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Affordable energy-saving switch control system for homes with differently disabled persons

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ABSTRACT

The need for energy conservation has become increasingly urgent in today's world, especially as energy costs continue to rise and the demand for sustainable living grows. For persons with physical disabilities, simple tasks like turning light switches on and off can be challenging, resulting in higher energy usage, increased electricity bills and increased physical strain. Existing solutions often prioritize energy efficiency but overlook affordability and accessibility, making them impractical for low-income households. To address these issues, this paper proposes an affordable automated energy-saving lighting switch control system using Arduino Uno, ultrasonic sensors for human presence detection, and a relay to control lighting. A person-counter mechanism ensures accurate operation based on room occupancy. Experimental results show that the proposed system achieves 100% accuracy in detecting human presence in a room, effectively reducing energy consumption from 0.4 kWh to 0.2 kWh per day, corresponding to 50% energy savings. Additionally, it is 42.41% less expensive than the most affordable system compared in the paper. These findings underscore the system's potential to offer an affordable, accessible, and energy-efficient solution that enhances the convenience and comfort of disabled persons while contributing to energy conservation efforts

INTRODUCTION

The global emphasis on energy conservation has become increasingly vital as the world faces escalating energy demands and the urgent need to adopt more sustainable practices (Afolabi, 2024). Residential energy consumption represents a significant portion of total energy use, with lighting being a major contributor (Olajiga, *et al.*, 2024). As a result, optimizing lighting control systems in homes is a critical step toward achieving energy efficiency and conservation. For individuals with physical disabilities, the challenge of managing lighting can be particularly pronounced. Tasks that are simple for able-bodied individuals, such as switching lights on and off, can become burdensome or even unmanageable, leading to unnecessary energy consumption. This not only results in higher electricity bills but also adds to the physical and mental strain experienced by these individuals. Therefore, there is a pressing need for solutions that cater to the specific needs of physically disabled persons while also contributing to energy conservation. Automated lighting control systems offer a promising solution by removing the need for manual operation and ensuring that lights are only used when necessary. However, the cost of such systems can be prohibitive, limiting their accessibility, especially for low-income households. The system's design prioritizes affordability and ease of installation, making it accessible to a broader range of users. The components used are readily available and inexpensive, ensuring that the system can be implemented without requiring significant financial investment.

Many automated switch control solutions have been proffered by many authors in the past and in recent times. Akinsanmi *et al*. (2015) proposed an automatic headlight-switching system for automobiles. When humans' eyes are exposed to a light source with a high intensity of around 1,000 lumens, it experience a glare produced by overexposure of eye rods and cones. This glare leaves an after-image that creates a blind spot even when the source of light is removed. Using components that consist of a DC power supply, resistors, a transistor, diodes, a relay, switches, a light-dependent resistor, and LEDs, they designed a system that senses and switches vehicles' headlights according to the required conditions. The system automatically reduces the headlights' intensity when it senses a vehicle nearby approaching from the other direction and switches it back after the vehicle passes. Their solution solves the problem of a repeated off-on manual switch of headlamps and reduction in eye damage caused by light intensity flashed on drivers' eyes by on-coming vehicles. Mtshali and Khubisa (2019) proposed a system that leverages smart plugs, cameras, power strips, and digital assistants like Amazon Alexa to enable persons with physical disabilities to control home appliances through voice commands, offering them greater independence with minimal effort. Gandhi *et al*. (2021) deployed a real-time IoT-based headlight dimmer system due to the rising concerns of vehicular accidents caused by erroneous beam switching by car drivers during fog or rainy climatic conditions. Their prototype constitutes three major LDR sensors that provide inputs to the Arduino microcontroller to provide a control mechanism. The mechanism toggles the beam from low to high or otherwise when there is a sudden change in climate conditions when driving. In Flamini *et al*. (2023) a cost-effective and reliable building automation and monitoring system, demonstrated through a case study of a typical home equipped with smart devices was proposed. The system monitors energy consumption, and environmental factors like temperature, humidity, and light levels, and tracks the status of windows and room occupancy. These elements are integrated into an open-source SCADA platform, "Home Assistant," accessible via a simple web dashboard. Okomba (2024) proposed an intelligent lighting control system (ILCS) for hospital buildings to enhance energy efficiency and user comfort by considering natural light and occupancy. The system uses Artificial Neural Networks (ANN) and various machine learning algorithms to process sensor data for optimal lighting control. With the increasing use of smart devices. Kshirsagar *et al*. (2024) introduce a comprehensive energy monitoring system designed to address the challenges of power consumption in homes. The system features a Thin-Film Transistor (TFT) capacitive touch display that provides real-time insights into energy usage and allows users to control their devices' power states. By offering immediate feedback and a user-friendly interface, the system empowers users to make informed decisions, leading to significant energy savings and reduced environmental impact. A cost-effective IoT-based bi-directional guest enumerator with smart light control was proposed by Aru (2024). The system uses infrared sensors to detect human presence and reports via a Blynk app. Afolabi *et al*. (2024) developed a cost-effective intrusion detection and reporting system for home security in Nigeria, utilizing passive infrared (PIR) sensors for motion detection, ultrasonic sensors to measure intruder's distance, and a NodeMCU ESP8266 microcontroller for signal coordination, integrated with Blynk app.

