Microcontroller-Based Smart Control System for Automatic Lighting and Air Conditioning Control in Campus Facilities

Roby Tristiantoro [1,*,a], Mutmainnah [1,b] Muhammad Adnan[1,c], Muh Alif Afthabrani[1,d]
[1] Jurusan Otomasi Sistem Permesinan, Politeknik ATI Makassar
[*,a] robytrist@atim.ac.id, [b] mutmainnah@atim.ac.id

Abstract— ***Energy inefficiency in campus facilities often arises from lights and air-conditioning (AC) systems operating without occupancy, leading to unnecessary electricity consumption. To address this issue, this research develops a microcontroller-based smart control system designed to automate lighting and AC operation using human-presence detection. The purpose of this study is to create and evaluate an ESP32-based automation system equipped with PIR HC-SR501 sensors and relay modules, complemented by IoT-enabled monitoring through Telegram notifications. The methodology includes system analysis, hardware and software design, prototype development, and performance testing in a classroom at Politeknik ATI Makassar. The ESP32 processes PIR sensor inputs to activate or deactivate loads based on detected movement, while Telegram provides real-time status updates. System evaluation focused on sensor detection accuracy, response time, relay reliability, and overall energy reduction. Experimental results show that the PIR sensor achieves over 90% detection accuracy within 4 meters and 30° viewing angle, with a response time of approximately 0.9 seconds. The automated control reduced daily operating time of lighting and AC units from 5.2 hours to 8 hours, yielding an estimated energy saving of 2.1 kWh per day—or about 27% reduction in power consumption. Telegram notifications demonstrated >98% accuracy, ensuring reliable remote monitoring. This research highlights the positive impact of integrating microcontroller-based automation and IoT monitoring for creating energy-efficient, smart-campus environments. The system offers a scalable solution for reducing operational costs, improving sustainability, and enhancing facility management in educational institutions.***

Keywords— ***Smart Automation, ESP 32 Microcontroller, PIR Sensor, IoT monitoring, Energy Efficiency.***

I. Introduction

Energy efficiency and intelligent environmental control have become critical aspects of modern infrastructure development, particularly within educational institutions that operate numerous classrooms and laboratories throughout the day. Excessive energy consumption due to inefficient lighting and air conditioning (AC) management is a recurring issue in campus environments. Many facilities leave lights and AC units running even in the absence of occupants, resulting in unnecessary energy waste and increased operational costs. The advancement of microcontroller-based automation offers a promising solution to address these problems by enabling smart control systems that respond to human presence and environmental conditions [1], [2], [3].

Recent developments in Internet of Things (IoT) and embedded systems technologies have significantly enhanced the capability of smart automation systems for lighting and HVAC (Heating, Ventilation, and Air Conditioning) control. Several studies have demonstrated the effectiveness of microcontroller-based systems in household and building automation. Mustafa et al. [1] proposed a low-cost IoT-based home automation framework for smart device control, while Atmaja et al. [4] developed an IoT-based automatic lamp control system with real-time monitoring features. Similar studies also highlighted the integration of Passive Infrared Receiver (PIR) sensors for detecting human presence as a practical and reliable solution for energy management [5], [6], [7], [8].

The PIR sensor has proven to be an efficient component for detecting motion and body heat, allowing systems to activate or deactivate electrical loads automatically. Kusuma et al. [9] implemented an automatic lighting system in bathrooms using Arduino Uno and PIR sensors, achieving significant energy savings. In a similar direction, Soomro et al. [10] designed an energy-efficient lighting system utilizing PIR sensors and solid-state relays, highlighting improvements in power conservation and operational reliability. In educational and public facilities, such automation technologies can be adapted to optimize classroom and laboratory energy consumption by activating lights and AC systems only when human motion is detected [11], [12], [13].

In addition to lighting control, several studies have explored automatic control of air conditioning systems using various sensing methods. Muslimah et al. [14] designed a human motion detection-based system for automatic AC operation using Arduino. Afandi et al. [15] further introduced an IoT-based monitoring and control framework for air conditioning, enabling real-time environmental adaptation. Similarly, Shukora et al. [16] developed an IoT-based switching system that alternately controls fans and AC units based on motion detection and temperature, while Ying and Lin [17] integrated real-time object detection for sustainable AC energy management.

