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Design and Implementation of an ESP32-Based Smart Cooling System with Real-Time Web Monitoring

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Abstract

The advancement of Internet of Things (IoT) technology has enabled the development of smart home automation systems aimed at enhancing comfort and maximizing energy efficiency. This study focuses on the development and implementation of a real-time web-based intelligent cooling system for a bedroom environment. The primary concerns identified are thermal discomfort resulting from increased room temperatures and the inadequate performance of lighting and cooling systems. The proposed system employs an ESP32 microcontroller, a DHT22 temperature sensor, a PIR motion sensor, and an LDR light sensor, together with actuators including a servo-controlled fan and LED lights. The ESP32 is configured as a local web server, enabling real-time monitoring through an HTTP connection. Experimental results suggest that the system can autonomously activate the cooling fan when the room temperature exceeds 30°C and promptly adjust illumination based on ambient light levels. Real-time synchronization between physical components and the web dashboard enables continuous monitoring of WiFi connectivity, light intensity, and fan position. The suggested system offers an efficient and easily monitored smart cooling solution for bedrooms, suggesting the potential to enhance household energy efficiency through automated device management.

Keywords: Smart Cooling System, Internet of Things, Room Automation, Energy Efficiency, ESP32

1. Introduction

Recent developments in Internet of Things (IoT) technology have supported the adoption of smart home automation systems aimed at improving comfort, energy efficiency, and security. IoT enables the integration of sensors and actuators that can be monitored and controlled in real time through internet-based communication. Web-based systems are widely used due to their accessibility, cross-platform compatibility, and ability to present sensor data using standard communication protocols such as HTTP [1][2].

Room comfort is strongly influenced by environmental factors, including temperature, illumination, and human presence. Elevated room temperatures may cause thermal discomfort, while insufficient lighting can disrupt daily activities. Therefore, an automated system capable of evaluating indoor conditions and adjusting devices accordingly is required. Several studies have explored alternative cooling approaches to improve environmental sustainability and operational efficiency [3].

Various sensors and actuators are commonly employed to support intelligent cooling in indoor spaces. The DHT22 sensor provides temperature and humidity measurements, the PIR sensor detects human presence to ensure system operation only when the room is occupied, and the LDR sensor measures ambient light intensity to regulate lighting conditions. When integrated with actuators such as LED lighting and cooling fans, these sensors enable autonomous and efficient room management. Sensor data can be transmitted via HTTP communication and displayed through a web-based interface for real-time monitoring [4].

Previous studies have demonstrated the feasibility of web-based monitoring and control systems in indoor environments. Maulana et al. developed a web-based air conditioning monitoring system using the NodeMCU ESP8266 and the PZEM-004T sensor [5], while Topan et al. proposed a multi-room monitoring system based on Wireless Sensor Network (WSN) technology [6]. However, many existing systems rely on cloud-based platforms or focus on limited environmental parameters, resulting in the absence of integrated occupancy detection and localized real-time monitoring.

This study investigates the design and implementation of a real-time, web-based smart cooling system for a bedroom environment using an ESP32 microcontroller. The proposed system integrates temperature, lighting, and occupancy sensors with a local web server to enable real-time monitoring and autonomous device control without reliance on cloud services. The main contributions of this study include (1) the development of an ESP32-based smart cooling system with multi-sensor automation, (2) real-time monitoring through a lightweight web interface using HTTP communication, and (3) experimental validation of system functionality and responsiveness in a bedroom environment.

2. Methodology

An engineering-based design approach was adopted to develop an IoT-based smart cooling system. Previous IoT-based temperature monitoring studies have demonstrated that environmental data can be acquired and visualized in real time using comparable system architectures [7]. The proposed system was subsequently evaluated through real-time experimental testing of both hardware and software components.

2.1 System Architecture Design

In this work, the system was implemented by integrating hardware and software components under the control of an ESP32 microcontroller. Earlier IoT-based temperature monitoring studies have shown that environmental data can be collected and visualized in real time using comparable system designs [6], [9]. In the present system, internet connectivity is provided directly by the ESP32, allowing monitoring to be carried out through a simple web-based interface.

2.2 System Workflow and Automation Process

The overall operation of the smart cooling system is represented through the use case and activity diagrams shown in Figures 1 and 2. The automation process runs continuously, while the web interface serves as a real-time monitoring tool that displays sensor values and device status [8].