The works of these various authors serve as motivation for this paper. However, while prior systems emphasize general energy efficiency and smart automation, they do not address the unique needs of disabled persons, nor the financial constraints of many households. Existing solutions like smart plugs, voice-activated systems and artificial intelligence, can be costly and complex to implement, especially in regions with limited technological infrastructure. This paper will bridge this gap by proposing a low-cost, easy-to-implement automated lighting control system that prioritizes accessibility for disabled users, allowing them to manage lighting more independently and with minimal effort. While this system offers a practical, efficient solution that not only reduces energy consumption but also significantly improves the quality of life for persons with physical disabilities in a cost-effective manner; it also implements the use of a bi-directional person counter mechanism and ultrasonic sensors to achieve human presence detection in homes.

MATERIALS AND METHODS

i. Microcontroller: The Arduino Uno microcontroller as shown in Figure 1, serves as the system's control unit, featuring multiple input/output pins, a USB port, a power jack, and a reset button. It is cost-effective, energy-efficient, compact, and programmed using Arduino software via a USB connection to a computer.

ii. Ultrasonic Sensor: Ultrasonic sensors (HC-SR04) detect human presence by emitting high-frequency sound waves and calculating the distance to objects based on the echo's return time. They offer better range performance than infrared sensors, making them ideal for detecting movement and presence within a specified range. Figure 2 shows how the signal reflection of the ultrasonic signal appears when it encounters an object.

iii. Relay Module: As shown in Figure 3, a relay is an electrically operated switch that controls the flow of current, powered by the 5-V Arduino pins of the microcontroller. Its high-voltage pins manage power, while the low-voltage pins connect to components like the Arduino.

iv. Electric Light Bulb: The electric bulb is a component of the system that provides light on the application of electricity. It is the component used to test the automated switch control system.

v. LED: LEDs (light emitting diodes) are energy-efficient, have a long lifespan, and are commonly used for indication, illumination, and display purposes in a wide range of electronic devices and systems. They are used as indicators in this work.

vi. LCD Display: A liquid crystal display (LCD) modulates light to produce color or monochrome images, using a backlight or reflector. In this work, it is used to display the number of people in the closet under observation, as shown in Figure 4.

vii. Jumper cables: Jumper cables, shown in Figure 5, are used to open or close electrical circuits and regulate circuit boards. Made with conductive material sheathed in plastic to prevent short circuits, they function like on/off switches and are less vulnerable to power failure-induced corruption since they are configured once.

viii. BreadBoard: A breadboard, shown in Figure 6, is a cost-effective tool for prototyping and testing circuits, allowing easy insertion, rearrangement, or removal of components without soldering, making it ideal for experimentation.

ix. 5-V DC power supply: 5-V DC Power Supply: The onboard USB port of the microcontroller unit (NodeMCU) is used to supply 5-V power to the system by connecting a micro-USB cable from the board to an appropriate power source.

x. Potentiometer: the potentiometer is used to control the contrast of the LCD.