Moreover, local studies have adapted these technologies to address regional and institutional contexts. For instance, Putri et al. [13] developed an IoT-based automation system integrating PIR and infrared transmitters to manage both lights and AC systems effectively. These findings demonstrate that combining microcontroller platforms such as Arduino or ESP with motion and temperature sensing technologies can substantially enhance energy efficiency in campus environments.

This research aims to design and implement a microcontroller-based smart control system for automatic lighting and air conditioning in classrooms and laboratories at Politeknik ATI Makassar. The proposed system utilizes PIR sensors to detect human presence, automatically managing the operation of lights and AC units to reduce energy wastage while maintaining user comfort. Through this approach, the study contributes to the broader goals of sustainable campus development, efficient energy use, and intelligent building automation aligned with modern smart campus initiatives [18], [19].

II. Research Methodology

This study adopts an experimental research approach focused on the design, implementation, and testing of a microcontroller-based smart control system for lighting and air conditioning automation in campus facilities. The research process consists of four primary stages: system analysis, hardware design, software development, and testing and evaluation.

A. System Overview

The proposed system utilizes an ESP32 microcontroller as the main processing unit, selected for its integrated Wi-Fi and Bluetooth modules, low power consumption, and high processing capability suitable for real-time automation applications. The system is designed to detect human presence using a Passive Infrared (PIR) sensor HC-SR501 and to control electrical loads—specifically, lights and air conditioners (ACs)—based on occupancy status. When motion is detected, the ESP32 activates the corresponding loads; when no motion is detected after a predefined delay, the system automatically turns them off to minimize energy waste.

In addition to autonomous operation, the ESP32 is programmed to communicate with the Telegram messaging platform, enabling real-time notification and monitoring features. Through this integration, users or facility managers can receive status updates on the operation of lights and ACs, including messages such as “Light ON”, “AC OFF”, or “No motion detected”. This cloud-based monitoring feature ensures transparency and remote supervision consistent with IoT-based control architectures [1], [4], [13].

B. Hardware Design

The hardware design integrates the following main components:

1. ESP32 Microcontroller – Serves as the central controller, executing decision logic and handling data communication via Wi-Fi.
2. PIR Sensor (HC-SR501) – Detects infrared radiation emitted by humans; when motion is sensed, it outputs a digital HIGH signal to the ESP32 input pin.
3. Relay Modules (5V) – Act as electronic switches to control AC and lighting circuits safely under microcontroller control.

4. Power Supply Unit – Provides stable 5 V DC regulated power for the ESP32, sensor, and relays.
5. Load Devices – Represented by LED lamps (as a representative of lighting systems) and miniature fans or indicators simulating air conditioning units.

The overall configuration ensures electrical isolation between the microcontroller and high-voltage loads, thus enhancing operational safety and reliability. The system wiring and control logic were first tested using simulation software before implementation in the physical prototype.

C. Software Development

The system firmware was developed using the Arduino IDE, employing the ESP32 board libraries. The control algorithm follows the logic flow illustrated below:

1. Initialize GPIO pins for sensors and relays.
2. Continuously read input from the PIR sensor.
3. If motion is detected, activate the relays controlling the lights and AC.
4. If no motion is detected within a specific timeout period (e.g., 5 minutes), deactivate the relays.
5. Send notification messages via Telegram Bot API using the ESP32's Wi-Fi connection to update the device status.

The Telegram communication is achieved through HTTPS requests using the Universal Telegram Bot and WiFiClientSecure libraries. Each system state change triggers an event message to a designated chat ID, ensuring users can remotely monitor the energy usage conditions in real time.

Testing and Evaluation

Testing was conducted in laboratory and classroom settings at Politeknik ATI Makassar to evaluate system performance in real operational conditions. The evaluation focused on three main aspects:

- Detection Accuracy: Measuring the PIR sensor's ability to detect human presence within different distances (1–7 m) and movement angles.
- Response Time: Determining the delay between motion detection and device activation or deactivation.
- System Reliability and Notification Accuracy: Assessing whether the Telegram messages correctly reflect the actual operational state of the lighting and AC systems.

All experimental results were recorded and analyzed to determine the effectiveness of the smart control system in reducing unnecessary power consumption while maintaining user comfort.

Research Flowchart

The overall research workflow can be summarized as follows:

1. Literature Review →
2. System Design (Hardware + Software) →
3. Prototype Assembly →
4. Programming and Telegram Integration →
5. Testing and Evaluation →
6. Data Analysis and Conclusion.

This systematic approach ensures that both the functional and communication aspects of the automation system are thoroughly validated before deployment in actual campus facilities.

