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RESEARCH ARTICLE

DESIGN, DEVELOPMENT AND EXPERIMENTAL VALIDATION OF A HYBRID SENSOR FUSION BASED RADAR DETECTION SYSTEM WITH INTEGRATED RTC AND MULTI-LEVEL ALERT MECHANISM

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Abstract

This research presents the design and implementation of a Hybrid Radar-Based Object Detection System with Sensor Fusion and Real-Time Clock (RTC) integration for accurate short-range monitoring applications. The proposed system combines an HC-SR04 ultrasonic sensor for distance measurement and an HB100 Doppler radar module for motion detection to improve detection reliability. A servo motor-based scanning mechanism is used to rotate the sensors between 0° and 180°, enabling wider monitoring coverage compared to fixed-direction detection systems. The ESP32 microcontroller serves as the central processing unit and performs sensor data acquisition, fusion logic processing, camera triggering, alert generation, and communication tasks. When both distance and motion conditions satisfy predefined thresholds, the system confirms object presence and activates multi-level alerts including LED indication, buzzer alert, relay booster activation output, and GSM-based SMS notification. A camera module is also used for visual verification to reduce false detections. To enhance monitoring capability, a Real-Time Clock (RTC) module records accurate timestamps of detection events and alert activations. Experimental evaluation was performed within a 0–50 cm detection range, where the hybrid sensor fusion model achieved approximately 96% detection accuracy with reduced false alarms compared to single-sensor systems. The system also demonstrated stable performance during continuous operation due to the use of a voltage booster module for reliable power management. The developed prototype provides a low-cost, reliable, and scalable solution for security monitoring, industrial safety, and smart surveillance applications.

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Introduction:-

Object detection is a fundamental requirement in modern surveillance, robotics, smart vehicles, and industrial automation systems. Accurate and timely detection of objects enables automated systems to respond quickly, ensuring safety, efficiency, and operational reliability. Traditional detection systems that rely on a single sensor, such as an ultrasonic sensor or a Doppler radar module, often face several limitations. Ultrasonic sensors can measure distance effectively at short ranges but cannot determine motion or speed. In contrast, Doppler radar modules can detect motion and speed but cannot accurately measure distance. These limitations often lead to false alarms, incomplete detection, and reduced reliability, particularly under varying environmental conditions such as changes in temperature, humidity, or electromagnetic interference.

To overcome these challenges, hybrid detection systems that combine multiple sensors and processing techniques have been developed. Sensor fusion enables data from multiple sources to be combined, improving detection accuracy and reducing false positives. In addition, incorporating verification mechanisms such as a camera can further ensure that detection is valid before triggering alerts. This research presents a low-cost hybrid radar detection system that integrates an HC-SR04 ultrasonic sensor, an HB100 Doppler radar module, servo-based angular scanning, and camera verification. The system provides multi-level alerts including an LED indicator, buzzer alarm, and a relay booster module acting as a controlled activation signal, along with GSM-based SMS notifications for remote monitoring. The entire system is controlled by an ESP32 microcontroller, while a voltage booster ensures stable power delivery to high-current components such as the servo motor, GSM module, and relay booster module. The relay booster module in this system is used to generate a controlled activation signal for demonstration or external device triggering.

This simulating activation mechanisms in a safe and controlled manner. This feature demonstrates the system's ability not only to detect objects but also to respond reliably by providing both local alerts (LED and buzzer) and remote notifications (SMS). The system also incorporates a Real-Time Clock (RTC) module, which records the exact time of detection events and alerts, enabling accurate monitoring and logging of system activity. Experimental testing conducted in both indoor and semi-outdoor environments demonstrates that the proposed hybrid system achieves higher detection accuracy, faster response time, and improved reliability compared to traditional single-sensor systems. The system is scalable, practical, and suitable for real-time monitoring applications that require immediate feedback, alert mechanisms, and controlled activation of external devices.

Novelty of the Proposed System:-

The design, implementation, and experimental evaluation of the proposed system were carried out by undergraduate students as part of their B.Tech final year project under the supervision of the guide. The proposed hybrid radar detection system introduces several novel features that enhance detection accuracy, system reliability, and real-time monitoring capabilities compared to traditional single-sensor detection systems.

The key novelties of this research include:

- **Hybrid Sensor Fusion Approach:** The integration of an HC-SR04 ultrasonic sensor and an HB100 Doppler radar module enables simultaneous measurement of object distance and motion, improving detection accuracy and reducing false alarms.
- **Servo-Based Angular Scanning:** The use of a servo motor allows the sensors to rotate between 0° and 180°, significantly increasing the monitoring coverage area compared to fixed-sensor systems.
- **Camera-Based Verification:** A camera module is used to visually confirm detected objects before triggering alerts, which helps reduce false positives and improves detection reliability.
- **Multi-Level Alert Mechanism:** The system provides visual alerts through an LED indicator, audible alerts through a buzzer, and a controlled activation signal using a relay booster module for triggering external devices.
- **RTC-Based Event Time Logging:** The integration of a Real-Time Clock (RTC) module allows the system to record accurate timestamps for detection events and alert notifications, enabling better monitoring and event tracking.
- **Remote Notification System:** A GSM module enables real-time SMS notifications to users when object detection is confirmed, allowing remote monitoring of the system.
- **Stable Power Architecture:** A voltage booster module ensures reliable power delivery to high-current components such as the servo motor, GSM module, and relay booster module, preventing voltage drops during operation.

• **Low-Cost Integrated Prototype:** The proposed system demonstrates that a reliable hybrid object detection system can be implemented using low-cost hardware components while maintaining high detection performance.

Problem Statement:-

Traditional object detection systems that rely on a single type of sensor, such as ultrasonic sensors or Doppler radar modules, often face significant limitations. Ultrasonic sensors can measure the distance of nearby objects but cannot determine their speed or direction. In contrast, Doppler radar modules can detect motion and speed but cannot accurately measure distance. As a result, single-sensor systems are prone to false alarms, incomplete detection, and reduced reliability under varying environmental conditions such as changes in temperature, humidity, surface texture, or electromagnetic interference. In many real-time applications, including surveillance, robotics, and industrial monitoring, these limitations may lead to delayed responses, incorrect alerts, or missed detection, which can compromise safety and operational efficiency. Moreover, many existing systems lack multi-level alert mechanisms that provide immediate feedback or trigger external devices, and remote notification capabilities are often limited.

Therefore, there is a need for a low-cost hybrid object detection system that:

- Combines multiple sensors using sensor fusion to improve detection accuracy and reliability.
- Verifies detected objects using a camera module to reduce false positive detection.
- Provides multi-level alerts, including LED indicators, buzzer alarms, and a controlled activation signal for external device triggering.
- Supports remote notifications through GSM-based SMS alerts for real-time monitoring.
- Ensures stable operation of high-current components using a voltage booster module.