Figure 1: Arduino Uno microcontroller

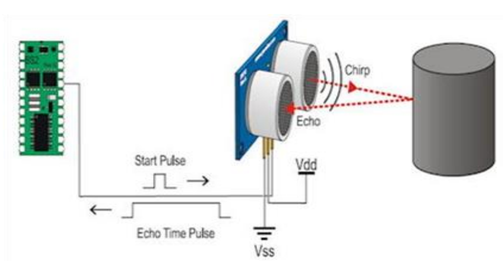

Figure 2: Representation of ultrasonic signal deflection from a target object

xi. Arduino IDE: This software is an open-source environment that was used to write, compile and upload code to the Arduino Uno board.

xii. Python: Python is the programming language used to write the code on Arduino IDE.

xiii. Windows 10: Windows 10 is the Operating System platform used on the personal computer PC that programs the Arduino code.

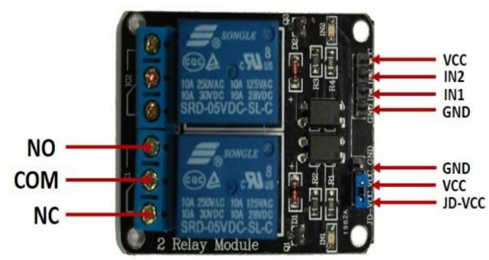

Figure 3: Two-Channel Relay

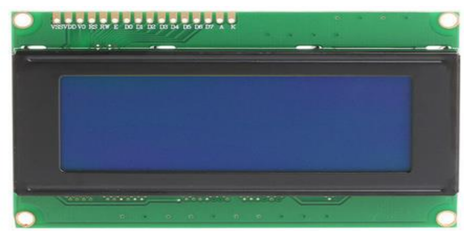

Figure 4: Liquid Crystal Display (LCD)

Figure 5: Jumper cable

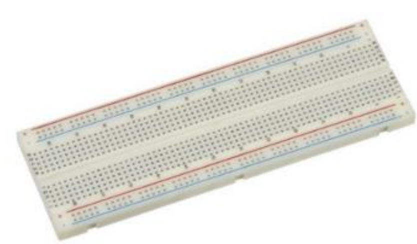

Figure 6: Breadboard

System Design

The block diagram in Figure 7 shows the architecture of the proposed system. As shown in the diagram; the two ultrasonic sensors are the input units to the Arduino microcontroller which serves as the central controller of the system (one for entry and the other for exit). The relay, LCD, and light bulb are the output units that respond based on the signal supplied by the inputs.

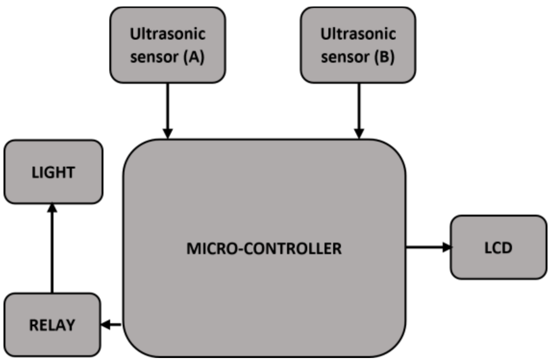

Figure 7: Block diagram of system architecture

System Implementation

The circuit diagram for the integrated system, as illustrated in Figure 8, was implemented by interfacing each component with the breadboard using appropriate configurations to form a complete circuit. The ultrasonic sensors, LED, and relay are connected to the microcontroller unit, while the light bulb is connected to the relay pins. The I2C pins of the LCD are connected to the digital pins of the NodeMCU (microcontroller unit). The output pins of the pair of ultrasonic sensors are connected to the D12 and D10 pins of the NodeMCU. Likewise, the 5-V relay module is connected to the D8 pin of the NodeMCU. Since 5-V ultrasonic sensors and a relay module are used in the system, a 5-V DC power supply is provided by connecting a USB cable from the onboard USB port of the NodeMCU to a computer USB port, which is used as a suitable power source. Using the circuit diagram

