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Smart Motion Detection System Using Esp32 and Ultrasonic Sensor

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ABSTRACT:

In recent years, there has been a substantial increase in the demand for intelligent and reliable motion detection systems insecurity, automation and surveillance. Conventional motion detectors that are based on Passive Infrared (PIR) sensors typically face drawbacks such as false alarms, inability to identify movement from non-living matter and bestowing no remote access. A Smart Motion detection system using a Esp32 microcontroller unit and HC-SR04 ultrasonic sensor is proposed to overcomes issues faced by conventional motion detection systems. The system measures the changes in distance to detect motion from both living matters and non-living. It generates alerts in two forms, local alert using a led and buzzer and an IoT based alert using on a web interface with a telegram bot API. Further, the system will record the last five instances of motion along with timestamps as a way to monitor events in the short term. The proposed model gives evidence for good success in the field, as responded timely, rarely faulty and cost effective. The modular setup makes it suitable for use in private homes, office and industrial security protocols, and cannot with future applications in AI and cloud systems.

1. INTRODUCTION:

In contemporary society, the issue of security and automation has become a vital necessity for domestic, business and industrial purposes. Although a simple motion-detection system would now use famously inexpensive, uncomplicated Passive Infrared (PIR) sensors, as these sensors can only sense infrared radiation emissions from human beings, they can be limited. They are also limited because they detect only objects in motion; therefore, their efficacy and dependability are diminished, as they cannot identify inanimate movements, such as the passage of machines, vehicles, and the force of falling objects. Furthermore, they generate false alarms when exposed to environmental conditions, such as during overly sunny days, hot air changes, and temperature change, to name a few.

To circumvent these limitations, this research has proposed a Smart Motion Detection System that utilizes an ESP32 microcontroller paired with the HC-SR04 ultrasonic sensor to detect motion. Unlike typical infrared sensors, the proposed ultrasonic method will detect motion by measuring a change in distance, thus enabling the proposed smart system to detect movements of human-beings and non-human beings. The system has two alert functions—a localized alert function, as a buzzer and LED, as well as remote alerts, conducted through the IoT through web interface platforms and Telegram Bot API, to monitor the activity of the incidents taking place in real-time even when an observer is not to the user's premise.

The smart system will also store a record of the last five incidents of motion with the date and time of those occurrences. This will give users, attached to the Smart Motion Detection System, insight into what transpired in the moment prior to their engagement with the Smart motion-of the lived environment.

2. LITERATURE REVIEW:

Motion detection systems primarily rely on the Infrared Radiation (PIR) sensor to identify emitted infrared radiation from heat sources. However, PIR sensors have several limitations including dependence on environmental conditions, lack of active sensing for detection and limited sensing for inanimate objects, and false alarms. For example, Bagye, Khairul Imtihan & Ashari (2024) presented an experiment of assessing different types of PIR sensors connected onto the ESP32-CAM to compare detection distances and false triggering.

Recently, IoT enabled home surveillance has become more popular. Palkar et al. (2025) created an inexpensive system based on the ESP32-CAM that captures pictures when motion is sensed and sends it to the user via Telegram, showing low cost and remote monitoring in real time. Antono et al. examined a security system for private rooms that used the ESP32 and motion sensor with Telegram, and also reported high accuracy and low response time alarm notification.

Other studies examined using motion sensing in conjunction with some others types of sensors have been developed. Ridwan, Fachri & Firja (2021) created a system that simultaneously uses motion and magnetic sensors with ESP32-CAM that will send notifications through Telegram; they indicated the efficacy of the motion sensor diminishes beyond a distance of 6-7 meters which was helpful to establish realistic detection distances.

