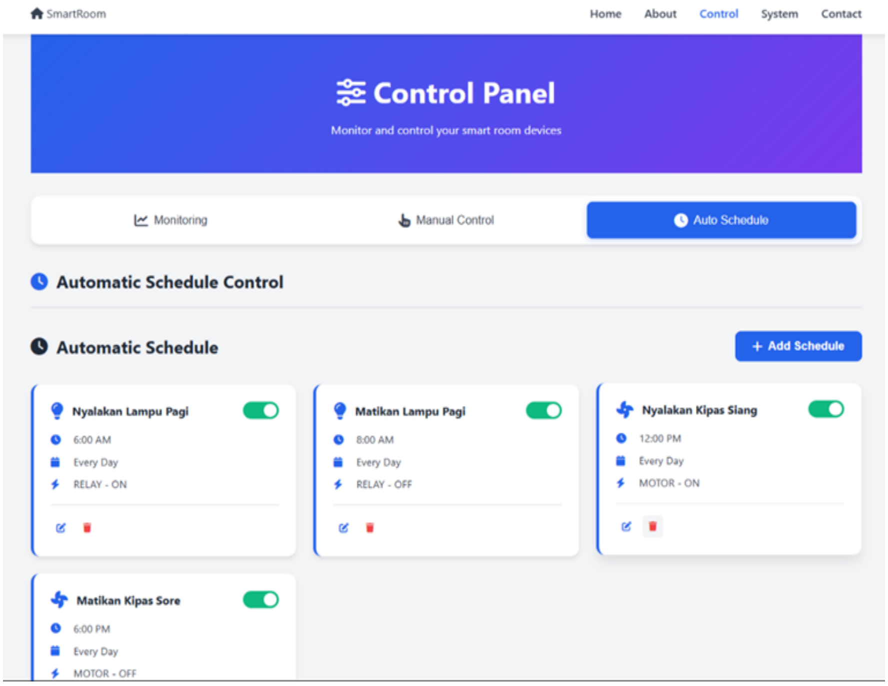

Figure 8. Automatic Scheduling

3.2 Functional and Performance Testing

Results Functionality testing was conducted to ensure that all the main features of the Smart Room System could operate as designed. Testing was conducted in three main stages:

temperature control using DHT22 sensors and DC fans, automatic ventilation mechanism via servo motor actuators, and automatic lighting based on presence using PIR sensors. The testing also included validating the manual control features thru an ESP32-based web platform, where all manual control scenarios were successful with a 90 % success rate, while the remaining failures were due to response delays between commands given from the web and system execution. This problem can be overcome by optimization during the validation process and by improving the system's communication performance.

Table 1. Functional Testing of the System

No	Tested Feature	Test Scenario	Test Result	Status
1	Temperature control (DHT22 & DC Fan)	Temperature raised above threshold	Fan activates automatically and adjusts speed to temperature (±1 s delay)	Succesful
2	Automatic Ventilation (Servo Motor)	Temperature > threshold	Ventilation opens (0°–90°) and closes within (1 s response)	Successful
3	Automatic Lighting	PIR detects motion	Light turns on automatically, and off when no activity is detected	Succesful
4	Web Manual Control (ESP32)	ON/OFF command via dashboard	System response ±0.5–1 s	Succesful (with notes)
5	Status Synchronization	Actuator status changes	Dashboard updates status in real-time < 200 ms	Succesful
6	System Stability	System runs continuously for 12 hours	No crashes, stable connection maintained	Successful

From a system performance testing perspective, response time testing showed that manual control commands from the web dashboard to the ESP32 were processed on average within <1 s, while status updates via WebSocket were received by the dashboard within < 200 ms. These results are quite low for room automation applications, as device status changes occur with sufficient speed. Then, a stress test was conducted by running the device continuously for 8 hours without interruption, which showed that the WebSocket connection was stable and the ESP32 did not crash or overheat. This proves that the server design and schedule storage mechanism are relatively scalable for a dorm room.

Table 2. System Performance Testing

Parameter	Result	Remarks
Manual response time	0.5 - 1 s	Fast
WebSocket update time	< 200 ms	Real-time
Connection stability	12 hours	No Crash
ESP32 CPU Load	18-23 %	Safe
RAM Consumption	± 42 %	Safe
Sensor Reading Delay	150 – 250 ms	Stable
Actuator Response (Servo & Fan)	< 1 s	Highly responsive

Usability was tested by involving users thru interaction evaluation with the control dashboard. The test results show that the interface display is easily understandable and the control features are easy to operate without difficulty. Users find the process of monitoring temperature, device status, and controlling fans and lights via the web more practical than using regular switches. Overall, the system is already in line with the needs of room automation for boarding houses.

3.3 Energy Savings Evaluation

The evaluation of energy savings was conducted through an estimation study (simulation) based on data obtained from the designed prototype. It is important to note that the reported energy savings represent an estimated percentage (potential), as the system has not yet been implemented in a real boarding room environment. The estimation calculations were performed by comparing two scenarios: the baseline condition and the condition with the Smart Room (automation) system implemented.