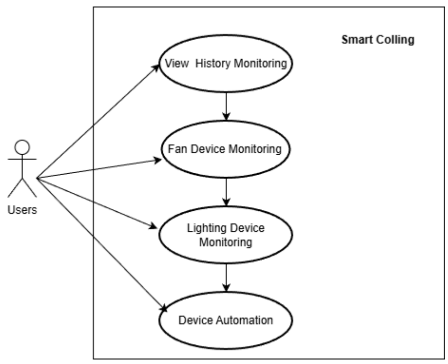

Figure 1. Use Case Diagram

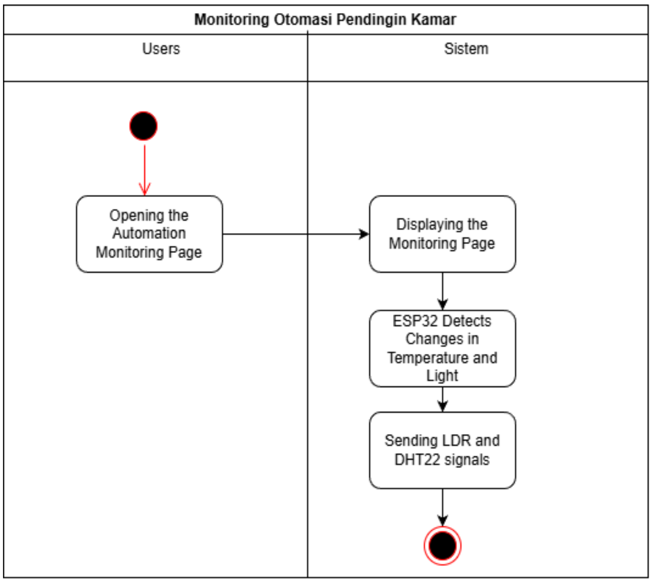

Figure 2. Room Monitoring Activity Diagram

2.3 Software Design and Communication

The ESP32 was configured to function as a local web server and to host a lightweight web interface built with HTML, CSS, and JavaScript. Data communication with the web dashboard was performed using HTTP-based requests and periodic polling, through which sensor information was updated and displayed in near real time [6], [9]. All control processes were carried out directly on the ESP32, allowing the system to function independently without relying on cloud-based services.

2.4 Control Logic and Automation Strategy

System operation was governed by predefined environmental thresholds combined with intelligent control mechanisms [9]. The cooling fan was triggered once the room temperature exceeded 30 °C, whereas lighting intensity was regulated according to ambient light conditions detected by the LDR sensor. Automated operation was activated only upon detection of occupant presence by the PIR sensor, thereby reducing unnecessary energy consumption.

2.5 Hardware Implementation and Wiring Configuration

The hardware system was built around an ESP32 microcontroller acting as the main control unit. Sensor data obtained from the DHT22 temperature sensor, PIR motion sensor, and LDR light sensor were used to control the servo motor and LED lighting. The overall electronic circuit configuration is illustrated in Figure 3.

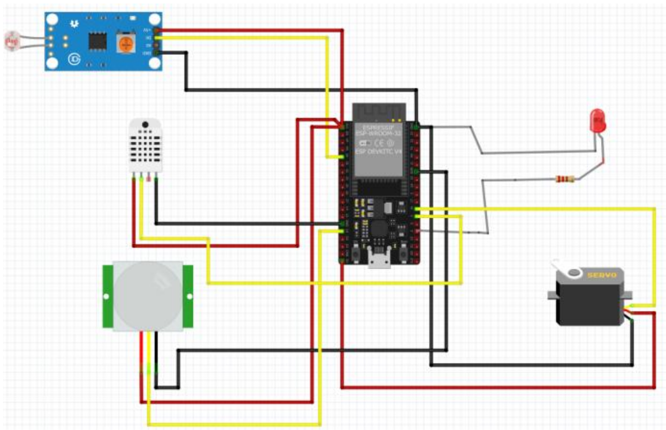

Figure 3. Electronic Circuit Diagram of the Device

Table 1. Wiring Description

No	Cable	Description
1	Red	Positive for sensors (3.3 V) and servo motor (5 V)
2	Black	Common ground reference for all components
3	Yellow	Data signal lines for sensors and servo motor
4	Grey	LED control signal and ground path

The wiring configuration ensured stable power distribution and reliable data communication between system components.

2.6 System Implementation and Experimental Validation

The web-based smart cooling system was implemented using an ESP32 as the primary control unit. The hardware setup included an ESP32, a DHT22 temperature sensor, a PIR motion sensor, an LDR light sensor, and a servo motor actuator. Initial functionality was examined through simulations on the Wokwi platform before deployment on physical hardware. Experimental validation was performed by varying room temperature, ambient lighting conditions, and occupant presence, and system responsiveness was evaluated in real time [10].