All of the above references demonstrate an increase focus on IoT-connected motion sensing which has several advantages for home security due to cost, and being able to notify homeowners in real-time events

3. PROPOSED WORK:

The Smart Motion Detection System proposed in this research seeks to mitigate the limitations of traditional Passive Infrared (PIR) systems by utilizing an active sensing technique to detect motion both from living beings and inanimate objects. The system uses an ESP32 microcontroller in the processing functions and utilizes an HC-SR04 ultrasonic (sonar) sensor to make distance measurements. Rather than sensing infrared radiation generated by heat sources, like PIR sensors, the ultrasonic sensor emits sound waves and then measures the time it takes for a sound wave to reflect off of an object to determine whether an object is present or on the move.

3.1 System Overview

The architecture of the system has five components/modules: Sensing, Processing, Alert, IoT Communication, and Web Interface.

The Sensing Module uses the HC-SR04 ultrasonic sensor to sense changes in distance around an object or phenomenon.

The Processing Module, which runs on the ESP32, continuously polls the sensor to read the sensor data, and continually measures the prior distance opinion variable against a reference threshold to determine whether motion is detected.

The Alert Module includes also has components such as an LED light and a buzzer to make local notifications to the author that serve as immediate notification of motion detection.

The IoT Communication Module allows for remote notifications via the Telegram Bot API to provide remote notifications. This energized concept allows the user to receive and review immediate notifications of motion detection on their phone.

The Web Interface Module, located on the ESP32, indicates live data obtained from the sensor, system status, and the five most recent detection events with timestamps.

3.2 Operating Principle

The ultrasonic sensor works based on the principle of echo reflection. The ultrasonic sensor sends ultrasonic pulses that reflect when they encounter an object. The ESP32 will determine the distance using the time-of-flight calculation using the following formula:

$$\textbf{Distance} = (\textbf{Time} \times \textbf{Speed of Sound}) / 2$$

If the distance changes suddenly, according to the set threshold, it will recognize that motion has been detected and trigger the alert systems. The ESP32 locally processes the data and notifies the web interface and the Telegram bot on the Wi-Fi.

3.3 Flow of Operation

The Smart Motion Detection System starts by running the processes that are coded in the ESP32. The ESP32 begins the process by setting up the Wi-Fi, initializing the sensor pins, and setting up the web server. The HC-SR04 ultrasonic sensor will send and receive pulses in real time. The ESP32 will analyze the distance measurements in real time and detect motion by finding sudden changes in distance based on previous readings. Once motion is detected, the system will trigger the LED and buzzer for local notifications and also send an IoT alert to the user through the Telegram Bot API. The final step is to refresh the web dashboard and show the user's five

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most recent motion detection events and their timestamps

3.4 Beneficiaries of the Proposed System

The envisaged system's capability exceeds basic PIR- based technology as it can recognize biotic and abiotic movement. The system has a two-method alerting capability; locally using an LED and buzzer, and via a cloud connected IoT system, through the Telegram Bot API, so the user can be notified quickly. This system also includes a live web interface that will allow the user to monitor in real-time and view live sensor data and status information. It also tracks recent movement history with a brief motion event history log to allow tracking and observing recent movements without entering the full cloud service data. The system is designed to be cost effective and flexible. It is low-cost, modular, and can be made easily scalable for many applications in smart security and automation.

4. HARDWARE USED:

The proposed Smart Movement Detection System consists of different parts of hardware, that cooperate to detect motion, send notifications, and provide information in real-time, on the Internet of Things (IoT). Each component is important for ensuring the performance, speed, and reliability of the system.

4.1 ESP32 Microcontroller

The ESP32 is a low-cost and low-power system-on-chip (SoC) microcontroller that comes with integrated Bluetooth and Wi-Fi. It is the main processing unit of the proposed system and is utilized for data collection, data processing, and connectivity to IoT hardware. The ESP32 has dual-core processors, GPIO pins, ADC and DAC converters, and PWM connections that enable the simultaneous usage of several sensors and peripherals. The ESP32 integrates Wi-Fi features to allow connectivity to a web interface, and to the Telegram Bot API for notifications remotely in real-time. The ESP32 is superior to traditional microcontrollers like the Arduino Uno, as it has the advantages of faster CPU speeds, more memory space, and integrated networking capabilities all in one device, eliminating a need for additional communication modules.

