Signal Processing Framework for Occupancy-Aware Energy Optimization in Smart Buildings

Ms. Anusuya[1], anusuya.ece@krce.ac.in[1]
Department of ECE, K. Ramakrishnan college of engineering, Tamilnadu
Ridhusha P[2], Priyadharshini B[3], Yuvapriya N[4], Puvieswar B[5]
ridhushaprasad@gmail.com[2], priyadharshinib.ece24@krce.ac.in[3], yuvapriya2006ramu@gmail.com[4], puvinjeeva@gmail.com[5]
Department of ECE, K. Ramakrishnan college of engineering, Tamilnadu

Abstract — The smart buildings consume lot of electricity because lights and air conditioners are used too much. That's why these devices often stay on even when no one is present in the hall. There is a growing environmental concern about the saving of energy so that this signal processing framework is required. By checking if a room is occupied, buildings can save energy by making the space comfortable for people without any disturbances. The system uses sensors to detect people and turns lights and air conditioners on or off as per the movement and heat released from humans. The system operates with minimum response delay ensuring effective framework for smart buildings.

Key Word*: Occupancy Detection; PIR Sensor; Smart Room Automation; Signal Processing; Real-Time Simulation; Energy Efficiency; IoT Integration; Human Presence Detection; Virtual Device Control; Smart Building System.*

I INTRODUCTION

In current scenario, there is a huge demand for energy- saving devices because more and more people are using household appliances at home, in offices, and in businesses. Lights and air conditioners use a lot of electricity. At many times, these systems run even when no one is around, leading to a lot of waste. As people become more concerned about the environment and also rising electricity bills, there's a great need for smarter systems that can control energy use based on how busy a place is at any moment. It detects the presence of people in a place and automatically switches the lights and ac on or off according to the need. When people are in a room, the lights and air conditioners are turned on. When the room is empty, they are turned off. This helps in reduction of energy usage and hence large amounts of energy is saved. These systems ar now commonly available in all places including hi-tech cities. In this work, an occupancy detection module is proposed based on the basics of signals and systems. Sensors like the Passive Infrared (PIR) sensor send electrical signals when presence or motion of a person is sensed. These signals are the input data. The controller reads and processes the data to decide what action to take. Basic signal processing techniques like filtering, setting thresholds, and adjusting signals, are used and the output becomes clean and accurate. This output is then used to automatically switch lights and air conditioners on or off according to the need.

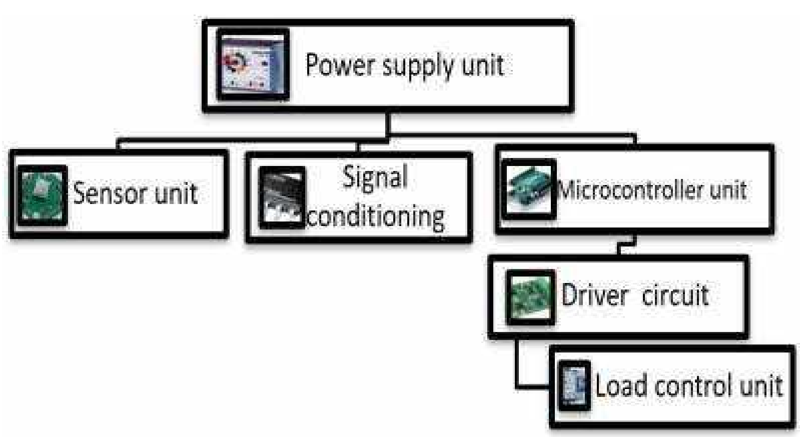

Fig 1. Block Diagram of Smart Room Occupancy Detection and Control System

The signals are detected via a PIR sensor, which sends a series of on and off signals over a given time period. When someone moves, the sensor sends a high signal (1) indicating the presence a person in the room. When there's no movement, it sends a low signal (0) which means the room is empty. Sometimes, the sensor may throw an error, confused by things like wind or quick movement, which leads to mixed and multiple distorted signals. This can cause lights and air conditioners to turn on and off too often, which isn't suitable for ideal purpose. To correct this issue, the system uses special signal processing techniques.