The estimation of energy savings in this study is based on the following simulation assumptions:

- Baseline scenario without automation: Users are assumed to frequently neglect turning off electrical devices.
- User session duration: User sessions include entering the boarding room, performing activities, and leaving the room.
- Automation activation: The lights are activated only when the PIR sensor detects motion, while the fan and ventilation system (servo) operate only when the temperature exceeds a predefined threshold.
- System efficiency: The system is assumed to operate with 100% effectiveness in turning off devices when no motion is detected or when normal temperature conditions are met.

1 Initial condition without automation
  - LED lights and DC fans are turned on and off manually.
  - In user simulations, devices often remain on even when there is no human presence for some time.
  - Based on prototype testing, the lights and fans have unnecessary active times of between 15-30 minutes per user session, especially when users forget to turn off the devices.

2 Conditions with the Smart Room System
  - The LED lights will turn on based on motion detection from the PIR sensor.
  - The DC fan is only active when the room temperature exceeds the threshold set by the DHT22 sensor.
  - The ventilation servo helps with air circulation, reducing the duration the fan is on in the simulation.
  - In the testing scenario, the device's active time is reduced by 70-80 % because the device will automatically turn off when there is no activity and conditions exceed the threshold.

Table 3. Estimated Energy Savings Based on Prototype Simulation Scenarios

Parameter	Before Automation	After Automation	Change
Lighting active time per session	30-40 minutes	5-10 minutes	↓ up to 80 %
Fan active time per session	2-30 minutes	8-12 minutes	↓ up to 60 %
Device active time without occupancy	15-30 minutes	0 minutes	Highly effective
Automation effectiveness	–	93.00 %	Highly effective
Potential energy savings	–	20-30 %	Achieved

The estimated test results indicate that the implementation of automation scheduling and more effective control has the potential to reduce energy consumption by approximately 20–30%. This potential level of energy savings is consistent with various studies reporting that sensor-based automation and scheduling can achieve significant energy reductions in boarding room residences.

3.4 Discussion

The implementation and testing results show that the IoT-based Smart Room system developed is able to address the energy efficiency and comfort challenges identified in the introduction. First, the use of a web-based interface provides significant access flexibility for boarding house residents; users can remotely monitor and control room conditions without device limitations or special application installations, addressing common concerns about forgetting to turn off electrical appliances when traveling. Second, the integration of a hybrid temperature control mechanism combining DC fans with servo-based automatic ventilation proved more effective in maintaining air circulation compared to relying solely on conventional fans. This approach allows for a more natural and adaptive reduction in room temperature based on environmental conditions, a feature rarely found in simple room automation systems. Third, the implementation of the WebSocket protocol in the system architecture provides highly responsive data communication performance. The recorded manual control latency ranged from 0.5-1 s, and visual status updates were under 200 ms, proving that the system is capable of providing a reliable real-time experience, unlike typical HTTP request-based systems which often experience significant delays. Fourth, from the perspective of energy efficiency, which is a crucial research objective, reducing unnecessary device active duration thru PIR sensors and automatic temperature management results in potential energy savings of 20-30 %. This figure indicates that technological intervention in boarding house management can significantly reduce monthly electricity operating costs.

Nevertheless, this study has several limitations that should be acknowledged. First, the system relies heavily on a stable Wi-Fi connection to support real-time monitoring and manual control through the web dashboard. Any disruption in network connectivity may restrict remote access and monitoring functionality; however, the automatic control mechanisms continue to operate locally. Second, the system implementation and testing were conducted only on a single-room prototype scale. Consequently, the system's performance and reliability in multi-room or large-scale boarding house environments have not yet been evaluated. These limitations suggest that further research is necessary to enhance system robustness, scalability, and adaptability for broader real-world applications.

4. Conclusion

This research successfully developed an integrated Smart Room system for boarding rooms that is capable of automating temperature, ventilation, and lighting control, as well as providing remote monitoring facilities thru a web dashboard. This system, built on the ESP32 microcontroller, successfully synergizes the DHT22 sensor, PIR sensor, and mechanical actuators (servo and fan) within a responsive control architecture. All major functions have performed as designed, as evidenced by connection stability during long-duration testing and rapid system response (<1 s for command execution). Based on performance evaluation, the implementation of this system has a significant positive impact on energy efficiency, with estimated savings reaching 20-30 % obtained from eliminating the use of lights and fans when the room is empty or the temperature is within normal limits.

Overall, this solution successfully addresses the energy management issues in boarding house environments that are often overlooked due to human negligence. This system offers a balance between resident comfort thru environmental automation and operational cost efficiency. The potential for future development of this system is very open, particularly in its expansion to a centralized (multi-room) cost management system and the application of artificial intelligence to learn occupant behavior patterns for more precise energy optimization.

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