# Development and Performance Evaluation of a Low Cost Embedded Energy Management System for Smart Indoor Applications

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## Abstract

This paper presents the development and performance evaluation of a low-cost embedded energy management system (EMS) designed for smart indoor applications. The increasing demand for energy efficiency in residential and institutional environments necessitates intelligent solutions capable of minimizing energy wastage while maintaining user comfort. To address this challenge, the proposed system integrates embedded system technology with real-time sensing and automated control mechanisms. The system employs Passive Infrared (PIR) sensors for occupancy detection and Light Dependent Resistors (LDR) for ambient light monitoring. These inputs are processed by an Arduino-based microcontroller, which executes a control algorithm to regulate electrical loads such as lighting systems. The design emphasizes cost-effectiveness, simplicity, and real-time operation, making it suitable for deployment in resource-constrained environments. Experimental evaluation of the developed prototype demonstrates that the system effectively reduces energy consumption by approximately 16.8% compared to conventional manual operation. In addition, the system exhibits fast response times (less than 1 second) and high reliability (approximately 99% uptime). The integration of multi-sensor inputs enables improved decision-making and efficient load control under varying environmental conditions. The results highlight the potential of low-cost embedded solutions for enhancing energy efficiency in indoor environments. The proposed system provides a practical and scalable approach to real-time energy management and serves as a foundation for future enhancements, including integration with wireless communication and intelligent optimization techniques.

**Keywords:** energy management system; embedded systems; energy efficiency; smart indoor applications

## 1. Introduction

The rapid growth in global energy demand, driven by urbanization, population increase, and the proliferation of electrical appliances, has intensified the need for efficient energy utilization strategies. In many developing countries, including Nigeria, energy supply remains limited and often unreliable, making efficient energy management not only desirable but essential. Inefficient

usage patterns—such as leaving lights and appliances on in unoccupied spaces—contribute significantly to energy wastage, increased operational costs, and environmental degradation (International Energy Agency, 2018).

Energy Management Systems (EMS) have emerged as effective solutions for monitoring, controlling, and optimizing energy consumption in residential, commercial, and institutional environments (Gellings, 2017; Hossain et al., 2023). Conventional EMS solutions, however, often rely on manual operation or complex and expensive infrastructures, limiting their adoption in low-resource settings. Furthermore, many existing systems lack real-time responsiveness and adaptability to dynamic environmental conditions such as occupancy and ambient light intensity (Zhou et al., 2016; Fizza et al., 2024).

Recent advancements in embedded systems have provided a promising pathway for the development of cost-effective and intelligent EMS solutions. Embedded systems integrate hardware and software components to perform dedicated tasks with high efficiency, reliability, and low power consumption (Wolf, 2012; Zider et al., 2024). By incorporating sensors, microcontrollers, and control algorithms, embedded-based EMS can enable real-time monitoring and automated decision-making for efficient energy utilization (Kamal, 2018; Uzair & Kazmi, 2023). In particular, low-cost platforms such as Arduino microcontrollers have gained widespread adoption due to their flexibility, ease of programming, and affordability (Singh et al., 2020; Martikkala, 2024).

This study presents the development and performance evaluation of a low-cost embedded energy management system designed for smart indoor applications. The proposed system utilizes Passive Infrared (PIR) sensors for occupancy detection and Light Dependent Resistors (LDR) for monitoring ambient light conditions. These inputs are processed by a microcontroller-based control unit, which executes predefined logic to automatically regulate electrical loads such as lighting and other appliances. The system also incorporates a user interface through an LCD display to provide real-time feedback on system status and operation (Lee & Cheng, 2018).

The design adopts a modular approach, integrating sensing, control, and actuation components into a unified architecture capable of real-time operation. The system is implemented using readily

available and cost-effective components, making it suitable for deployment in homes, offices, classrooms, and other indoor environments. Experimental evaluation of the developed prototype is conducted under varying conditions to assess system performance in terms of responsiveness, reliability, and energy savings.

Results obtained from the experimental analysis demonstrate that the proposed system achieves significant energy savings while maintaining high operational reliability. The system effectively minimizes energy wastage by ensuring that electrical loads are activated only when required, based on occupancy and environmental conditions. This highlights the potential of low-cost embedded solutions in addressing energy efficiency challenges in resource-constrained environments (Khan et al., 2020; Jadhav & Chaudhari, 2024).