A low pass is used to filter smooths out the signals so sudden changes from the sensor doesn't affect the system. There's a hold or latch function that keeps the signal active for a short time even after someone leaves, which prevents lights or air conditioners from turning off too quickly. These methods are used to give a stable and smooth signal for controlling lights. This signal can now automatically turn lights and air conditioning on or off, depending on whether the room is occupied or not. By observing the signal during a certain period shows how the system reacts to people and the working of filtering, and also how the hold function helps in maintaining a stable signal. From this a clear example we can infer how digital signal processing and system control functions in real-time situations. The system can be used across multiple rooms or large zones, allowing for smart energy management throughout a building. The energy is saved automatically by adjusting the lights and air conditioning with people-detecting sensors, ensuring comfort and by avoiding unnecessary electricity use. This shows how the concepts of signals and systems can be applied in real situations to build intelligent, energy-saving applications which are used in modern infrastructure.

II REVIEW OF LITERATURE

Occupancy-based energy management has gained a popularity because of the need for better energy efficiency in building systems. Engineers are currently working upon combining sensors, automatic controls, and signal processing to make lighting and air conditioning systems more efficient.
The research team led by Siddharth S, Kumar P, Ramesh B, etc., did a study in 2020 et al[1]. The study showed how to understand human emotion recognition by using advanced machine learning. Researchers have used deep learning models with visual inputs and physiological signals to improve performance. Even though the study gave more importance on emotion recognition, it still helps us to understand the presence of humans. This study shows that combining input from multiple sensors can improve system reliability and accuracy in detecting the presence of human.

Nguyen T, Park J, and Kim H did a study in 2022 et al[2]. Using passive infrared sensor, the system collects data intellectually and give the output. Human activity is sensed by motion. This system was tested by researchers under various lightning conditions in order to provide accurate results. This study proves PIR sensors are cost effective. Patel R, Shah M, and Verma K did a study in 2021 et al [3]. The paper talks about detecting the motion of people and giving signals. Before each operation the system cleans it up. The method used in this study is similar to the preprocessing step in our project, where disturbances are removed before deciding to activate or deactivate devices. The study Good signal handling and effective energy saving techniques.

Li X, Chen Y, and Zhang L did a study in 2022 et al[4]. The researchers have designed a system which controls household devices by sensing human presence. The system adjusts lighting and electronic devices based on movement of person. The simulation tested the system's response time, performance, and energy usage. The study tells us that using smart controls for devices can save energy during automatic operations. Anaka S and Yamamoto K did a study in 2020 et al[5]. This study helped in reducing building energy use by using PIR technology to detect occupancy. The researchers have developed a lighting system that turns on lights only when human presence is detected. Their study showed real-world energy. The study enhances the role of simple sensors like PIR detectors in managing residential properties. The idea from these sensors forms the basis of our project, which uses PIR sensors for automatic equipment control. Alam M, Reaz MBI, and Ali MAM did a study in 2024 et al[6]. This paper shows an intelligent office space monitoring system based on IoT technology. The system uses sensors like PIR motion detectors, thermometers for temperature, CO_2 sensors, and entry/exit detectors connected to a microprocessor linked with individual databases through the internet. Based on lightning and cooling systems data is collected. Combining IoT technology with continuous data tracking can start new possibilities for our project in the future.

Gunay HB, O'Brien W, Beausoleil-Morrison I. (2021) et al[7]. This report uses different methods, like data from heating, ventilation, and air conditioning systems. The system uses motion sensors, security cameras, and carbon dioxide meters to monitor activity in smart buildings. The authors talk about how to balance comfort with energy savings by using control systems effectively. They suggest using delays or holds in the systems when people leave an area to avoid errors. This method is similar to our signal-hold system, which helps the system run smoothly during automated operations. Owlet F, Parisi A, Jones C N, et al.