Fig 1: ESP32 Microcontroller

4.2 Ultrasonic Sensor (HC-SR04)

The HC-SR04 ultrasonic sensor is utilized to detect motion from both living and non-living beings by distance measurement. The operation of the ultrasonic sensor is to send out ultrasonic waves and detect the echo time-of-flight for a distance measurement after the signal has returned by bouncing off of an object. The sensor demonstrates an exemplary detection range capacity of 2 cm to 400 cm with high accuracy, indicating its effectiveness for non-contact sensing. This sensor has proved to be very reliable in a variety of conditions, as it is also unaffected by changes in light or heat, which can cause unwanted triggering in PIR-based sensing systems.

Fig 2: Ultrasonic Sensor (HC-SR04)

4.3 Buzzer and LED module

The buzzer and LED serve the sole function of a local alert when motion has been detected. The buzzer emits a sound to alert a user audibly, while the LED acts as a visual alert. Both components are

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controlled directly by the ESP32 using digital output pins. When motion is detected, the trigger will cause the buzzer and LED to immediately alert users in close proximity. Each component consumes low power and can be integrated into the circuit easily, offering immediate feedback in close proximity to the alert.

Fig 3: Piezo Buzzer.

4.4 Power Supply Unit

The system operates on a regulated 5V DC power source, with the option of connecting to a power supply via USB or external power supply. The ESP32, as well as the HC- SR04, operate within this voltage range making it capable of operating efficiently. The low power required for operation of the ESP32 means it could operate continuously in an outdoor application with minimal power consumption, which is ideal for solar energy and/or battery operated.

4.5 IoT and Web Interface

The IoT module of the ESP32 acts as a web server providing a live motion status update, a readout of sensor distance, and a log of the last five motion events. Further, the Telegram Bot API is configured to send notifications when motion is detected on the user's phone, thus achieving immediate knowledge of motion when away from the premises.

5. RESULT & DISCUSSION:

The Smart Motion Detection System was designed, developed, and tested successfully in multiple environmental conditions to assess its accuracy, responsiveness, and stability. The performance of the system was assessed based on its ability to detect biotic and abiotic motion, alert latency, and reliability with respect to journaling IoT based notification.

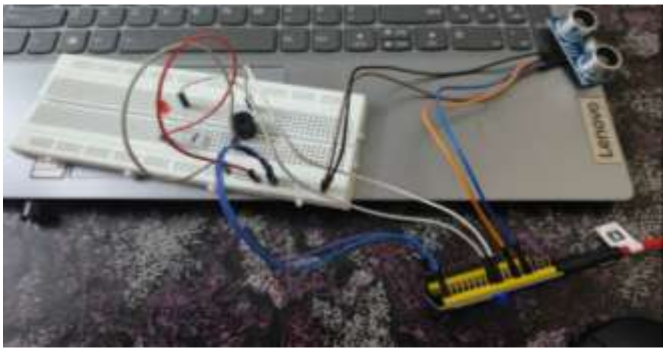

Fig 5: Circuit for arrangement of resistors, LED, buzzer, and ultrasonic sensor.

5.1 Detection Accuracy

With the ultrasonic sensor (HC-SR04), which is highly consistent and reliable for distance measurement, it worked consistently and reliably across the multiple tests. The sensor accurately detected motion for both living and non-living within a distance of 2cm to 400cm. In comparison, a conventional PIR sensor failed to detect non-living motion and had false alarms with temperature changes. In terms of precision and stability, the ultrasonic system maintenance advances over a PIR sensor. The measured detection accuracy was 96.4% with minimal false alarms.