3. Results and Discussion

3.1 Functional Testing Results

Functional testing was conducted to validate the precision of system performance under various environmental conditions. The assessments focused on the efficacy of temperature-controlled fans, automated lighting systems, and occupancy sensors.

During thermal testing, the system consistently activated the cooling fan when the ambient temperature exceeded 30°C and deactivated it when the temperature fell below this threshold. The lighting automation adeptly adapted to fluctuations in ambient light conditions detected by the LDR sensor. Occupancy-based control ensured that both the fan and lighting systems remained inactive in the absence of movement.

Table 2. Functional Testing Results

Test Scenario	Sensor Condition	Expected Response	Observed Response
Temperature control	Temperature > 30 °C	Fan ON	Fan ON
Temperature control	Temperature ≤ 30 °C	Fan OFF	Fan OFF
Lighting control	Dark environment	Lamp ON	Lamp ON
Lighting control	Bright environment	Lamp OFF	Lamp OFF
Occupancy detection	No motion detected	Devices OFF	Devices OFF
Occupancy detection	Motion detected	Automation enabled	Automation enabled

Table 2 demonstrates that the proposed system successfully implemented all specified automation rules during functional testing.

3.2 System Responsiveness and Real-Time Monitoring Performance

System responsiveness was evaluated by observing the delay between changes in sensor conditions and the resulting actuator responses displayed on the web dashboard. This delay accounted for the time required for sensor sampling, control logic execution, and data transmission via HTTP.

Experimental data indicate that actuator responses occurred immediately after detecting environmental changes. The cooling fan and lighting system operated dependably, with changes displayed on the dashboard after a brief, acceptable delay appropriate for interior automation. The temperature graph on the dashboard enabled users to track temperature variations over time and evaluate the impact of fan operation on room conditions.

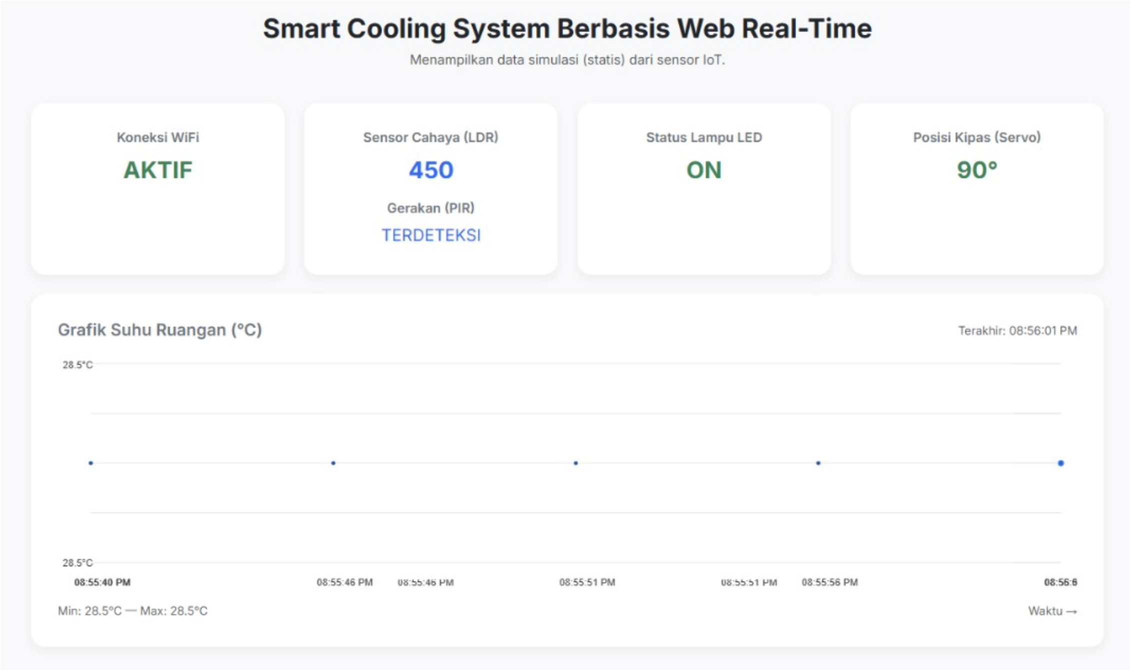

Figure 4. Dashboard Interface Presentation

Figure 5. WiFi Connectivity Interface

Figure 6. LDR Light Sensor Visualization

Figure 7. LED Lamp Status Indicator

Figure 8. Servo Fan Display

The WiFi connection indication remained stable during testing, confirming reliable connectivity between the ESP32 and the monitoring interface.