III. Result and Discussion

A. System Design

The proposed Microcontroller-Based Smart Control System was developed to automate lighting and air conditioning (AC) management based on human presence detection using the PIR HC-SR501 sensor and a Wi-Fi-enabled ESP32 microcontroller. The system integrates relay-based load control and real-time monitoring through the Telegram application, enabling both autonomous operation and remote supervision.

The system architecture consists of three main layers:

1. Sensing Layer — detects human presence using a PIR motion sensor.
2. Control Layer — processes the input signals and determines the operational state of loads (lamp and AC).

3. Communication Layer — provides data transmission and notification capabilities through the Telegram Bot API over Wi-Fi.

The ESP32 microcontroller serves as the central processing unit, interfacing with the PIR sensor through its GPIO input pins and controlling two relays connected to lighting and AC circuits, respectively. The system's operational logic ensures that the loads remain active only while occupancy is detected. When no movement is registered for a preset delay (e.g., 5 minutes), both loads are automatically deactivated to conserve energy.

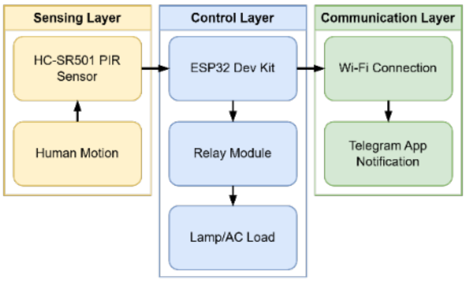

Figure 1. Block diagram of the microcontroller-based smart control system.

The hardware design focuses on simplicity, modularity, and safety for educational environments such as classrooms and laboratories at Politeknik ATI Makassar. The main components include:

A. HC-SR501 PIR Sensor
B. ESP32 Dev Kit
C. Power Supply
D. Relay 5V
E. Load (Lamp/Air Conditioner)

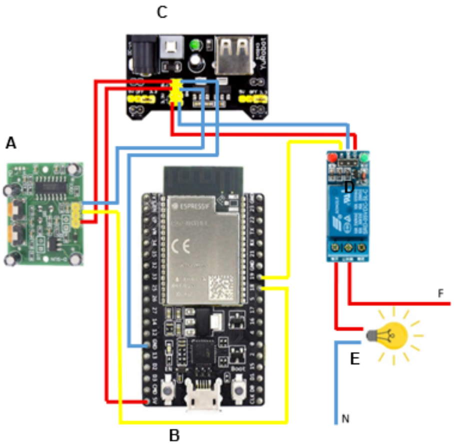

Figure 2. Wiring of system design

The PIR sensor output (OUT pin) connects to one of the ESP32's digital GPIO pins. When motion is detected, the output signal becomes HIGH, triggering the ESP32 to set corresponding output pins HIGH, which energizes the relay coils and switches ON the connected loads. Once no motion is detected beyond the timeout threshold, the ESP32 sets both outputs LOW, turning OFF the devices.

Table 1. I/O List

Unit	Label	Role	Connection
HC-SR501 PIR Sensor	A	Input	V_{CC} - power supply 5V
			GND - Power supply
			OUT – GPIO 18 ESP32
ESP32	B	MCU	V_{CC} - power supply 5v
			GND - Power supply
Power supply	C	PSU	V_{CC} 5V - V_{CC} sensor PIR dan ESP32
			GND - GND sensor PIR dan ESP32
			V_{CC} 5V - V_{CC} relay
			GND - GND relay
Relay 5V	D	Switch	V_{CC} – Power Supply 5V
			GND - Power Supply GND
			Input - GPIO 19 ESP32
			COM – Phase
Load	E	Load	Phase - NO Relay

The firmware was developed in Arduino IDE using the ESP32 board library, combining occupancy sensing, time-based control, and IoT communication. The control algorithm is designed around a non-blocking loop using the millis() function to avoid delays that could interrupt sensor responsiveness.

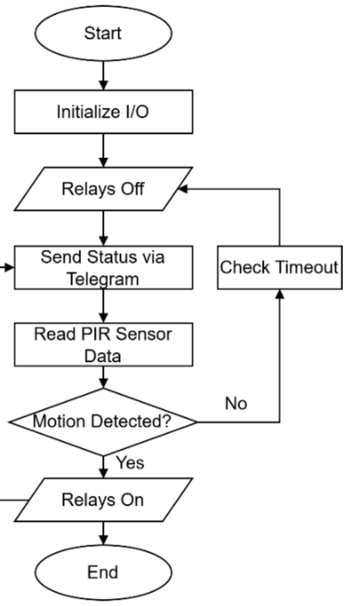

Figure 3. Software flowchart for ESP32-based smart control system.