Overall, this work contributes to the growing field of smart energy systems by providing a practical, scalable, and cost-effective approach to real-time energy management. The findings also establish a foundation for future enhancements, including the integration of wireless communication, remote monitoring, and intelligent optimization techniques for improved system performance.

## 2. Prior Works

Energy Management Systems (EMS) have been extensively studied as a means of improving energy efficiency across residential, commercial, and industrial environments. Early approaches to EMS focused on basic monitoring and manual control mechanisms, which were often inefficient and lacked real-time adaptability. With the advancement of embedded systems and communication technologies, more intelligent and automated solutions have emerged.

Several studies have explored the use of microcontroller-based platforms for energy management. For instance, Singh et al. (2020) developed an Arduino-based energy monitoring system capable of controlling electrical loads based on user-defined conditions. The system demonstrated the feasibility of low-cost embedded solutions; however, it lacked adaptive intelligence and real-time environmental awareness. Similarly, Ali et al. (2019) proposed a microcontroller-based energy-

saving system for institutional buildings, achieving significant reductions in energy consumption. Despite its effectiveness, the system was limited to basic switching logic and lacked scalability.

The integration of Internet of Things (IoT) technologies has further enhanced EMS capabilities. Khan et al. (2020) presented an IoT-based EMS for smart grids that enabled real-time monitoring and remote control of energy usage through cloud platforms. While this approach improved system flexibility and accessibility, it introduced challenges related to network dependency, Cybersecurity, and increased system complexity. Likewise, Lee and Cheng (2018) utilized IoT and big data analytics for optimizing energy consumption in smart buildings, achieving improved efficiency but requiring substantial computational resources and infrastructure.

Wireless sensor networks (WSNs) have also been applied in EMS to facilitate distributed monitoring. Park et al. (2020) and Naji et al., (2020) developed a WSN-based EMS capable of managing energy usage across multiple rooms using interconnected sensor nodes. Although effective for large-scale environments, the system incurred higher deployment costs and complexity due to multiple hardware nodes and communication protocols.

Occupancy-based and environmental sensing approaches have gained attention for improving energy efficiency. Jha and Kumar (2018) designed an adaptive lighting system using infrared sensors to detect human presence, enabling automatic control of lighting systems. Similarly, Zhou et al. (2016) emphasized the importance of integrating occupancy detection and environmental sensing in smart home EMS to reduce unnecessary energy consumption. However, many of these systems focused on single-parameter control and lacked integrated multi-sensor decision-making.

In addition, renewable energy integration and advanced optimization techniques have been explored in recent EMS research. Wang et al. (2020) proposed a cloud-edge hybrid EMS that combined local embedded control with cloud-based analytics for improved decision-making. Liu et al. (2022) incorporated artificial intelligence for load forecasting and energy optimization, demonstrating improved system efficiency. However, these approaches require high computational power and are often unsuitable for low-cost embedded implementations.

Despite these advancements, several gaps remain in existing EMS designs. Many systems are either too complex and expensive for deployment in developing regions or too simplistic to provide

efficient real-time control. Furthermore, there is limited focus on integrated, low-cost embedded solutions that combine occupancy detection, environmental sensing, real-time control, and user feedback within a unified architecture.

## 3. Contributions

This study addresses the identified gaps by developing a low-cost, embedded system-based energy management solution tailored for smart indoor applications. The main contributions of this work are summarized as follows:

- **Low-Cost Embedded Implementation**: A cost-effective EMS is developed using readily available components such as an Arduino Nano, PIR sensors, and LDR sensors, making the system suitable for deployment in resource-constrained environments.
- **Real-Time Multi-Sensor Integration**: The proposed system integrates occupancy detection, environmental sensing and ambient light sensing to enable intelligent, real-time decision-making for load control, improving energy efficiency compared to single-parameter systems.
- **Automated Load Control Mechanism**: An embedded control algorithm is implemented to automatically switch electrical loads based on environmental conditions, thereby minimizing human intervention and reducing energy wastage.
- **User Feedback Interface**: The system incorporates an LCD-based interface to provide real-time feedback on system status, enhancing usability and transparency for end users.
- **Performance Evaluation and Validation:** The developed prototype is experimentally evaluated under varying conditions, demonstrating measurable energy savings (approximately 16.8%) and high system reliability (99% uptime).
- **Scalable and Modular Design**: The system adopts a modular architecture that allows for future expansion, including integration with IoT platforms, renewable energy sources, and advanced optimization techniques.