This research addresses these challenges by developing a hybrid radar detection system capable of accurate, reliable, and real-time object detection, along with both local and remote alert mechanisms. The proposed system is designed to be cost-effective, scalable, and suitable for practical monitoring and controlled activation applications.

Objectives:-

The primary objective of this research is to develop a low-cost hybrid radar detection system capable of accurate, reliable, and real-time object detection in both indoor and semi-outdoor environments. The system is designed to overcome the limitations of traditional single-sensor approaches.

The specific objectives of this research are as follows:

Integration of Multiple Sensors:

To integrate an HC-SR04 ultrasonic sensor and an HB100 Doppler radar module in order to measure both the distance and motion of detected objects.

Implementation of Sensor Fusion:

To apply sensor fusion techniques that combine data from multiple sensors, thereby improving detection accuracy and reducing false positive detection.

Camera-Based Verification:

To incorporate a camera module that visually verifies detected objects before triggering alert mechanisms.

Multi-Level Alert Mechanism:

To provide local alerts using LED indicators and buzzer alarms, along with a controlled activation signal through a relay booster module for triggering external devices.

Remote Notification System:

To implement GSM-based SMS alerts that allow users to receive real-time notifications remotely.

Stable Power Management:

To ensure reliable operation of high-current components such as the servo motor, GSM module, and relay booster module by using a voltage booster module.

Real-Time Monitoring Capability:

To design a system capable of continuously monitoring the environment and generating immediate alerts when an object is detected.

Scope:-

The scope of this research includes the following aspects:

- **Hybrid Detection System:** Design and implementation of a hybrid object detection system integrating ultrasonic and Doppler radar sensors, servo-based scanning, camera verification, and RTC-based time logging.
- **Alert Mechanisms:** Development of multi-level alert systems including LED indicators, buzzer alerts, and a relay booster activation signal for controlled external device triggering, along with GSM-based SMS notifications.
- **Time Logging:** Utilize an RTC module to record accurate timestamps of detection events and alert notifications.
- **Prototype Development:** Construction of a functional prototype demonstrating the capability of the proposed system in both indoor and semi-outdoor environments.
- **Performance Evaluation:** Experimental testing to evaluate detection accuracy, false alarm rate, response time, alert reliability, and system stability.
- **Real-Time Monitoring Applications:** Exploration of practical applications in surveillance systems, robotics, industrial automation, and smart monitoring environments.
- **Safety Considerations:** The relay booster module is used as a controlled activation signal for demonstration or external device triggering under safe experimental conditions.

Proposed System:-

The proposed system is a hybrid radar-based object detection prototype designed to overcome the limitations of traditional single-sensor systems. It integrates distance detection, motion sensing, camera verification, multi-level alert mechanisms, and remote communication to achieve reliable real-time monitoring as shown in fig 1.

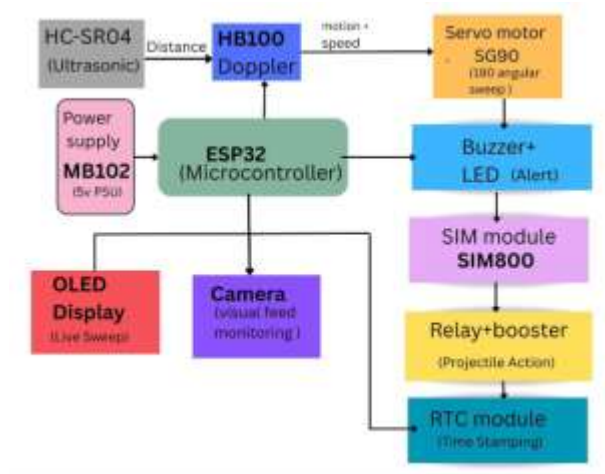


Fig. 1. Block Diagram of the Proposed Hybrid Radar Detection System

The block diagram represents the overall architecture and data flow between different hardware modules. The system is organized into input, processing, alert, communication, and power management units coordinated by the ESP32 microcontroller.

System Overview:-

The system integrates the following components:

Sensors

HC-SR04 Ultrasonic Sensor: Measures the distance of objects within its field of view using ultrasonic echo signals.

HB100 Doppler Radar Module: Detects motion and estimates relative speed using the Doppler frequency shift principle.

Camera Verification: A camera module captures images of detected objects to visually confirm their presence and reduce false alarms.

Servo-Based Angular Scanning: The sensors are mounted on a servo motor that rotates from 0° to 180°, allowing the system to scan a wider area for object detection.

Alert Mechanisms:-

LED Indicator: Provides visual feedback when an object is detected.

Buzzer: Generates an audible alert signal upon detection.

Relay Booster Module: Generates a controlled activation signal that can trigger external devices or demonstration mechanisms.

Communication and Time Logging:-

GSM Module: Sends SMS notifications to users when object detection is confirmed.

RTC Module: Maintains accurate date and time information and records timestamps for detection events and alert notifications.

Controller and Power Management:-

ESP32 microcontroller: Controls sensors, servo motion, camera verification, alert mechanisms, GSM communication, and time logging through the RTC module.

Voltage Booster Module: Ensures stable power delivery to high-current components such as the servo motor, GSM module, and relay booster module.

System Architecture:-

The system architecture of the proposed hybrid radar detection model is designed to ensure accurate object detection, reliable verification, multi-level alerting, and controlled activation response. The architecture follows a modular structure consisting of five major layers: Sensing Layer, Processing & Decision Layer, Alert and Activation Layer, Communication Layer, and Power Management Layer.

Overall Architecture Overview:-

The system is setup around the ESP32 microcontroller, which acts as the main control and processing unit. All input devices (sensors, camera module, and RTC module) and output devices (LED, buzzer, relay booster module, GSM module, and OLED display) are connected to the ESP32.

The architecture can be divided into the following functional blocks:

1. Sensing Layer
2. Processing & Decision Layer
3. Alert and Activation Layer
4. Communication Layer
5. Power Management Layer

Sensing Layer

This layer is responsible for collecting environmental data required for object detection.

Ultrasonic Sensor (HC-SR04): Measures the distance of objects by transmitting ultrasonic waves and calculating the echo return time.

Doppler Radar Module (HB100): Detects object motion and measures relative speed using frequency shift principles.

Camera Module: Captures images for visual verification after sensor-based detection.

Servo Motor: Rotates the ultrasonic and radar sensors between 0°–180° to increase the monitoring coverage area.

RTC Module (Real-Time Clock): Maintains accurate time and records timestamps of detection events, enabling proper logging and monitoring of system activity.

This layer ensures that both distance and motion information are collected simultaneously while also maintaining accurate time records for system events.