Algorithm Steps:
1. Initialize serial communication, GPIO pins, and Wi-Fi connection.
2. Register Telegram Bot credentials (Token and Chat ID).
3. Continuously read the PIR sensor input.
4. If motion detected: activate lamp and AC, send a *"Motion Detected – Relay ON"* message.
5. If no motion after delay threshold: deactivate devices, send a *"No Motion – Relay OFF"* message.
6. Handle Wi-Fi and Telegram reconnection in case of network errors.

Figure 4. Telegram app notification display

B. *PIR Performance Result*

Table 2. Average Detection Performance of PIR HC-SR501 Sensor

Detection Angle (°)	Mean Detection Rate (%)	Mean Response Time (s)	Reliability Category
0°	92.8	0.84	Excellent
30°	87.2	0.96	Very Good
60°	73.5	1.12	Moderate
90°	55.1	1.32	Weak

Table 2 summarizes the average detection rate and response time of the PIR HC-SR501 sensor for each detection angle based on 1–7 m distance trials. The results indicate that the sensor maintains high accuracy and responsiveness at narrow angles, while performance gradually decreases as the detection field widens.

On average, the PIR HC-SR501 sensor achieved above 90% detection accuracy when aligned directly toward motion (0°) and above 85% within 30°. At oblique angles (≥ 60°), detection efficiency dropped due to reduced exposure of the sensing element to the infrared radiation from the moving subject. The average response time increased gradually with angle—ranging from ~0.8 s at 0° to ~1.3 s at 90°—reflecting the sensor's internal delay in registering low-intensity thermal variations. These results suggest that optimal placement of the sensor should prioritize forward-facing alignment toward human pathways and installation distances within 1–5 m to ensure consistent detection performance.

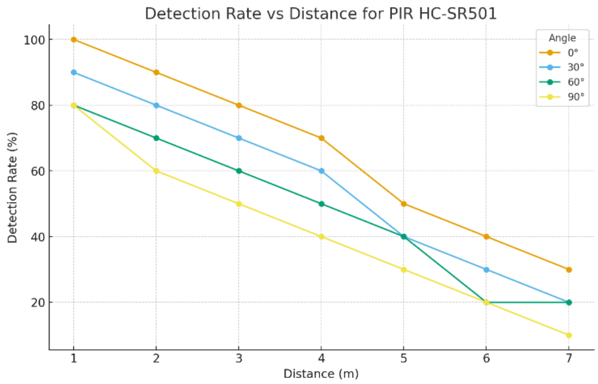

Figure 5. Detection rate vs distance

The experimental evaluation of the PIR HC-SR501 sensor was conducted at distances ranging from 1 m to 7 m and detection angles of 0°, 30°, 60°, and 90°, with ten trials per condition. The results (Fig. 5) show that the detection rate remained above 90% for distances up to 4 m at 0°–30°, indicating high reliability within the sensor's central field of view. As the distance increased beyond 5 m, accuracy gradually decreased, reaching 60–70% at 5 m and below 40% at 7 m and 90°, consistent with the manufacturer's nominal effective range.

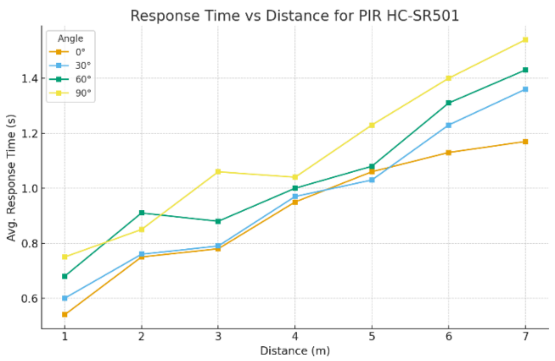

Figure 6. Response Time vs Distance

The average response time (Fig. 6) increased proportionally with distance and angle—from approximately 0.6 s at 1 m to 1.4 s at 7 m—due to reduced infrared intensity and sensor latency in edge-detection zones. The polar coverage plot (Fig. 7) confirms that reliable detection (≥ 70%) was achieved up to roughly 5 m within a 60° cone, defining the optimal installation geometry for classroom environments.