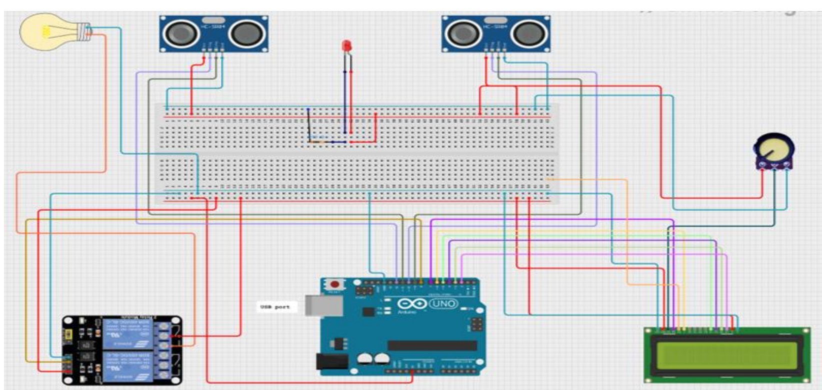

Figure. 8: Schematic circuit diagram of system implementation

of Figure 8, the prototype of the integrated system as shown in Figure 9, was developed.

System Operation

The human presence detector device is usually mounted at the door point where the sensor can easily detect the entry and exit of persons into the room. To power the system, a USB cable is connected from the onboard USB port of the NodeMCU to a computer USB port. The operation of the system begins when it is switched on and the ultrasonic sensors start to send signals, the sensors calculate the time the signal travels from the trigger to the object and reflect to the sensors

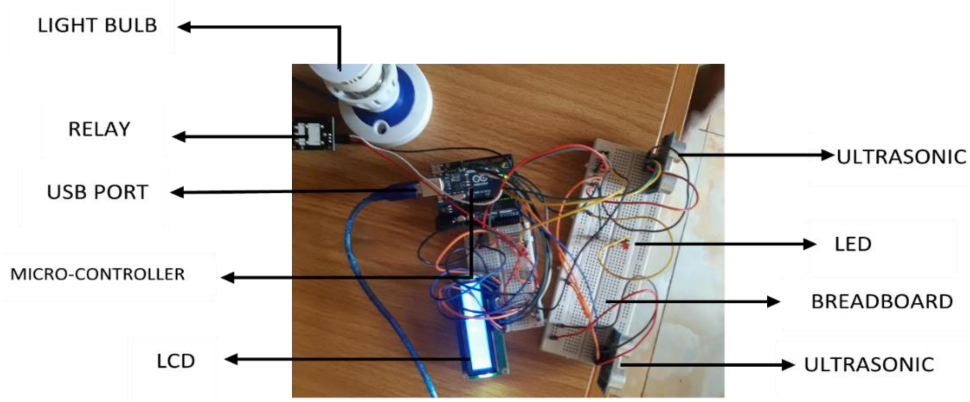

Figure. 9: Integrated developed system

which are used to detect a person passing by. As shown in Figure 10, the LCDs the real-time person count in the closet while the relay controls the light bulb switch based on the status of the counter. A count (increment) is recorded when a person passes from sensor 1 to sensor 2 (this indicates entrance into the room) and a decrement is registered when a person moves from Sensor 2 to Sensor 1 (this indicates an exit from the room), the light bulb will remain OFF when the count is zero (this shows that the room is empty) and ON when the count is greater or equal to one (1). The microcontroller in this case stores the program that increments the counter and triggers an event if a specific number is reached, in this case 6. Figure 11 shows how the bulb is illuminated when the device detects human presence. In Figure 12, the final picture of the coupled prototype is shown.