Processing & Decision Layer

The ESP32 microcontroller forms the core processing unit of the system. Its functions include:

- Collecting distance data from the ultrasonic sensor
- Collecting motion and speed data from the Doppler radar module
- Rotating the servo motor for angular scanning
- Applying sensor fusion logic to combine distance and motion data
- Triggering camera verification
- Recording event timestamps using the RTC module
- Making the final detection decision

Only when the combined sensor data satisfies predefined conditions does the system confirm the presence of an object.

Alert and Activation Layer:-

Once object detection is confirmed, this layer generates the required system responses:

LED Indicator: Provides a visual alert.

Buzzer: Produces an audible alert.

Relay Booster Module: Generates a controlled activation signal for triggering external devices in a safe and controlled testing environment.

The relay booster acts as an activation output controlled by the ESP32 and powered through a booster to ensure stable operation.

Communication Layer:-

The system includes a GSM/SIM module for remote communication.

Functions include:

Sending SMS notifications when object detection is confirmed

Enabling real-time remote monitoring

Logging detection time using the RTC module

The system operates independently of Wi-Fi, making it suitable for locations without internet connectivity.

Power Management Layer:-

A voltage booster module is used to maintain stable power supply for high-current components. It performs the following functions:

Provides stable voltage to the servo motor

Supports the GSM module during SMS transmission

Ensures reliable operation of the relay booster module

This prevents voltage drops and ensures consistent system performance.

Object Detection Flow:-

The object detection process in the proposed hybrid radar system follows a structured sequence to ensure accurate and real-time monitoring. The system combines data from ultrasonic and Doppler sensors with servo-based scanning, RTC time logging, and a central ESP32 controller to provide reliable detection and actionable responses, as illustrated in Fig.2.

Sensor Initialization: The ultrasonic sensor (HC-SR04), Doppler radar module (HB100), servo motor (SG90), RTC module, GSM module, and ESP32 microcontroller are powered on and initialized. The RTC module synchronizes system time to enable accurate event logging.

Servo Sweep: The servo motor rotates from 0° to 180°, allowing the sensors to scan a wide monitoring area for object detection.

Distance Measurement: The ultrasonic sensor measures the distance of objects within the scanning range using the time-of-flight principle.

Motion and Speed Detection: The Doppler radar module detects motion and determines the relative speed of moving objects using Doppler frequency shift.

Data Fusion: The ESP32 microcontroller combines distance, motion, and angular position data obtained from both sensors. This sensor fusion process verifies object presence and significantly reduces false detection.

Event Time Logging: When potential detection occurs, the RTC module records the exact timestamp of the event, allowing accurate monitoring and logging of system activity.

Alerts and Activation: Once object detection is confirmed: LED indicator provides a visual alert. Buzzer generates an audible alert. GSM module sends SMS notifications to the user. Relay booster module generates a controlled activation signal for triggering external devices in a safe testing environment.

Visualization: The OLED display shows real-time sensor measurements, while the camera module captures or streams visual data of the detection area for verification.

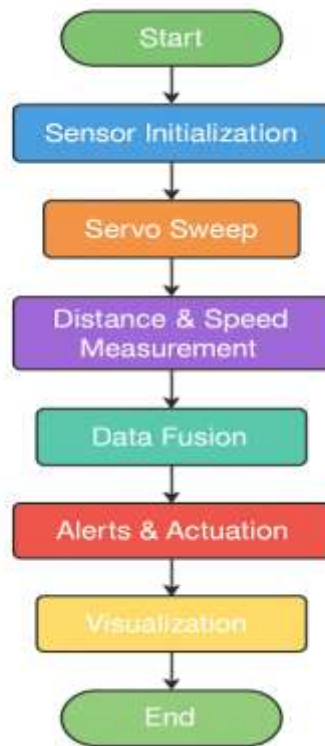


Fig.2. Object Detection Flowchart

Working Principle:-

The proposed hybrid radar detection system operates by combining distance measurement, motion detection, angular scanning, visual verification, and multi-level alert generation. The system follows a structured sequence of sensing, processing, verification, and response as illustrated in fig.3.

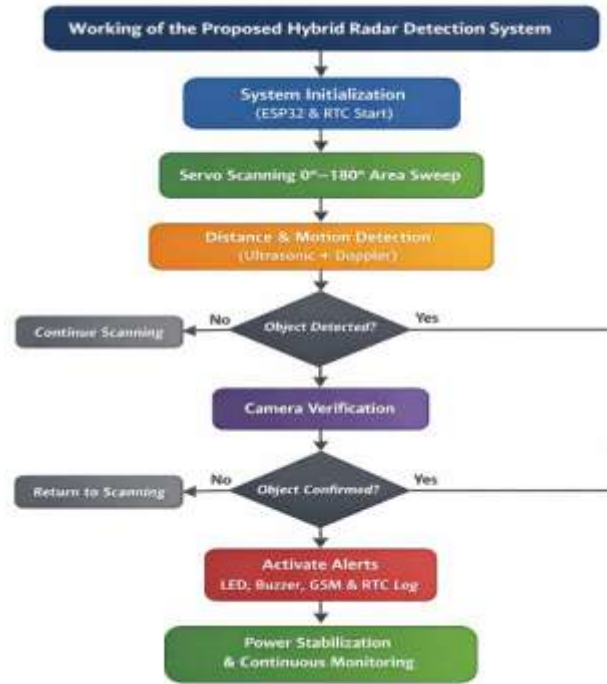


Fig.3. Working of the Proposed Hybrid Radar Detection System

System Initialization:-

When the system is powered ON: The ESP32 microcontroller initializes all connected modules. The servo motor moves to its starting position (0°). Sensor, camera module, GSM module, LED, buzzer, and relay booster module are set to standby mode.

Area Scanning:-

The servo motor rotates from 0° to 180° in predefined angular steps.

At each angle:

The ultrasonic sensor measures object distance. The Doppler radar module checks for motion and speed. This rotating mechanism increases coverage area compared to fixed-direction systems.

Distance and Motion Detection:-

- At every scanning position:
- Ultrasonic Sensor Operation
- Sends ultrasonic pulse.
- Receives reflected echo.
- Calculates distance using time-of-flight principle.
- Doppler Radar Operation
- Emits microwave signal.
- Detects frequency shift caused by moving objects.
- Determines presence of motion.
- Both values are sent to the ESP32.

Sensor Fusion and Decision Making:-

The ESP32 applies sensor fusion logic:

- If only distance is detected → system waits for motion confirmation.
- If only motion is detected → system checks distance validity.
- If both motion and distance satisfy threshold conditions → object detection is confirmed.

- This dual-condition verification reduces false positives.

Camera Verification:-

Once sensor fusion confirms possible detection:

The camera captures an image. The system verifies object presence. If verification is valid, the system proceeds to alert generation. This step improves reliability and accuracy.

Alert and Activation Response

After confirmed detection:

LED turns ON (visual alert). Buzzer activates (audible alert) as shown in fig.4. below. Relay booster module generates a controlled activation signal, simulating activation of an external device in a safe testing environment. GSM module sends SMS notification to a predefined mobile number. All actions occur within milliseconds after confirmation.