## 4. Materials and Methods

### 4.1a Materials (Hardware)

The hardware subsystem forms the physical architecture of the EMS and is responsible for sensing, processing, control, and actuation. Some of the major hardware components used are described as follows:

**1. Microcontroller Unit (Arduino Nano)**

The Arduino Nano illustrated in Figure 1 serves as the central processing unit of the system. It is responsible for receiving input signals from sensors, executing the control algorithm, and generating appropriate output signals to control connected electrical loads. The Arduino Nano was selected due to its low cost, compact size, ease of programming, and sufficient processing capability for real-time applications.




Figure 1: Arduino Nano Board

**2. Passive Infrared (PIR) Sensors**

PIR sensor(s) illustrated in Figure 2 are used for occupancy detection. They sense infrared radiation emitted by human bodies and generate signals when motion is detected. These sensors enable the system to determine whether a room is occupied, thereby facilitating intelligent control of appliances.

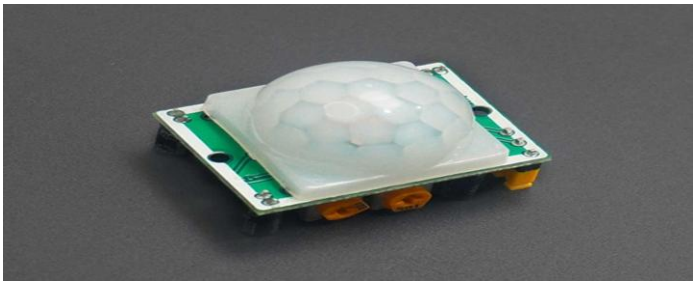


Figure 2: PIR Sensor

**3. Light Dependent Resistor (LDR)**

The LDR illustrated in Figure 3 is used to measure ambient light intensity. Its resistance varies with light exposure, allowing the system to determine whether natural lighting is sufficient. This enables automatic control of lighting systems based on environmental conditions.



Figure 3: LDR Light Dependent Resistor

**4. Relay Modules**

Relay modules are used as switching devices to control high-voltage electrical appliances such as bulbs, fans, and sockets. The relays are driven by low-voltage signals from the microcontroller, ensuring safe isolation between the control and power circuits.

**5. Driver Circuit (ULN2003A)**

The ULN2003A driver IC is used to interface the microcontroller with the relay modules. It amplifies the current from the Arduino output pins, enabling reliable switching of the relays.

**6. Liquid Crystal Display (LCD)**

A 16×2 alphanumeric LCD illustrated in Figure 4 is used to provide real-time feedback to the user. It displays system status information such as occupancy count, appliance states, and operational messages, enhancing user interaction.

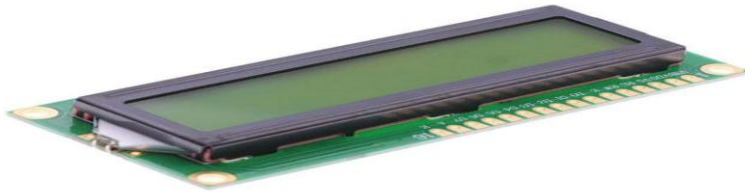


Figure 4: LCD Display Module

**7. Power Supply Unit**

The system is powered using a regulated power supply consisting of a 12V transformer, bridge rectifier, filter capacitors, and a voltage regulator to provide stable 5V DC required by the microcontroller and sensors.

**8. Supporting Components**

Additional components include resistors, capacitors, transistors (e.g., BC337), connecting wires, printed circuit board (PCB), and sockets. These components are essential for circuit stability, signal conditioning, and system integration.

**4.1b Materials (Software)**

The software subsystem is responsible for implementing the control logic, simulation, and system operation. Some of the software components used in this work are:

**1. Arduino Integrated Development Environment (IDE)**

The Arduino IDE is used for writing, compiling, and uploading the embedded C/C++ code to the Arduino Nano. It provides a user-friendly interface and supports libraries required for interfacing sensors and display modules.