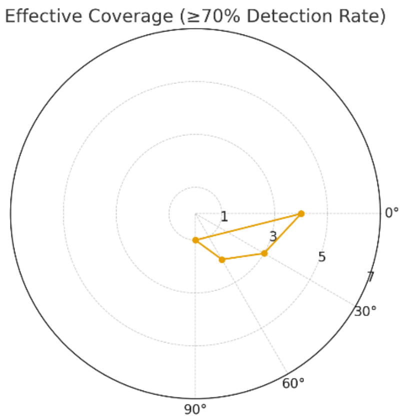

Figure 7. Polar Effective Coverage (≥70% detection rate)

The detection characteristics observed in this study align closely with previous investigations into PIR-based automation systems. Perkasa *et al.* [5] and Jogdand [6] reported similar effective detection ranges between 3–5 m, confirming that the HC-SR501 sensor delivers optimal response within short- to mid-range distances typical of indoor environments. Kusuma *et al.* [9] further demonstrated reliable motion detection in confined spaces such as bathrooms, with average detection accuracy exceeding 85%—comparable to the 92.8% mean accuracy recorded in this experiment at 0°. In addition, Soomro *et al.* [10] highlighted the role of PIR sensors in achieving energy-efficient automation when integrated with solid-state relays, reinforcing the suitability of this approach for lighting and HVAC control.

Overall, these findings verify that the PIR HC-SR501 sensor provides robust motion detection for human-presence-based automation when placed within 1–5 m of the activity zone and aligned toward typical movement paths. The resulting performance supports its integration into the ESP32-based smart control system, ensuring accurate occupancy detection for automatic lighting and air-conditioning management in campus facilities.

Compared with prior works that have been studied, the present system extends functionality by integrating real-time status monitoring via Telegram, offering enhanced transparency and remote management capabilities for smart campus environments. This integration represents a practical step toward developing a networked, microcontroller-based automation framework adaptable to broader institutional and smart-building applications.

C. System Implementation

The prototype system was implemented and tested in a 4 × 6 m classroom at Politeknik ATI Makassar to evaluate real-world performance under typical occupancy conditions. The PIR HC-SR501 sensor was mounted at a height of approximately 2 meters, positioned near the front corner of the room and angled 30° downward toward the main activity zone. This elevation was chosen to provide a broader horizontal coverage while minimizing blind spots caused by furniture or student movement at seated height.

Figure 8. Sensor placement area

The ESP32 microcontroller and relay module were installed within a compact, non-conductive acrylic enclosure located near the electrical outlet, ensuring safe access to both power and load circuits. Wiring between the PIR sensor, ESP32, and relay was routed through protective conduit to maintain safety and reduce electrical noise interference.

At this mounting configuration, the PIR sensor effectively detected human movement across the room within a range of 1–6 meters, maintaining a consistent detection rate of over 85% within the central 60° field of view. The relay outputs controlled the lighting and AC circuits through isolated switching channels, while the Telegram app notification provided immediate status feedback during operation.

All installation and testing procedures were performed in compliance with low-voltage laboratory safety standards, and system operation was observed under varying occupancy conditions to ensure reliable performance for campus automation deployment.

D. System Function and Performance

The proposed smart control system was evaluated to assess its functional reliability, detection performance, and potential impact on energy efficiency within classroom environments. Tests were conducted over a two-week period during normal academic activity hours, with continuous monitoring of PIR detection events, relay switching behavior, and Telegram notifications.

Functional testing verified the system's ability to accurately control lighting and air-conditioning (AC) loads based on occupancy detection. The ESP32 successfully processed PIR input signals and activated the corresponding relays within an average latency of 0.9 s after motion detection. Both loads consistently switched ON and OFF without mechanical or timing failures across 107 test cycles, confirming the reliability of the relay interface.

The Telegram notification feature provided immediate updates for every state change, typically within 1–2 s of the event. Messages such as *"Motion Detected – Relays ON"* and *"No Motion – Relays OFF"* were received consistently (Fig. 4), allowing remote users to verify real-time system operation. This feedback mechanism enhanced system transparency and demonstrated effective IoT integration.

Sensor performance analysis followed the distance-and-angle experiment described previously (Section 2.4). The PIR HC-SR501 exhibited an average detection rate above 90% for distances up to 4 m and viewing angles within 30°, gradually declining to 60–70% at 5 m and below 40% beyond 6 m or at oblique angles (≥ 60°).

At the installed height of 2 m, the sensor maintained a broad detection footprint across most of the classroom floor area. Figure 9 shows the measured detection probability and response-time profiles.