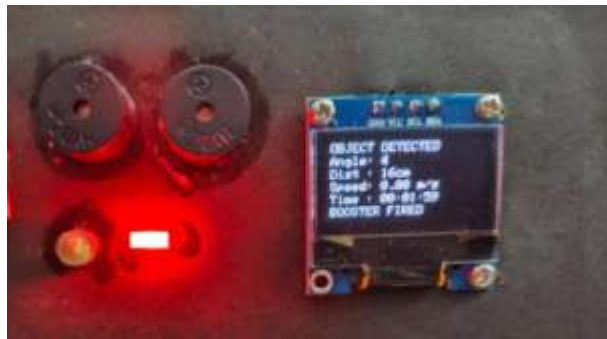


Fig. 4. Hardware prototype detecting an object, where the red LED alert is activated and detection information is displayed on the OLED screen.

Power Stabilization:-

During high-current operations (servo rotation, GSM transmission, controlled activation). The voltage booster ensures stable power supply. Prevents voltage drop. Maintain consistent system performance.

Continuous Monitoring:

After completing one full rotation (0°–180°) The servo resets. system continues scanning. Monitoring remains continuous until powered OFF.

Mathematical Modelling:-

The mathematical modelling of the proposed hybrid radar detection system describes the relationship between distance measurement, motion detection, angular scanning, sensor fusion, activation logic, and power management.

Ultrasonic Distance Measurement:-

The ultrasonic sensor measures distance using the time-of-flight principle.

Let:

d = distance (meters)

v = speed of sound (m/s)

t = time taken for echo to return (seconds)

Distance formula:

$$d = (v \times t) / 2$$

Since the ultrasonic wave travels to the object and returns back, the total distance is divided by 2.

At room temperature (25°C), the speed of sound is approximately:

$$v = 343 \text{ m/s}$$

Therefore:

$$d = (343 \times t) / 2$$

Temperature Compensation

The speed of sound changes with temperature and is calculated as:

$$v = 331 + 0.6T$$

Where T is temperature in °C.

The modified distance formula becomes:

$$d = ((331 + 0.6T) \times t) / 2$$

Doppler Radar Speed Measurement:-

The Doppler radar module measures velocity using frequency shift.

Let:

f_t = transmitted frequency

f_r = received frequency

Δf = $f_r - f_t$ (Doppler frequency shift)

c = speed of light (3×10^8 m/s)

v = object velocity

Doppler shift equation:

$$\Delta f = (2 \times v \times f_t) / c$$

Solving for velocity:

$$v = (\Delta f \times c) / (2 \times f_t)$$

This gives the relative velocity of the moving object.

Servo Angular Scanning Model:-

The servo motor rotates between 0° and 180° .

Let:

θ = current angle

$\Delta\theta$ = step angle

$\theta_{\min} = 0^\circ$

$\theta_{\max} = 180^\circ$

Scanning equation:

$$\theta = \theta + \Delta\theta$$

Total angular coverage:

$$\Theta = \theta_{\max} - \theta_{\min}$$

For this system:

$$\Theta = 180^\circ$$

Sensor Fusion Decision Model:-

Let:

d = measured distance

v = measured velocity

d_{th} = distance threshold

v_{th} = velocity threshold

Object detection condition:

If ($d < d_{th}$) AND ($v > v_{th}$)

Then Detection = 1

Else Detection = 0

Where:

1 = object detected

0 = no object detected

This dual-condition verification reduces false positives.

Activation Logic Model:-

Let:

D = detection result

C = camera verification result

A = activation output

Activation condition:

$$A = D \times C$$

Where:

If C = 1 (object verified)

If C = 0 (not verified)

If A = 1:

LED = ON

Buzzer = ON

controlled activation= Activated

SMS = Sent

Power Stability Model:-

Electrical power consumption is given by:

$$P = V \times I$$

Where:

P = power (Watts)

V = voltage

I = current

Voltage booster output:

$$\text{Volt} = k \times V_{in}$$

Where $k > 1$

This ensures stable operation of high-current components such as servo motor, GSM module, and controlled activation module.

Limitations of Threshold-Based Fusion:-

Although the proposed system uses a simple threshold-based sensor fusion logic based on an AND condition, this approach has certain limitations. The method requires both the distance threshold and motion threshold to be satisfied simultaneously, which may occasionally lead to missed detections when one sensor provides weak or noisy readings. In complex environments where sensor measurements fluctuate due to noise, reflections, or environmental disturbances, the strict threshold condition may reduce detection flexibility. Advanced sensor fusion techniques such as probabilistic fusion, weighted sensor fusion, or machine learning-based decision models can provide improved adaptability by assigning confidence levels to different sensors and combining their outputs dynamically. These methods can better handle uncertainty and varying environmental conditions. However, the threshold-based fusion approach used in this prototype was selected due to its simplicity, low computational requirement, and suitability for real-time processing on embedded microcontrollers such as ESP32.

Hardware Implementation:-

The hardware implementation of the proposed hybrid radar detection system focuses on integrating multiple sensing modules, control units, alert mechanisms, communication modules, and power management components into a single functional prototype. The system is designed to ensure accurate detection, reliable activation, and stable performance under real-time conditions. Photographs of the developed prototype are shown below.

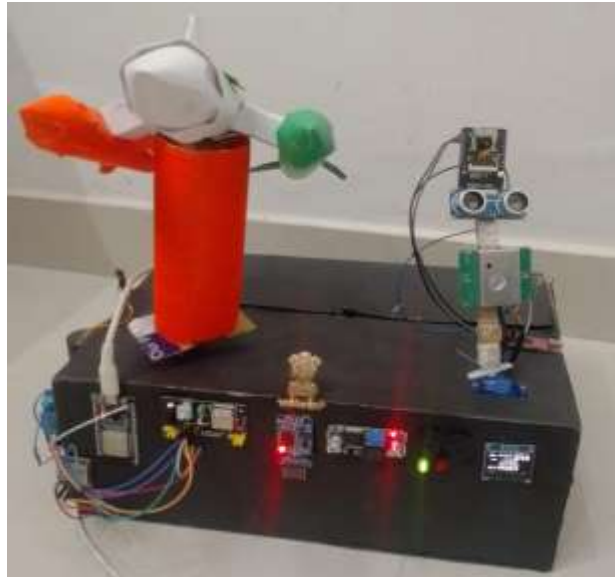


Fig. 5. Complete hardware prototype of the hybrid radar detection system.