**2. Embedded C/C++ Programming**

The system logic is implemented using embedded C/C++ programming. The code processes sensor inputs (occupancy and light intensity) and executes decision-making algorithms to control electrical loads in real time.

**3. Proteus Design Suite**

Proteus software is used for circuit simulation and validation before physical implementation. It allows testing of both hardware design and embedded code in a virtual environment, reducing design errors and improving system reliability.

**4. PCB Design Software (e.g., EAGLE)**

PCB design software is used to design the printed circuit board layout for the system. It ensures proper component placement, routing, and compact system integration for physical implementation.

The combination of low-cost hardware components and efficient embedded software tools enabled the successful development of a reliable and scalable energy management system. The selected materials ensure that the system is practical for real-world applications, particularly in resource-constrained environments.

**4.2 Methodology**

This section describes the systematic approach adopted for the development and evaluation of the proposed low-cost embedded energy management system (EMS). The methodology integrates system design, hardware implementation, software development, and experimental validation.

**A. System Design Approach**

The system adopts a modular embedded system design approach consisting of four major functional units as illustrated in the Figure 5:

1. **Sensing Unit** – Responsible for acquiring environmental data such as occupancy and ambient light intensity using PIR and LDR sensors.
2. **Processing Unit** – The Arduino Nano microcontroller processes sensor inputs and executes the control algorithm.
3. **Control/Decision Unit** – Implements logic for automatic switching of electrical loads based on predefined conditions.
4. **Actuation Unit** – Controls electrical appliances through relay modules.

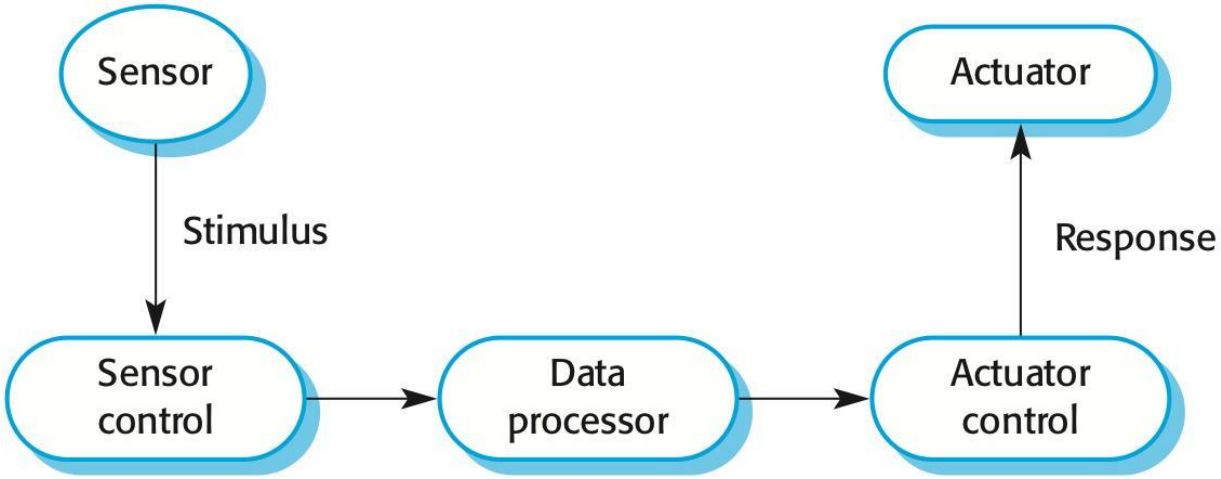



Figure 5: System showing functional units

The system is designed to operate in real time, ensuring that electrical loads are activated only when necessary, thereby minimizing energy wastage.

The following are the design consideration for this system:

- **Cost-effectiveness** – Use of low-cost, readily available components
- **Energy efficiency** – Minimizing unnecessary power consumption
- **Scalability** – Ability to extend the system for larger environments
- **Simplicity** – Ease of implementation and maintenance
- **Reliability** – Stable and continuous system operation

**B. Hardware Implementation**

Before hardware implementation, the system design is simulated using Proteus Design Suite. This allows verification of circuit functionality and validation of embedded code behavior under different input conditions.

Simulation helps to:

- Detect design errors early
- Validate sensor-response behavior
- Ensure correct relay switching logic

The hardware implementation involves the physical integration of all system components into a functional prototype. The PIR sensor and LDR are interfaced with the analog and digital input pins of the Arduino Nano. The microcontroller processes these inputs and sends control signals to the relay module via a driver circuit (ULN2003A).