(2019) et al[8]. These researchers focused on predicting the number of people held in space depending upon data from monitoring devices. The system tries to display future occupancy to improve energy efficiency. Using statistical and machine learning methods, they predicted short-term room occupancy. Maaspuro M, Seppänen O. (2018) et al[9]. This report incorporates different infrared sensing devices, including those that reflect and those that emit light. The researchers compare infrared sensors to other options like ultrasound and microwave. The findings show that PIR sensors are the most cost-effective and high-quality option for usage in small spaces. This research supports our choice of using PIR sensors for detecting movement in these activities. Zhang W, Chen C, Wang L, Zhou M. (2018) et al[10]. This study uses thermal imaging devices and AI algorithms to detect the presence of people in areas and track their presence in rooms. The researchers said that AI significantly improves performance, but it needs more computational power and large amounts of data for efficient operation. This method performs well compared to PIR sensors.

As the system runs the PIR sensor senses the presence of person in the room and turns on and off automatically. The project builds a system that senses when someone is in a room using a PIR sensor. The sensor detects heat from people and sends a signal which controls the AC and light in a simulated room. The main aim is to show how the system automatically turns the appliances on and off and how the signals are generated.

The signal from the sensor looks like this:

S(t) = 1, person is detected, and 0 if no person is detected.

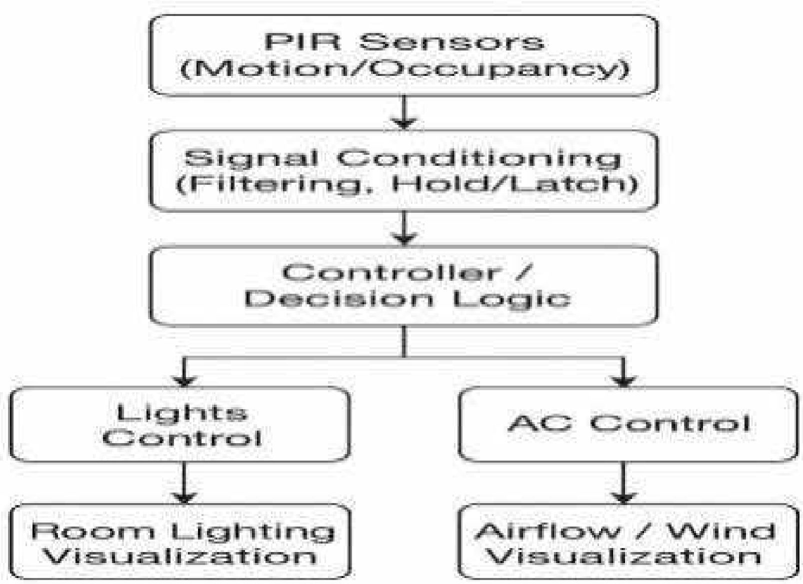

Fig.2 Block diagram of Occupancy based signal conditioning.

1. Signal Acquisition

Real time tracking in the system is done using JavaScript, where buttons simulate a person entering or leaving the room. Pressing the "Enter" button changes the signal to 1, and pressing the "Exit" button changes it back to 0.

To make system more accurate and to prevent false triggers, a simple method of filtering is used:

O(t) = average value of the signals over a short period of time. This average helps reduce shorten changes that might not mean someone is actually there.

The system uses the filtered signal to decide when to turn the AC and bulb on or off:

If filtered signal is ≥ 0.5, the appliance turns on. If filtered signal
< 0.5, it turns off.

A real-time graph shows the signal and keep's on updating each time when there's a change. The graph shows time on the x-axis and the signal value on the y-axis. It clearly depicts how often people come and go and how the appliances respond Whenever signal changes, the code keeps on updating both the appliances and the graph at the same time. This setup allows the system to monitor the room in real time, control the appliances automatically, and provide a clear visual of the room's occupancy. It's practical and a smart room working is shown. In future, the system could be improved by using saved data and machine learning to predict when people will enter or leave, this helps in saving energy and better management of smart buildings.

III. METHODOLOGY

The proposed system follows a systematic approach to detect human presence and helps in controlling electrical appliances based on occupancy. The method has four main stages: signal acquisition, preprocessing, decision logic, and control action. Each stage plays a major role in ensuring efficient energy optimization within smart buildings. A Passive Infrared (PIR) sensor is used as the primary element for sensing. As shown in Fig 3, The system detects infrared radiation emitted by human bodies. When a person enters the room, the sensor outputs a high digital signal ("1"), and when no movement is detected, it outputs a low signal ("0"). The binary signals act as the input for the microcontroller. The sensor is placed at a correct level to ensure that the entire room is covered, also minimizing false detection from background heat or airflow.