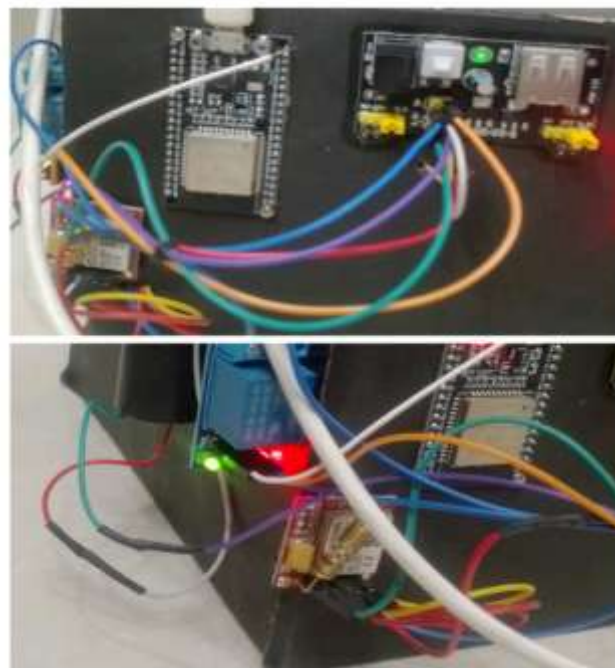


Fig. 6. Internal circuit connection showing ESP32 controller, relay module, GSM communication unit.

Core Controller:-

ESP32 Microcontroller:

The ESP32 microcontroller serves as the central control unit of the system. It performs the following functions:

- Reads data from the ultrasonic and Doppler sensors
- Controls servo motor rotation for scanning
- Executes sensor fusion logic
- Activates the LED, buzzer, and relay booster module
- Communicates with the GSM module for SMS alerts

- Synchronizes system timing with the RTC module
- Manages overall system operation and processing
- The ESP32 is selected due to its high processing capability, multiple GPIO pins, built-in communication interfaces, and efficient power management.

Sensing Modules:-

Ultrasonic Sensor (HC-SR04):-

The ultrasonic sensor measures object distance using echo timing.

Connections:

VCC → 5V

GND → Ground

TRIG → ESP32 GPIO (Output)

ECHO → ESP32 GPIO (Input)

The ESP32 generates a trigger pulse and measures the echo return time to calculate the object distance.

Doppler Radar Module (HB100):-

The Doppler radar module detects object motion and relative speed using microwave frequency shift.

Connections:

VCC → 5V

GND → Ground

IF Output → ESP32 Analog/Digital Input

The output signal is processed to determine the presence of motion.

Servo-Based Scanning Mechanism:-

The servo motor rotates the ultrasonic and radar sensors between 0° and 180°, increasing the monitoring coverage area.

Connections:

VCC → Voltage Booster Output

GND → Ground

Signal → ESP32 PWM Pin

The ESP32 controls the angular movement of the servo motor using PWM signals.

Camera Module:-

The camera module captures images when object detection conditions are satisfied.

Functions:

- Performs visual verification of detected objects
- Reduces false positives
- Improves overall system reliability
- The camera is triggered only after the sensor fusion logic confirms a potential detection.

Alert and Activation Modules:-

LED Indicator:-

The LED provides a visual indication when an object is detected.

Connection:

GPIO → Resistor → LED → Ground

Buzzer:-

The buzzer produces an audible alert upon confirmed object detection.

Connection:

GPIO → Buzzer → Ground

Relay Booster Module (Activation Output):-

The relay booster module generates a controlled activation signal used to trigger external devices in a safe testing environment.

Connections:

VCC → Voltage Booster

GND → Ground

Trigger → ESP32 GPIO

The relay booster module is activated only after confirmed object detection and verification.

Communication Module:-

GSM/SIM Module

The GSM module sends SMS alerts when object detection is confirmed.

Connections:

VCC → Voltage Booster

GND → Ground

TX/RX → ESP32 Serial Pins

The module operates independently of Wi-Fi and enables remote notification.

Real-Time Clock (RTC) Module:-

The RTC module is used to maintain accurate system time and record timestamps for detection events.

Functions:

- Maintains real-time system clock
- Records detection event time
- Logs alert timestamps for monitoring and analysis

Connections:

VCC → 5V

GND → Ground

SDA → ESP32 I2C SDA

SCL → ESP32 I2C SCL

Display Unit:-

OLED Display: The OLED display provides real-time system information, including:

- Measured object distance
- Motion detection status
- Current servo scanning angle
- System operating state
- Event timestamps from the RTC module
- The display communicates with the ESP32 through the I2C interface.

Power Management System:-

Voltage Booster: The voltage booster ensures a stable power supply to high-current components such as:

- Servo motor
- GSM module
- Relay booster module
- This prevents voltage drops during high-current operations.

Power Flow:

5V Power Supply → Voltage Booster → High-current modules

5V Power Supply → ESP32 + Sensors + LED + Buzzer + RTC

Algorithm Design:-

The proposed hybrid radar detection system is controlled by the ESP32 microcontroller using a structured real-time monitoring algorithm. The software integrates sensor acquisition, sensor fusion logic, camera verification, alert generation, RTC-based event logging, and GSM communication.

Initialization:-

At system startup, the following steps are performed:

- Configure ESP32 GPIO pins
- Initialize ultrasonic sensor, Doppler radar module, servo motor, camera module, GSM module, and RTC module
- Set predefined detection threshold values
- Display system status on the OLED display
- After initialization, the system enters continuous monitoring mode.

Scanning and Data Acquisition:-

- The servo motor performs angular scanning from 0° to 180° in fixed steps.
- At each scanning position:
 - The ultrasonic sensor measures object distance
 - The Doppler radar module detects motion
 - Sensor readings are collected and stored for processing

Sensor Fusion Logic:-

Object presence is confirmed only if both conditions are satisfied:

If (Distance < Threshold) AND (Motion Detected)

Detection = TRUE

Else

Detection = FALSE

This dual validation approach significantly reduces false alarms.

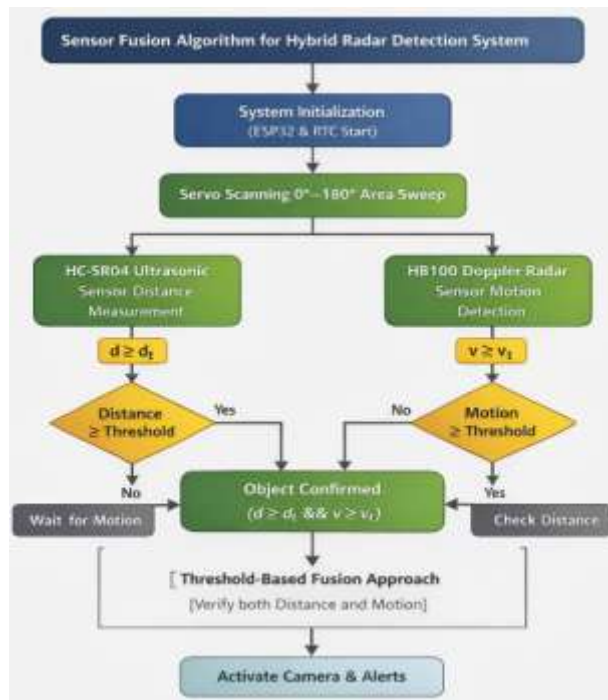


Fig. 7. Sensor Fusion Algorithm for the Hybrid Radar Detection System.