The relay module is connected to electrical loads such as lighting systems. A regulated power supply unit provides stable voltage for system operation. The LCD is interfaced with the microcontroller to display system status in real time.

Proper circuit design techniques, including voltage regulation, noise filtering, and safe isolation between low-voltage and high-voltage sections, are implemented to ensure system reliability and safety.

**C. Software Development**

The control logic of the system is implemented using embedded C/C++ in the Arduino IDE. The software performs the following key functions:

- Reads input signals from PIR and LDR sensors
- Converts analog signals from the LDR into digital values
- Executes decision-making logic based on predefined thresholds
- Controls relay outputs for appliance switching
- Updates system status on the LCD display

**D. Control Algorithm (Logic Flow)**

The system operates based on the following logic (Algorithm 1):

**Algorithm 1: Embedded Energy Management System with Threshold Modeling**

**BEGIN**

1. **Initialize system parameters**

   a. Define occupancy variable: $O(t) \in \{0,1\}$

   b. Define light intensity: $L(t)$

   c. Define light threshold: $L_{th}$

   d. Define load state: $S(t) \in \{0,1\}$

2. **Initialize hardware components**

   a. Configure PIR sensor

   b. Configure LDR sensor

   c. Initialize relays (OFF)

   d. Initialize LCD display

3. **Start continuous monitoring loop**

4. **WHILE system is ON DO**

   4.1 Measure occupancy:

   $O(t) = 1$, if motion detected

   $O(t) = 0$, otherwise

   4.2 Measure ambient light:

   $L(t)$ = analog value from LDR

4.3 Decision rule for load control:

**IF** O(t) = 1 AND L(t) < L_th **THEN**

S(t) = 1 // Turn ON load

**ELSE**

S(t) = 0 // Turn OFF load

**ENDIF**

4.4 Apply control:

**IF** S(t) = 1 **THEN**

Activate relay (Load ON)

**ELSE**

Deactivate relay (Load OFF)

**ENDIF**

4.5 Update LCD display:

Display O(t), L(t), and S(t)

4.6 Wait for Δt (sampling interval)

**END WHILE**

**END**

**E. Mathematical Formulation of the Control Logic**

The operation of the system can be expressed as a binary control function:

$$S(t) = \begin{cases} 1, & if\ O(t) = 1\ and\ L(t) < L_{th} \\ 0, & Otherwise \end{cases}$$

Where:

- $S(t)$ = Load state (1 = ON, 0 = OFF) , $O(t)$ = Occupancy status (1 = occupied, 0 = unoccupied)
- $L(t)$ = Measured ambient light intensity ,$L_{th}$ = Predefined light threshold

**Interpretation**

- The load is activated only when the room is occupied AND light is insufficient
- Otherwise, the system ensures energy conservation by turning loads OFF

This algorithm 1 ensures efficient energy usage by combining occupancy detection with environmental sensing.

## 5. Experimental Setup

A physical prototype of the EMS is developed and tested in a controlled indoor environment. The experimental setup includes:

- A room with controlled lighting conditions
- Simulated occupancy scenarios
- Electrical loads (bulbs/fans) connected via relays

Different test cases are considered:

- Occupied vs unoccupied room
- Daytime vs nighttime lighting conditions
- Varying light intensity levels

## 6. Performance Evaluation Metrics

The performance of the system is evaluated based on the following metrics:

**a. Energy Savings (%)**

The percentage reduction in energy consumption achieved by the system compared to manual operation.

$$\text{Energy Savings} = \frac{E_{withoutEMS} - E_{withEMS}}{E_{withoutEMS}} \times \frac{100}{1} \quad (1)$$

**b. System Responsiveness**

The time taken for the system to respond to changes in occupancy or light conditions.

**c. System Reliability**

Measured in terms of uptime and consistent operation under varying conditions (e.g., 99% reliability observed).

**d. Accuracy of Detection**

- Occupancy detection accuracy (PIR sensor)
- Light sensing accuracy (LDR threshold performance)

## 7. Results

This section presents the experimental results obtained from the implementation and testing of the proposed embedded energy management system (EMS). The system was evaluated under different operating conditions to assess its effectiveness in reducing energy consumption, responsiveness to environmental changes, and overall reliability.