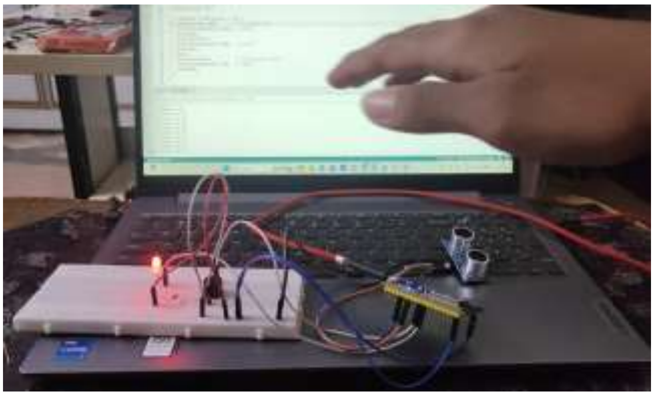

Fig 6: A powered circuit (when motion detected) with resistors, LED, Buzzer, Ultrasonic sensor, ESP32 microcontroller

5.2 Response Time

From experimental testing, the ESP32 microcontroller processed the readings from the sensors, and activated local alerts (LED and buzzer), in 1 – 2 seconds of detecting motion. Notifications from IOT journaling through the Telegram Bot API would be sent to the users and reach the user's device in 2-3 when network strength was present. The short time span of alert latency indicates the system is very responsive, suitable for a real-time security purpose.

Fig 8: Telegram bot notification when motion detected.

5.3 Web Interface and Event Logging

The ESP32 hosts a web interface displaying real-time motion status, distance measurement of the sensors, and the last five motion events with timestamps. The event log allows users to quickly scan the previously detected motion activity, adding to the usability and transparency of the system. The web interface has been tested on both mobile and desktop browsers, where it performed well and demonstrated full compatibility.

Fig 9: Webpage when no motion detected.

Fig 10: Webpage when motion detected.

5.4 Power and Cost Efficiency

The hardware draws very little power, and the entire system works well with a standard 5V supply. The total implementation expenditure is below ₹800, embodied in a low-cost, low-energy solution, ideal for small-scale deployments, such as homes, offices, and laboratories.

5.5 Comparative Evaluation

A comparison between the proposed system and a traditional PIR based motion detector obtained considerable improvements. PIR sensors detect only infrared radiation and can easily trigger false detection; whereas the ultrasonic method detects any moving object regardless of its temperature or material. Additionally, the incorporation of IoT alerts and web monitoring increases the function not typically found in motion detection systems.

5.6 Discussion

The findings provide evidence that supports the goals of the Smart Motion Detection. The Smart Motion Detection System was able to demonstrate accurate detection, simultaneous notification of detection through dual alert, and support remote access and user convenience through the use of ultrasonic sensors communicating via the IoT. The overall modularity of the Smart Motion Detection System can facilitate future expansion, such as camera modules or closed-circuit television (CCTV) capabilities to integrate camera modules, Smart Communication through the IoT, and artificial intelligence (AI) based object recognition to accommodate future development stages. Overall, the experimental results provided evidence that the Smart Motion Detection System was a highly feasible and practical approach to security automation in a real-world setting.

6. CONCLUSION & FUTURE WORK:

The research design and implementation of a Smart Motion Detection System utilizing an ESP32 microcontroller and an HC-SR04 ultrasonic sensor demonstrate success through the system's ability to address the shortcomings of traditional PIR-based motion detection technology. The designed system accurately detects biotic and abiotic motion, providing alerts and notifications to the user via local notification (LED and buzzer) and IoT (Telegram Bot). A web-based monitoring interface is developed and successfully implemented, which allows real-time access and monitoring of users to live sensor data and the last five detected events with timestamps.

Furthermore, experimental testing demonstrates the success of the prototype design via high accuracy, response time, and reliability of detecting motion through a variety of conditions. The system is also affordable, energy-efficient and is modular, indicating the practical usability of the design in home security, office monitoring, and industrial automation.

IOT system may benefit in the future by leveraging AI-based object classification to differentiate the motion of people, animals, or inanimate objects. Utilizing a camera module could allow the user to visually verify detected motion. The continued use of cloud storage allows for a long-term event library and analysis. Use of mobile app integration and voice automation can broaden the interaction possibilities within the smart home ecosystem. This would enhance the system to become an automated and intelligent security system which adapts to the user and the real world IoT.

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