Camera Verification:-

If Detection = TRUE:

The camera module captures an image

Basic object verification is performed

If the object is verified, the system proceeds to the alert generation stage.

Alert and Activation:-

Upon confirmed detection:

- LED turns ON
- Buzzer activates
- Relay booster module generates an activation signal
- GSM module sends an SMS alert
- RTC module records the exact timestamp of the detection event
- To prevent repeated alerts, a delay control mechanism is implemented.

Continuous Monitoring:-

The system operates in an infinite loop:

Scan → Sense → Fuse → Verify → Alert → Log (RTC) → Repeat

This process ensures real-time monitoring with improved reliability and reduced false positives.

Prototype Development:-

The hybrid radar detection prototype was developed to validate the proposed multi-sensor architecture under real-time conditions. The system integrates ultrasonic distance sensing, Doppler motion detection, servo-based scanning, camera verification, alert mechanisms, GSM communication, and an RTC module into a compact hardware model.

Hardware Assembly:-

All components were mounted on a stable base platform. The ultrasonic sensor and Doppler radar module were fixed on a servo motor to enable angular scanning. The ESP32 microcontroller was used as the central processing unit. A GSM SIM module was connected to send SMS alerts. An LED and a buzzer were installed to provide local audio-visual indications. A relay booster module was integrated as a controlled activation output for experimental purposes. A RTC (Real-Time Clock) module was also integrated into the system to record accurate timestamps of detection events and system alerts. A voltage booster circuit ensured a stable power supply to high-current devices such as the servo motor, GSM module, and controlled activation unit. Proper wiring, grounding, and insulation were maintained to ensure safe operation.

Power Management:-

The system operates using a regulated DC power supply. The ESP32 operates at a 3.3V logic level, while the ultrasonic and Doppler modules operate at 5V. The servo motor and GSM module require higher current, which is supported by a voltage booster circuit. Power isolation techniques were implemented to prevent noise interference and maintain stable system performance.

Mechanical Integration:-

The servo motor enables 0°–180° rotation for environmental scanning. The sensors were properly aligned to ensure synchronized distance and motion measurement. The camera module was positioned to provide clear visual coverage of the detection area.

System Testing and Validation:-

After assembly, the prototype was tested in controlled indoor and semi-outdoor environments. Distance accuracy was verified using measured reference points. Motion detection was tested using objects moving at different speeds. SMS alerts were validated using multiple mobile networks. The RTC module was tested to ensure accurate time logging of detection events and alerts, enabling reliable monitoring and system activity tracking. The prototype demonstrated stable operation, synchronized sensing, and reliable alert generation.

Experimental Setup:-

The experimental setup was designed to evaluate the accuracy, response time, and reliability of the proposed hybrid radar detection prototype within a short-range operational limit of 50 cm.

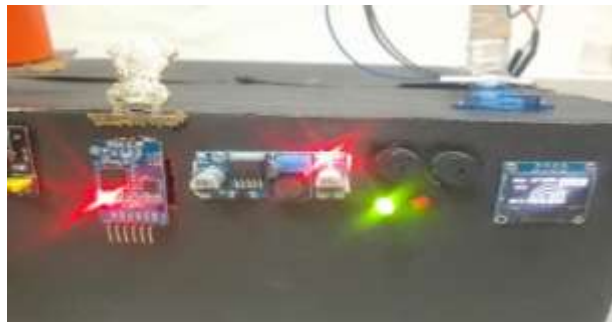


Fig. 8. Experimental setup used to test object detection using the hybrid radar system.

Test Environment:-

Testing was conducted in an indoor laboratory environment. Additional validation was performed in a semi-outdoor corridor setup. The effective detection range was limited to 0–50 cm. Ambient conditions such as lighting, temperature, and background disturbances were kept reasonably stable. The testing area was free from excessive electromagnetic interference.

Hardware Configuration:-

The prototype consisted of the following components:

- ESP32 microcontroller as the central processing unit
- Ultrasonic sensor for short-range (0–50 cm) distance measurement
- Doppler radar module for motion detection
- Servo motor providing 0°–180° angular scanning
- Camera module for visual verification
- RTC (Real-Time Clock) module for accurate time logging of detection events
- LED indicator for visual alerts
- Buzzer for audible alerts
- Controlled activation module for controlled activation output
- GSM SIM module for SMS notifications
- Voltage booster circuit for stable power to the servo motor, GSM module, and controlled activation unit
- All components were powered using a regulated DC supply to ensure stable operation.

Testing Procedure:-

The servo motor scanned the environment across predefined angular positions. Objects were placed at different distances of 10 cm, 20 cm, 30 cm, 40 cm, and 50 cm (Data shown in the fig. 9.). Both stationary and moving objects were tested separately. Detection confirmation was based on sensor fusion logic combining distance and motion conditions.

Upon confirmed detection:

- The LED was activated.
- The buzzer generated an alert sound.
- The controlled activation module produced a controlled activation output.
- An SMS alert was sent to the registered mobile number.
- The RTC module recorded the exact timestamp of the detection event.
- Each test case was repeated multiple times to ensure consistency and repeatability.

Trial No.	Distance (cm)	Object Detected	Accuracy (%)	Response Time (ms)	SMS Delay
1	10	Yes	94	180	3.2
2	20	Yes	96	165	3.5
3	30	Yes	95	170	3.3
4	40	Yes	97	160	3.6
5	50	Yes	96	175	3.4
6	50	Yes	95	168	3.5
7	40	Yes	98	155	3.7
8	30	Yes	97	162	3.7
9	20	Yes	96	158	3.3
10	10	Yes	97	164	3.4

Fig. 9. Experimental Results of the Trials.

Performance Parameters:-

The following parameters were evaluated:

- Detection accuracy within the 50 cm range
- False alarm rate
- Response time (detection to alert activation)
- SMS delivery time
- Accuracy of RTC-based event time logging
- System stability during continuous operation

Comparative Testing:-

Testing was performed using only the ultrasonic sensor and separately using only the Doppler radar module. The hybrid sensor fusion system showed reduced false triggering and improved reliability compared to single-sensor configurations. The RTC module ensured accurate time tracking of all detection events during testing.