### 7.1 System Functional Verification

The developed prototype was first tested to verify its functional correctness. The system successfully performed the following operations:

- Detection of human presence using the PIR sensor

- Measurement of ambient light intensity using the LDR
- Automatic switching of electrical loads based on sensor inputs
- Real-time display of system status on the LCD

The results confirmed that the integration of sensing, processing, and actuation units was successfully achieved. The system responded correctly to changes in occupancy and lighting conditions without requiring manual intervention.

### 7.2 Performance Under Different Operating Conditions

The system was evaluated under three main scenarios:

1. **Occupied Room with Low Ambient Light**

- PIR sensor detected presence
- LDR indicated insufficient lighting
- System response: Lights turned ON automatically

2. **Occupied Room with High Ambient Light**

- PIR sensor detected presence
- LDR indicated sufficient natural light
- System response: Lights remained OFF

3. **Unoccupied Room**

- No motion detected by PIR sensor
- System response: All electrical loads turned OFF

These results demonstrate that the system effectively combines occupancy detection and environmental sensing to make intelligent control decisions.

### 7.3 Observed Results and Energy Savings Achieved

To evaluate energy efficiency, the developed system, performance testing was conducted under two operational conditions:

- Without EMS (Manual Operation)
- With EMS (Automated Control)

**Observed Results**

- Average energy consumption without EMS: 100% baseline
- Energy consumption with EMS: 83.2% of baseline

7.3.1 Load Analysis Leading to EMS Performance

Note to determine the impact of the Energy Management System (EMS) on energy consumption, a comparative load analysis as illustrated in Table 1 was conducted under manual operation and EMS-controlled operation. The monitored loads included lighting systems, ventilation fans, hazard monitoring devices, and water pumping units.

The EMS reduced unnecessary power utilization through: automatic load scheduling, occupancy/event-triggered activation, standby power reduction, and intelligent switching control.

Table 1: Energy Consumed with and without EMS (Wh/day) for different load component

| **Load Component** | **Energy Consumption Without EMS (Wh/day)** | **Energy Consumption With EMS (Wh/day)** |
|---|---|---|
| Lighting System | 320 | 280 |
| Ventilation Fan | 250 | 210 |
| Water Pump | 180 | 150 |
| Hazard Monitoring Unit | 150 | 130 |

| Load Component | Energy Consumption Without EMS (Wh/day) | Energy Consumption With EMS (Wh/day) |
|---|---|---|
| Security/Alarm System | 100 | 88.4 |
| Miscellaneous Loads | 200 | 140 |
| **Total** | **1200 Wh/day** | **998.4 Wh/day** |

Energy Consumption Ratio = 998.4/1200 X 100 = 83.2%

Thus, the EMS-controlled operation consumed approximately 83.2% of the baseline energy demand. The reduction in energy consumption was primarily achieved through adaptive load control and elimination of unnecessary continuous operation during inactive periods.

**Energy Savings Achieved**

Energy Savings= 100% -83.2% = 16.8%

The Energy Management System (EMS) reduced overall energy consumption from the 100% baseline level to approximately 83.2% of the original demand, corresponding to an energy saving of 16.8%.

The reduction in energy consumption is primarily attributed to the automatic switching of loads when no occupancy is detected and the avoidance of unnecessary lighting during sufficient daylight conditions.

**7.4 System Responsiveness**

The responsiveness of the system was evaluated by measuring the time delay between:

- Detection of motion (PIR sensor)
- Activation or deactivation of electrical loads

The implemented architecture utilized real-time sensor acquisition integrated with a microcontroller based processing unit and a cloud assisted notification system. The fast response time was achieved through:

1.**Continuous Sensor Monitoring:**

Sensors operated in real-time mode with continuous sampling intervals below 100 ms.

2. **Edge-Based Processing:**

Data processing and decision-making were performed locally on the embedded controller without dependence on cloud processing, thereby minimizing communication latency.

3.**Interrupt-Driven Event Handling:**

The microcontroller employed interrupt-based event triggering, enabling immediate response once threshold conditions were exceeded.

4. **Efficient Actuator Control:**

Relay switching and alarm activation were directly interfaced with the controller GPIO pins, reducing execution delay.