Fig 3. Movement detection using PIR sensor

2. Signal Preprocessing

The raw output from the PIR sensor is unstable due to noise, temperature variations, or minor disturbances like airflow. Therefore, signal conditioning is applied to promote smooth work:

A low-pass filter smooths sudden spikes in signals and removes high-frequency noise.

A threshold function differentiates valid human motion from random disturbances.

A hold or latch mechanism is used to maintain the detection of signal for a few seconds after motion stops, preventing flickering or premature switch-offs.

This preprocessing is used to ensure that only stable and meaningful occupancy signals are used for controlling appliances.

3. Decision Logic

After preprocessing, the filtered signal has been analysed in real-time. The system uses the following logic:

$O(t) =$ Average value of signal samples within time T

If $O(t) \geq 0.5$, it implies occupancy (presence detected), and the control output is activated.

If $O(t) < 0.5$, it implies vacancy, and the devices are turned off. This decision logic balances sensitivity and stability, ensuring the system responds accurately to real occupancy events.

4. Control and Automation

The final control signal is sent from the microcontroller to appliances—eventually, a light bulb and an air conditioner (AC) in this project. As shown in Fig 4,

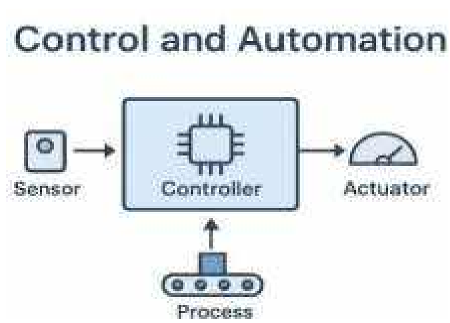

Fig 4. Control and automation process.

When a person enters, both devices are turned on automatically. When the room becomes empty, they are turned off in order to save energy. This real-time control loop explains how signal processing can be used to improve energy efficiency by automating building operations based on actual human presence.

5. System Flow and Real-Time Monitoring

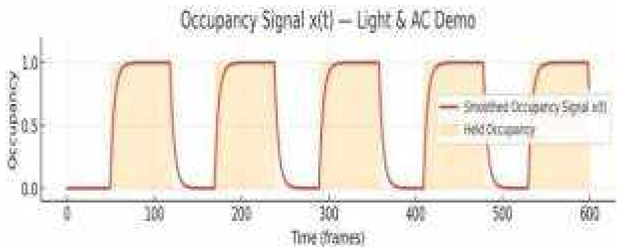

Fig 5. Signal waveform.

A JavaScript-based real-time interface has been used to simulate the environment, showing:

- The input signal (from the PIR sensor).
- The filtered output signals.
- Device status (Light and AC ON/OFF).
- A graph showing occupancy trends over time.
- This helps visualize how signal processing affects real- time decision-making and control.

IV RESULTS AND DISCUSSION:

The PIR sensor will generate a binary output signal S(t), where S(t) = 1 indicates presence of human and S(t) = 0 indicates no occupancy. To minimize false triggering caused by noise and minor disturbances, a moving average filter was applied to the sensor output. The filtered occupancy signal O(t) is given by:

$O(t) = (1/N) \times \Sigma S(i)$, for I = t – N + 1 to t

Where N represents the number of samples used to find average. A threshold-based decision rule is applied to find the occupancy state. The device control signal D(t) is given by:

$D(t) = 1$, if $O(t) \geq \theta$

$D(t) = 0$, if $O(t) < \theta$

Where the threshold θ is set to 0.5.

To avoid rapid switching of appliances, a hold mechanism is introduced. The hold function H(t) will maintain the active state for a duration Th after the last detected motion and expressed as:

$H(t) = 1$, if $(t - t\_last) \leq Th$

$H(t) = 0$, otherwise

The final control signal C(t) used to operate the lighting and air- conditioning systems is obtained by: C(t) = D(t) OR H(t)

The system response time Tr is calculated as the difference between the device activation(on) time and the motion detection time:

$Tr = t\_on - t\_detect$

An estimate of energy savings is obtained by comparing the operating time of appliance with and without automation: $E\_saved = P \times (T\_idle - T\_auto)$

Where P is the rated power of appliance, T_idle is the operating time without automation, and T_auto is the operating time with the proposed system. Experimental observations indicate that the proposed system responds fast to occupancy changes, ensures stable appliance operation, and reduces unwanted energy consumption. The results confirm that simple signal processing techniques can effectively improve energy efficiency in smart building environments.