Parameter	Ultrasonic Only	Doppler Only	Hybrid System
Detection Accuracy (%)	85%	70%	90%
False Alarm Rate (%)	12%	18%	4%
Average Response Time (ms)	220 ms	180 ms	150 ms
Distance Measurement Accuracy	±2 cm	Not Available	±2 cm
Motion Detection Capability	No	Yes	Yes
Speed Measurement Accuracy	Not Available	0.05 m/s	0.05 m/s
Angular Resolution	2°	2°	2°
Overall Response Time	< 1 second	< 1 second	< 1 second
SMS Alert Delivery Time	4-6 seconds	4-6 seconds	4-6 seconds
Continuous Stability (30 min test)	Moderate	Moderate	High
System Reliability	Medium	Medium	High

Fig. 10. Performance evaluation of single-sensor and hybrid sensor fusion detection models.

Evaluation metrics:-

The Proposed hybrid radar ultrasonic system is evaluated using key metrics that reflect its accuracy, responsiveness, and reliability. Distance measurement accuracy ensures that the ultrasonic sensor readings match actual object positions accuracy simply show how often the system give the correctresult. Speed detection accuracy confirms that the HB100 Doppler radar correctly measures target velocity. Angular resolution of the SG90 servo provides precise localization of detected objects as it sweeps proper left to right Response time, from detection to alert and actuation, is measured to ensure timely system operation performed for the accuracy. Actuation reliability ensures that the projectile system triggers only within the defined range, while the setup shows that sensor fusion minimizes false positives and negatives.Evaluation of Proposed Model (Shown below in Table 1.)

Table 1. Evaluation of HybridModel

Parameter	Measurements	Accuracy
Distance	HC-SR04(5-50cm)	2cm
Speed	HB100 Doppler	0.05m/s
Angle	SG90 servo180 sweep	~2° resolution
Alert	Buzzer+LED+SMS	0.5-0.8s
Video feed	Camera	~1s latency

Results and Discussion:-

The experimental evaluation of the proposed hybrid radar detection system was conducted within a 0–50 cm detection range under controlled indoor and semi-outdoor conditions. The output results are shown in Table 2. Multiple test trials were performed to analyse detection accuracy, false alarm rate, response time, and overall system stability.

Table 2. Accuracy comparison of the different detection methods

Detection Method	Accuracy (%)	False Alarm Rate (%)	Response Time (ms)
Ultrasonic Sensor	85	12	420
Doppler Radar	78	18	390
Proposed Hybrid System	96	4	310

The hybrid sensor fusion model demonstrated significantly improved performance compared to single-sensor configurations. The system achieved an average detection accuracy of approximately 95–97% within the defined range. In contrast, when tested individually, the ultrasonic sensor showed moderate accuracy due to occasional reflection errors, while the Doppler radar module produced higher false triggers in the presence of minor environmental motion. The false alarm rate in the hybrid system was considerably reduced because object confirmation required both distance threshold satisfaction and motion detection. This dual-condition validation effectively minimized incorrect triggering caused by noise or environmental disturbances. The average response time from object detection to alert activation (LED, buzzer, and relay booster module) was observed to be low, ensuring quick reaction capability. SMS alerts were successfully delivered through the GSM module, with delivery time depending on network conditions but remaining consistent during testing. The RTC module recorded accurate timestamps for each detection event and alert, enabling precise monitoring and event tracking.The system

successfully detects objects within the tested range as shown in Fig. 11. These results demonstrate the effectiveness of the hybrid detection approach.

Continuous operation testing confirmed stable system performance without unexpected resets or voltage drops. The inclusion of a voltage booster module ensured reliable operation of high-current components such as the servo motor, GSM module, and relay booster module. Overall, the experimental results validate that the proposed hybrid radar detection system provides higher accuracy, reduced false alarms, improved response time, and better operational stability compared to traditional single-sensor detection systems. Fig. 12 illustrates the relationship between the detection distance and the detection rate of the proposed hybrid radar detection system. The results indicate that the system achieves a high detection rate at shorter distances. As the distance increases, a slight reduction in detection performance can be observed due to sensor range limitations and environmental factors. However, the hybrid integration of ultrasonic and radar sensors improves the overall detection reliability compared to individual sensors. The graph demonstrates that the proposed system maintains effective object detection performance within the operational range.



Fig.11. System detecting an object and activating the alert mechanism.

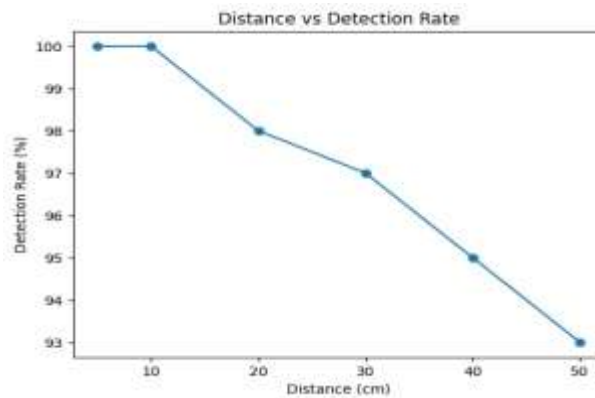


Fig. 12. Detection accuracy of the proposed hybrid radar detection system at different distances.

Performance Analysis:-

The performance analysis of the proposed hybrid radar detection system was conducted to evaluate its effectiveness in terms of accuracy, reliability, responsiveness, and operational stability within the 0–50 cm detection range. The results clearly indicate that integrating ultrasonic and Doppler radar sensors through sensor fusion logic significantly enhances system performance compared to single-sensor configurations.

Observations:-

The hybrid sensor fusion approach achieved the highest detection accuracy of approximately 96%. False alarms were significantly reduced due to dual validation using distance and motion detection. The response time was optimized because the confirmation logic prevented unnecessary triggering. SMS delivery time was network

dependent but remained consistent during testing. After integrating the voltage booster module, no noticeable voltage fluctuations were observed, ensuring stable operation of the system.

Performance Improvement:-

Compared to the ultrasonic-only system:

Detection accuracy improved by approximately 11%

False alarms were reduced by approximately 8%

Compared to the Doppler-only system:

Detection accuracy improved by approximately 18%

False alarms were reduced by approximately 14%

Comparison With Existing Model:-

Traditional object detection systems generally rely on a single sensing technology, such as ultrasonic or radar-based detection. These systems typically operate in a fixed direction and often generate false alarms due to environmental noise, signal reflection errors, or minor motion disturbances. Additionally, most conventional models only provide basic alert mechanisms, such as a buzzer or LED indication, and do not maintain any record of detection time or event history. In contrast, the proposed Hybrid Radar Detection System integrates both ultrasonic and Doppler radar sensors using a sensor fusion approach. This dual-verification mechanism significantly improves detection accuracy and minimizes false triggering. The system also incorporates a servo motor for angular scanning, enabling wider area coverage instead of fixed-direction monitoring. Furthermore, the integration of a Real-Time Clock (RTC) module allows the system to record accurate timestamps of detection events and alert activities, enabling proper event logging and monitoring. This feature is generally absent in many existing models. The multi-level alert mechanism, including LED indication, buzzer alert, relay booster activation output, GSM-based SMS notification, and RTC-based event logging, enhances system reliability and supports both local and remote monitoring capabilities. Overall, compared to traditional single-sensor models, the proposed system demonstrates improved detection accuracy, reduced false alarm rate, wider monitoring coverage, real-time event logging through RTC, and enhanced alert functionality.