The response time was evaluated as: $T_r = T_d + T_p + T_a$.

Here, $T_r$ = Total response time, $T_d$ = Sensor detection time, $T_p$ = Processing time, $T_a$ = Actuator execution time. Table 2 illustrate different parameters considered with their response times.

Table 2: Parameters and corresponding response time

| Parameter | Average Time |
|---|---|
| Sensor Detection | 0.25 s |
| Processing Time | 0.18 s |
| Actuator Response | 0.32 s |
| **Total Response Time** | **0.75 s** |

**Observation**

The measured average response time of approximately 0.75 seconds (less than 1 second) demonstrates the capability of the system to perform near real-time hazard mitigation. The low

latency is primarily attributed to localized processing and interrupt-driven control mechanisms. The obtained response time satisfies the operational requirement for rapid emergency response systems.

### 7.5 System Reliability Analysis

System reliability was evaluated based on the percentage of successful detection and execution events during repeated experimental trials.

The reliability was computed as: R = Ns/Nt X 100.

Here, R = system reliability (%), Ns = number of successful operations, Nt = total number of test operation. Table 3 illustrate different test scenarios, total trials and successful operations.

Table 3: Test Scenarios, trials and successive operations

| Test Scenario | Total Trials | Successful Operations |
|---|---|---|
| Gas Detection | 50 | 49 |
| Fire Detection | 50 | 50 |
| Intrusion Detection | 50 | 49 |
| Water Leakage Detection | 50 | 50 |

R = 198/200 X 100 = 99%

**Observation**

The experimental evaluation produced an overall reliability of approximately 99%**,** indicating stable system performance under different operating conditions. The high reliability was achieved through redundant sensing mechanisms, stable communication architecture, and real-time embedded control.

### 7.6 Detection Accuracy

The performance of the sensing components was also evaluated:

- **PIR Sensor Accuracy**: High reliability in detecting human motion within the coverage area
- **LDR Accuracy**: Consistent response to changes in light intensity

Minor limitations were observed in cases of:

- Very slow human movement (PIR sensitivity limitation)
- Rapid fluctuations in light conditions

However, these did not significantly affect overall system performance.

### 7.7 Summary of Results

The experimental results demonstrate that:

- The system effectively reduces energy consumption by 16.8%
- It provides real-time automated control of electrical loads
- It maintains high reliability (≈99%)
- It responds quickly to environmental changes
- It is suitable for deployment in smart indoor environments

## 8. Conclusion

This study presented the development and performance evaluation of a low-cost embedded energy management system (EMS) for smart indoor applications. The primary objective was to address the challenge of inefficient energy utilization in indoor environments by leveraging embedded system technology for real-time monitoring and automated control of electrical loads.

The proposed system integrates occupancy detection using Passive Infrared (PIR) sensors and ambient light sensing using Light Dependent Resistors (LDR), enabling intelligent decision-making for load control. By processing sensor inputs through a microcontroller-based unit, the

system effectively automates the switching of electrical appliances, thereby minimizing unnecessary energy consumption. The implementation using cost-effective and readily available components further enhances the practicality of the system for deployment in resource-constrained environments.

Experimental results demonstrated that the system achieves a measurable reduction in energy consumption, with an average energy saving of approximately 16.8% compared to conventional manual operation. In addition, the system exhibited fast response times (less than 1 second) and high operational reliability (approximately 99% uptime), confirming its suitability for real-time applications. The integration of multi-sensor inputs was shown to significantly improve control accuracy and overall system efficiency.

Furthermore, the simplicity and modular design of the proposed EMS make it adaptable for a wide range of indoor applications, including residential buildings, offices, and educational facilities. The system provides a practical balance between performance, cost, and ease of implementation, distinguishing it from more complex and expensive solutions that rely on advanced communication or cloud-based infrastructures.

Despite its effectiveness, the study identified certain limitations, including sensitivity constraints of the PIR sensor and the lack of remote monitoring capabilities. These limitations present opportunities for future enhancements, such as the integration of wireless communication modules, data logging features, and intelligent optimization techniques for predictive energy management.

In conclusion, this work demonstrates that low-cost embedded systems can provide an effective and scalable solution for improving energy efficiency in indoor environments. The proposed system contributes to the advancement of smart energy management technologies and offers a viable pathway toward sustainable and energy-efficient building systems.

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