Figure. 10: Real-time person count on LCD

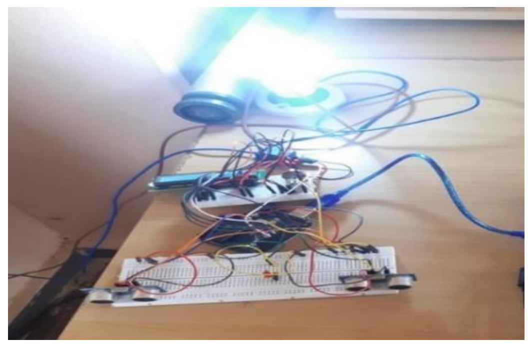

Figure. 11: Pre-coupled prototype implementation

Figure. 12: Coupled prototype

RESULTS AND DISCUSSION

Experiments were carried out several times with the developed system to generate some results. Figure 13 is the System operation's flowchart. The information

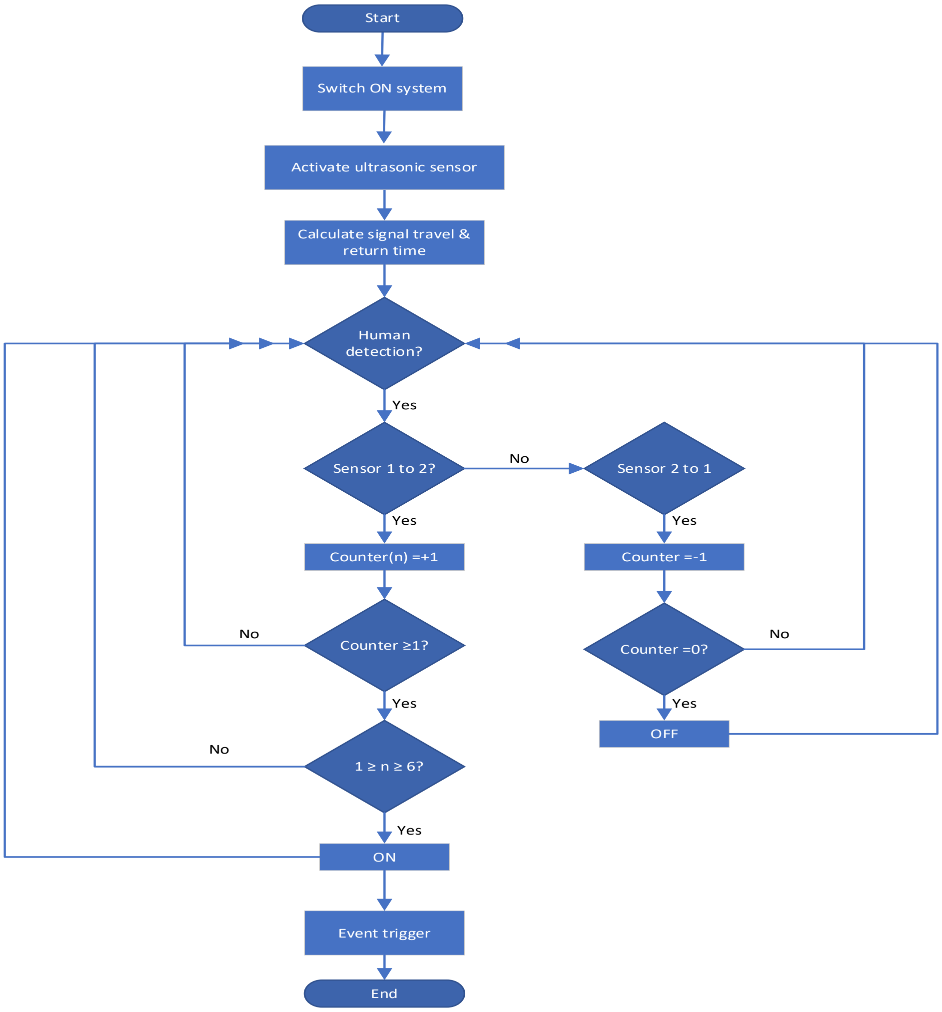

Figure. 13: System operation's flowchart

in Table 1 shows how the system was triggered into action when the movement of persons was picked by the sensors. It can be seen that the counter could not increment when Sensor 1 detected human presence until Sensor 2 also detected the same. Sensor 2 must confirm what Sensor 1 detects and vice versa for an event to trigger. Table 2 shows the reverse of events that occurred in Table 1 to show counter decrements when persons leave the room and until the light bulb is turned off.