Table 3. System Responsiveness Evaluation

Parameter	Observation
Sensor data update method	HTTP polling
Actuator response time	Near real-time
Dashboard update delay	Slight delay due to polling
System stability	Stable during continuous operation

The findings indicate that the system offers adequate responsiveness for bedroom-scale automation applications.

3.3 Real-Time Testing and System Validation

Real-time tests were carried out to ensure proper synchronization between the hardware components and the web-based monitoring interface. The ESP32 firmware was deployed via the Arduino IDE, and system performance was evaluated under varying temperature, lighting, and motion conditions.

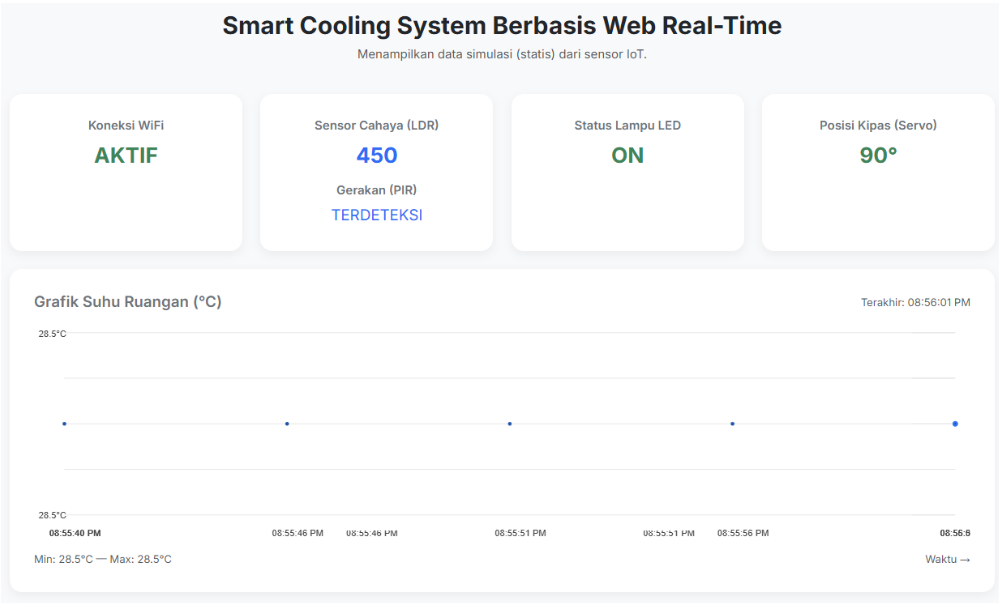

Figure 9. Web Dashboard Visualization

The results demonstrate that the sensor data displayed on the dashboard accurately matched the real-time measurements generated by the hardware components. The system functioned consistently without discernible malfunctions, validating its efficiency and reactivity in a bedroom setting.

3.4 Discussion

The experimental results demonstrate that the proposed IoT-based smart cooling system successfully integrates multi-sensor automation with real-time online monitoring. The system autonomously regulates room temperature and lighting based on environmental conditions and occupancy detection, in line with the objectives defined in this study.

Unlike cloud-dependent smart home systems, utilizing a local ESP32 web server increases system autonomy and reduces reliance on external infrastructure. The HTTP polling mechanism introduces minor latency compared to event-driven communication protocols such as WebSocket or MQTT. While this limitation did not significantly affect system performance in the assessed context, future endeavors may focus on improving communication efficiency and incorporating long-term data logging for comprehensive performance and energy consumption evaluation.

4. Conclusion

The design, implementation, and experimental evaluation of the proposed smart cooling system have numerous consequences. The IoT-based automatic room control system independently regulates cooling and lighting devices based on real-time data on temperature, light intensity, and occupancy. The test results verify that the system engages the cooling fan when the room temperature is beyond the specified threshold and modulates lighting based on ambient brightness levels. Secondly, system testing demonstrates consistent and adaptive performance across various environmental conditions. Sensor data acquisition, execution of control logic, and actuator operation were carried out successfully, with real-time system status accurately presented on the web-based monitoring interface. These results confirm the effectiveness of the ESP32-based local web server in supporting real-time monitoring without reliance on cloud services. The proposed system offers a practical and efficient smart cooling solution for bedroom environments by integrating multi-sensor automation with a streamlined online interface. Future work may concentrate on improving communication protocols, integrating long-term data logging, and conducting quantitative evaluations of energy consumption to further enhance system performance and efficiency.

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