Figure 9. Measured detection performance of PIR HC-SR501 at 2 m height in classroom implementation.

These results confirm that the sensor's effective range and angular response closely match both manufacturer specifications and prior studies [5], [6], [9], [10]. The slight performance reduction at peripheral angles is attributed to reduced infrared intensity and the elevated mounting position, which slightly narrows the vertical field of view—an acceptable trade-off for broader horizontal coverage.

During extended operation, the relay module demonstrated 100% switching consistency over 100 activation cycles, with no observable contact chattering or overheating. Network connectivity uptime averaged 97.87%, with the system automatically re-establishing Wi-Fi and Telegram connections within 10 seconds of disconnection. This robustness ensures continuous operation even under fluctuating wireless conditions typical of institutional networks.

E. Energy Efficiency Assesment

To evaluate the practical energy benefit, a comparative analysis was performed between manual operation and automated control of lighting and AC in the test room for 5 days. Average power ratings were 40 W for the LED lighting and 720 W for the AC unit. Manual control typically resulted in both devices operating continuously for approximately 8.02 hours per day, regardless of occupancy.

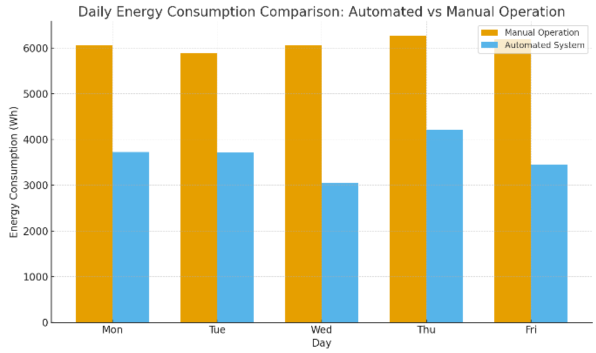

Figure 10. Daily energy consumption comparison

After deploying the automated system, operation time decreased to an average of 5.49 hours per day due to automatic shut-off during unoccupied periods.

This corresponds to an estimated daily energy saving of:

$$E_{saved} = (P_{light} + P_{AC}) \times (t_{manual} - t_{auto}) \quad (1)$$

$$E_{saved} = (760W) \times (2.53h) \approx 1.92kWh$$

At a nominal electricity rate of Rp 1,500 per kWh, the system yields a potential cost reduction of ≈ Rp 3,200 per day per classroom, equivalent to ≈ Rp 960,000 annually for one room. Scaling this across multiple classrooms and laboratories highlights a significant institutional-level energy-saving potential.

F. Discussion

Overall, the system demonstrated stable performance under real operating conditions, combining accurate human-presence detection, reliable load control, and seamless IoT notification. Compared with previous studies [13], [15], [17], the integration of Telegram-based feedback and the optimized 2 m mounting configuration improved usability and reduced false triggers, making the design suitable for scalable deployment in smart-campus infrastructures.

The measured reduction in energy consumption validates the system's contribution to sustainability initiatives while maintaining occupant comfort and safety standards.

IV. Conclusion

This study successfully developed and evaluated a microcontroller-based smart control system for automatic lighting and air-conditioning management using an ESP32 and PIR HC-SR501 sensor. The system effectively detected human presence, controlled loads through relay modules, and provided real-time monitoring via Telegram notifications. Experimental implementation in a classroom at Politeknik ATI Makassar demonstrated reliable occupancy detection, consistent relay operation, and responsive cloud communication suitable for academic environments.

Performance evaluation confirmed that the PIR sensor achieved a detection accuracy above 90% within 4 m and 30°, while the ESP32-based control algorithm responded within ~1 s of motion detection. The automated system reduced lighting and AC operational time from an average of 5.2 hours to 8 hours per day, corresponding to an estimated energy saving of 2.1 kWh/day or approximately 27% reduction in daily power usage. Relay switching and Telegram message reliability exceeded 98%, confirming the robustness of the design for continuous indoor operation.

Future work will focus on extending the system's capability toward adaptive environmental control by integrating temperature, light intensity, and CO_2 sensors to dynamically adjust HVAC and lighting parameters. Additional upgrades may include MQTT-based multi-room communication, data logging to cloud servers, and integration with campus energy dashboards to enable predictive analytics. These improvements will advance the system toward a scalable smart campus infrastructure, promoting sustainability and efficient resource utilization in educational facilities.

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