In comparison with the cost of selected related works, the cost-effectiveness of the proposed system stands out, balancing affordability with robust functionality. Previous systems, while offering energy-saving solutions, often incorporated more expensive components such as high-end microcontrollers, advanced sensors, or proprietary software, which considerably increased their overall cost. The key to the low-cost advantage of the proposed system lies in the strategic selection of hardware. Components such as the Arduino Uno microcontroller, ultrasonic sensors and standard LED were chosen for their low cost, without compromising performance. The use of an ultrasonic sensor combined with a person counter mechanism to detect human presence proves to be significantly more economical than alternative sensor

Table 1: Results of the Readings from Sensor 1 to Sensor 2

S/N	SENSOR 1	SENSOR 2	ACTION	LIGHT(ON/OFF)	COUNT
1	Triggers	Not Triggered	Entrance	OFF	0
2	Triggers	Triggers	Entrance	ON	1
3	Triggers	Triggers	Entrance	ON	2
4	Triggers	Triggers	Entrance	ON	3
5	Triggers	Triggers	Entrance	ON	4
6	Triggers	Triggers	Entrance	ON	5
7	Triggers	Triggers	Entrance	ON	6

Table 2: Results of the Readings from Sensor 2 to Sensor 1

S/N	SENSOR 2	SENSOR 1	ACTION	LIGHT(ON/OFF)	COUNT
1	Not Triggered	Triggers	Exit	ON	6
2	Triggers	Triggers	Exit	ON	5
3	Triggers	Triggers	Exit	ON	4
4	Triggers	Triggers	Exit	ON	3
5	Triggers	Triggers	Exit	ON	2
6	Triggers	Triggers	Exit	ON	1
7	Triggers	Triggers	Exit	OFF	0

technologies like infrared or LIDAR, which are more expensive and may provide redundant functionalities.

Furthermore, the integration of the low-cost 16x2 LCD for real-time monitoring, simple jumper cables for circuit connections, and an efficient relay module to regulate power, all contribute to the cost reduction. The system avoids licensing fees associated with proprietary platforms by using open-source software such as Arduino IDE and Python for programming. Additionally, the choice of off-the-shelf components like breadboards and low-cost 5-V power supplies ensures that the system remains scalable and maintainable at a lower price point.

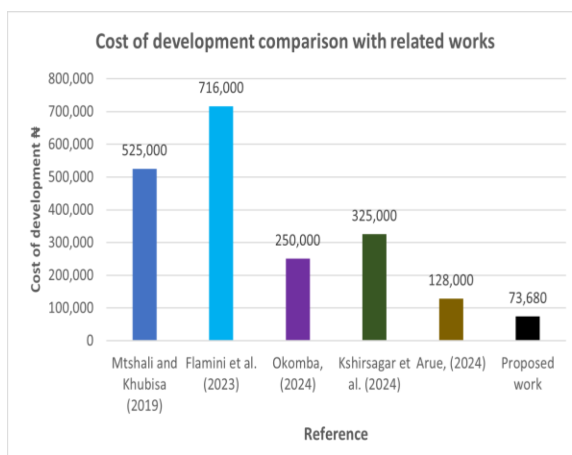

Figure. 14: Graph showing the cost of development comparison between related works and the proposed system.

The graph of Figure 14 provides a clear cost comparison between the proposed system and other related works, as measured by the cost of ₦128,000. This makes the proposed system an ideal solution for low-income homes with physically disabled persons, where both affordability and usability are paramount. This balance between cost and quality makes the system accessible to a broader audience, while still achieving significant energy savings and improving the independence and convenience of disabled occupants.

Energy Saving Validation

In this work, the load consists of a single 20-Watt AC light bulb, which is automated by the designed system. To establish the energy savings achieved by the system, two assumptions are made

i. For Band A customers in Nigeria, the tariff rate is ₦206.80 per kWh, with a minimum expected electricity supply of 20 hours per day (Akpan, 2024). Therefore, say tariff rate is ₦206.80k per unit of energy consumed per hour.

ii. At least one person is present in the room, for about 10 hours daily.