Time (s)	Occupancy Event	PIR Signal (S(t))	Bulb Stat
0–5	Room empty	0	OFF
6–12	Person enters	1	ON
13–20	Person exits	0	OFF
21–30	Person enters	1	ON
21–35	Person exits	0	OFF
31–35	Person exits	0	OFF

Table 1. Shows the status of PIR signal with respect to time.

By observing the table, it's clear that the devices have changed instantly with the PIR signal, showing a direct linkage between detection of people and turning devices on or off. This shows that the system's signal processing and control are working well, there were no false signals triggered when no one was around, showing that the system is reliable and efficient. Overall, the table shows how the system works in real time and gives clear data that enhances the results and discussion.

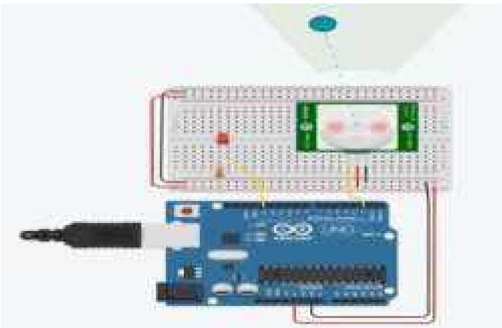

Fig 5. Occupied Room.

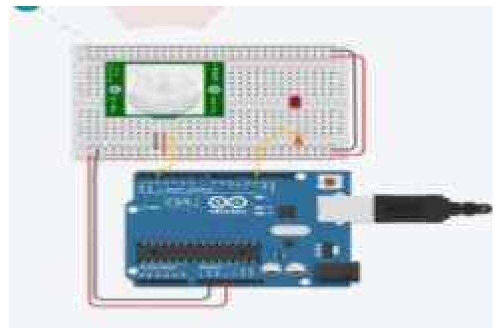

Fig 6. Unoccupied Room.

The experimental results show that the proposed framework efficiently reduces energy wastage while maintaining occupant comfort. The automation mechanism ensures that appliances operate only when needed, which contributes to important energy savings in modern smart building environments. The use of signal processing techniques such as filtering and threshold-based decision logic helped in removing false triggers, also ensures stable and reliable Performance of the system. Moreover, the real-time response of the system showed that the delay between motion detection and device activation was very low, highlighting its effectiveness for practical implementation. The integration of simple yet powerful sensors like the PIR makes the system cost-effective and integrable for larger infrastructures such as classrooms, offices, and conference halls.

The visualization module further improved the understanding of signal behavior and system response through live monitoring and data plotting. This real-time feedback allows users and building managers to calculate system efficiency and identify opportunities for optimization. The framework can also serve as a base for implementing advanced features such as machine learning–based occupancy prediction, adaptive threshold tuning, and also cloud- based IoT connectivity for remote monitoring.

In summary, the designed occupancy-aware automation system successfully brings down the gap between energy conservation and intelligent control. Its modular nature, low cost, and simplicity of implementation make it a practical solution for real-world energy management applications. Future enhancements could include integrating multiple sensing technologies (ultrasonic, temperature, and CO_2 sensors) and developing predictive models to further improve energy optimization in smart cities and sustainable infrastructures.

The system reacts in a very short span of time when people come in or go out, with little to no delay. The signal processing helps to stop false triggers, ensuring reliable work. The simulation we have designed lets you see and measure how devices respond, making it easy to test different situations without needing real equipment. The approach used here is simple and can be used in many places, and is significantly more efficient, when compared to other methods. The system supports using PIR sensors for real- time detection and makes it ready for connecting with smart home and IoT systems.

V CONCLUSION:

The study proved how a real-time system can detect people using PIR sensors and how it control's smart devices like a light bulb and air conditioner in a room. The system successfully estimated when people were there, giving clear on/off signals that matched the activation of the light and air conditioner.

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