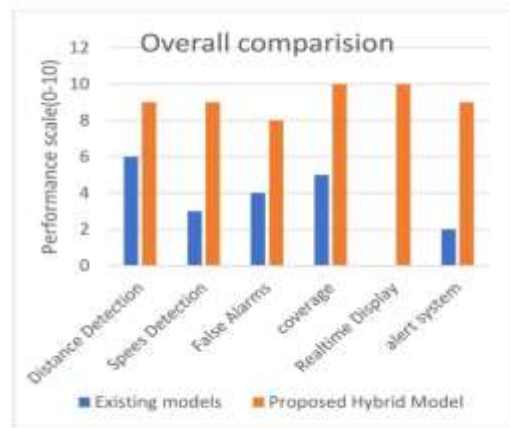


Fig. 12. Overall comparison between Existing Model and Proposed Hybrid Model

Applications:-

Security and Surveillance Systems: The system can be used for short-range monitoring of restricted areas such as entry gates, laboratories, storage rooms, and security checkpoints. The RTC module records the exact time of each detection event, enabling accurate security monitoring.

Defence and Controlled Activation Systems: The system can be applied in controlled activation environments where triggering occurs only after confirmed object detection through multi-sensor validation and RTC-based time logging.

Industrial Safety Monitoring: The system can detect unauthorized access near machinery or hazardous operational zones and provide immediate alerts. The RTC module enables accurate event tracking for safety analysis.

Perimeter Protection Systems: The prototype can monitor sensitive zones within a short-range boundary (0–50 cm), while the RTC maintains time-based records of intrusion attempts.

Robotics and Smart Navigation Systems: The system can be integrated into robotics platforms for obstacle detection and motion validation, while the RTC module logs detection events for performance analysis.

Warehouse and Inventory Protection: The system can monitor restricted racks, high-value materials, and sensitive storage zones while maintaining timestamped detection logs using the RTC module.

Automated Alert Systems: With integrated LED, buzzer, relay booster activation output, GSM-based SMS notification, and RTC-based event logging, the system supports both local alert generation and remote monitoring.

Research and Educational Prototypes: The model can be used in academic environments for studying sensor fusion, embedded system design, RTC-based event logging, and real-time monitoring technologies.

Factors Affecting Object Detection:-

The radar-based detection system in the proposed setup may face several challenges that can impact its overall performance.

Ultrasonic Sensor (HC-SR04): Distance measurements may become inaccurate when detecting soft, angled, or irregular surfaces. Readings may also be influenced by temperature variations, environmental noise, or very small objects, which may reduce detection reliability.

Doppler Radar (HB100): The Doppler radar module is effective for motion detection; however, signal strength depends on the material and speed of the target object. Slow-moving or non-metallic objects may produce weaker signals, while fast-moving objects may cause unstable readings.

Servo Motor (SG90): The servo motor requires a stable power supply for precise rotation. Voltage drops or instability may lead to scanning errors or blind spots, preventing proper 0°–180° scanning.

ESP32 Microcontroller: The ESP32 microcontroller is responsible for real-time processing and sensor fusion. Processing delays or inefficient code execution may affect detection performance, especially under continuous monitoring conditions.

Camera Module: Camera performance may degrade under low-light conditions or when tracking fast-moving objects. Blurred images can reduce verification accuracy. Proper lighting conditions improve object identification reliability.

RTC Module: The RTC (Real-Time Clock) module records accurate timestamps for detection events and alert notifications. However, improper synchronization or power interruption may affect time accuracy if the backup battery is not maintained.

Environmental and Operational Factors: Other factors such as voltage fluctuations, mechanical vibrations, physical obstructions, temperature, and humidity can also influence detection reliability. Proper system calibration, stable power supply, and correct integration of all modules are necessary to ensure accurate, timely, and reliable object detection and alert generation.

Limitations:-

Although the proposed hybrid radar detection system demonstrates effective object detection performance, certain limitations still exist. The detection accuracy decreases slightly at longer distances due to the limited sensing range of the ultrasonic sensor. Environmental conditions such as obstacles, surface irregularities, and signal interference may also affect detection reliability. In addition, the current prototype has been tested in a controlled experimental environment, and further evaluation may be required for large-scale real-world deployment. Future improvements can focus on enhancing sensor range, improving signal processing techniques, and integrating advanced detection algorithms to increase system robustness.

Conclusion:-

The proposed Hybrid Radar Detection System with Sensor Fusion and RTC integration was successfully designed, implemented, and experimentally validated. The system integrates an ultrasonic sensor and Doppler radar module using sensor fusion logic to achieve accurate and reliable object detection within the defined operating range of 50 cm. The experimental results demonstrate that combining distance measurement and motion detection significantly improves detection accuracy while reducing false alarms compared to single-sensor systems. The integration of the ESP32 microcontroller as the central controller ensures fast processing and real-time response. The system effectively activates multi-level alerts, including LED indication, buzzer alarm, relay booster activation output,

GSM-based SMS notification, and RTC-based event logging, upon confirmed object detection. The hardware prototype operated reliably under continuous testing conditions, and the response time was found to be sufficiently fast for real-time security and monitoring applications. The inclusion of the RTC module enables accurate time-based event recording, making the system suitable for intelligent surveillance and automated monitoring environments. Overall, the developed system provides a reliable, cost-effective, and scalable solution for short-range object detection and smart monitoring applications. Future improvements may include advanced probabilistic or machine learning-based sensor fusion techniques to further improve detection reliability in complex environments.

Future Scope:-

Future enhancements can further improve system performance and functionality. Machine learning-based sensor fusion techniques can be implemented to improve detection intelligence and decision-making capability. Long-range radar modules may be integrated to extend the detection range beyond the current 50 cm limitation. Integration with IOT platforms and cloud-based dashboards can enable remote monitoring, data analytics, and RTC-based historical event logging. Improved camera modules with low-light capabilities can enhance detection performance in poor lighting conditions. Additionally, the RTC module can be integrated with data storage systems to maintain long-term detection records for security analysis.

Safety and Ethical Remarks:-

All experiments involving the activation mechanism were conducted under controlled laboratory conditions to ensure safety. The relay booster activation output was used only as a controlled signal to simulate external device activation in a safe testing environment. The system response was triggered only after multi-sensor confirmation, reducing the possibility of accidental activation. Additionally, the RTC module recorded detection events and alert timings, ensuring transparency and traceability during experimental evaluation. Proper electrical insulation, stable power supply, and secure hardware integration were maintained throughout the testing process to ensure safe operation.

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