CASE 1:

To calculate the units of energy consumed in kilowatts per hour for 10 hours daily, in which room is occupied:

Energy units consumed for 10 hours is:

$$\frac{(20 - Watts\ \times 10\ hours)}{1000} = 0.2\text{kW}h$$

The energy charged is: ₦206.80k × 0.2kWh = ₦41.36k

Energy charged per month is:

₦41.36k × 30 days = ₦1,240.80k

Energy charged per year is:

₦1,240.80k × 12months = ₦14,889.6k

CASE 2:

To calculate the units of energy consumed in kilowatts hour in the room, when the system is not installed. Thus, the light bulb is constantly ON for 20 hours daily. Energy units consumed for 20 hours is:

$$\frac{(20 - Watts\ \times 20\ hours)}{1000} = 0.4kWh$$

The energy charged is:

₦206.80k × 0.4kWh = ₦82.72k

Energy charged per month is:

₦82.72k × 30 days = ₦2,481.60k

Energy charged per year is:

₦2,481.60k × 12months = ₦29,779.20k

From the above calculations, the annual energy savings per year/efficiency of the system can be obtained as follows:

From CASE 1, let E1 represent the annual energy cost when the system is installed in a room and the light bulb is ON for 10 hours daily.

From CASE 2, let E2 represent the annual energy cost when the system is not installed in a room and the light bulb is ON for 20 hours daily.

$$Efficiency\ = \frac{E2 - E1}{E2} \times 100 \qquad (1)$$

$$Efficiency\ = \frac{\text{₦29,779.20k} - \text{₦14,889.6k}}{\text{₦29,779.20k}} \times 100$$

$$Efficiency = \frac{₦14,889.6k}{₦29,779.20k} \times 100$$

$$Efficiency = 50\%$$

The above calculation shows that the system when deployed saves 50% of energy cost in a year when at least a person is present in the room for 10 hours daily. This further validates that this type of automation can help reduce energy wastage in homes. by automatically turning off lights when no one is present.

Table 3: Comparison with related works

Reference	Functionality	Cost Efficiency	Energy Efficiency	Adaptability for disabilities	Ease of deployment
Mtshali and Khubisa (2019)	A Smart Home Appliance Control System for Physically Disabled People	No	No	Yes	No
Flamini *et al*. (2023)	A Prototype of a Low-Cost Home Automation System for Energy Savings and Living Comfort	Yes	No	No	No
Okomba (2024)	Intelligent lighting control systems for energy savings in hospital buildings using artificial neural networks	No	Yes	No	No
Kshirsagar *et al*. (2024)	STM32-Based Home Automation and Energy Monitoring System with TFT Display	No	Yes	No	No
Arue (2024)	IoT Based Bi-directional Guest Enumerator with	Yes	Yes	No	No
Proposed system		Yes	Yes	Yes	Yes

Comparison with Related Works

A summary of the related works reviewed is shown in Table 3, with a comparative presentation of cost efficiency, energy efficiency, adaptability for disabled persons and ease of deployment.

CONCLUSION

This paper has presented the development of an affordable energy-saving lighting switch control system suitable for homes with physically disabled persons. The system's design leverages inexpensive, readily available components like the Arduino Uno, ultrasonic sensors, and relay modules, without compromising on functionality. By using a bi-directional person counter and human presence detection via ultrasonic sensing, the system offers a highly effective and scalable solution for controlling lighting in response to real-time occupancy. The key contribution of this work lies not only in its cost efficiency but also in its potential to significantly improve the quality of life for physically disabled persons by reducing their reliance on manual switch operations. The system was rigorously tested and demonstrated impressive energy savings, seamlessly switching lights based on occupancy. This eliminates unnecessary energy consumption and contributes to reduced electricity bills for users. The affordability and simplicity of installation further enhance the system's practicality, making it accessible for broader deployment, especially in low-income households. The proposed solution provides a promising and better alternative to the related works compared, offering both an enhanced living experience and a meaningful contribution to global energy conservation efforts. Future enhancements to the proposed system promise to integrate artificial intelligence and renewable energy sources, such as solar power, to further reduce the environmental impact of home energy consumption.

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