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Enhancing Surveillance Systems with Cost-Effective Ultrasonic Radar for Object Detection and Tracking

Research Article

Tanvir Ahammad* and Muhammad Golam Rohman Shafi

Department of Computer Science and Engineering, Jagannath University, Dhaka-1100, Bangladesh

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ABSTRACT

Object detection is critical in surveillance systems because it enables timely identification of unauthorized objects, which is essential for maintaining security and mitigating risks. Existing approaches to surveillance typically suffer from limited coverage, variable detection range, moderate accuracy, high cost, and complex setup requirements. This article presents an approach to object detection using microcontroller-based ultrasonic sensors. Our approach leverages four distinct processing phases to create a radar-like system capable of real-time detection and autonomous decision-making. In this study, we conducted experiments by integrating more than six peripheral modules with the Arduino platform. By evaluating 17 diverse test cases in various scenarios and environments, the approach demonstrated enhanced object tracking and robustness compared to existing methods. The system effectively detects objects within the targeted area, providing precise distance measurements (around 50 cm) and position information (0 to 360 degrees). Moreover, our approach enabled the identification of three risk zones—medium, high-risk, and mild danger—within the critical region, contributing to improved security and risk management. The results reveal the system's effectiveness in real-time detection, accurate distance estimation, and comprehensive risk assessment. Overall, our study significantly contributes to the advancement of object detection technology by effectively addressing the limitations of existing methods and offering a cost-effective and practical solution. Our research has the potential to monitor objects in surveillance systems across various domains, with significant implications for enhancing security, risk mitigation, and monitoring in industries reliant on effective object detection systems.

***Corresponding author:** Tanvir Ahammad
E-mail: tanvir@cse.jnu.ac.bd

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1. Introduction

Object detection is crucial in many fields, such as robotics, autonomous vehicles, and intelligent surveillance systems (Go et al., 2020; Xiao et al., 2020). Its primary objective is identifying and locating objects within a given environment, enabling machines to perceive and interact with their surroundings (Kaur and Singh, 2022). In particular, identifying unauthorized objects through surveillance systems is paramount in ensuring security and mitigating potential risks. Furthermore, by promptly detecting and alerting the presence of unauthorized objects, these systems enable rapid response and facilitate appropriate actions to be taken (Yao et al., 2021). In other words, the timely identification of such objects empowers security personnel to assess the situation, initiate appropriate security protocols, and prevent further unauthorized access or malicious activities.

Object detection for surveillance is a challenging problem due to varying lighting conditions, occlusion, scale and perspective changes, object variation, real-time processing requirements, large-scale data, and privacy concerns. These factors make it difficult for algorithms to detect and track objects in surveillance videos accurately. In literature, there are several techniques for object detection, including rule-based methods (Ozkan-Okay et al., 2021), object tracking and behavior analysis (Merad et al., 2016), video analytics and pattern recognition (Seidaliyeva et al., 2020), deep learning based (Arunnehru et al., 2023; Gautam and Singh, 2021; Saheed et al., 2022) and context-aware analysis considering the factors of time of day, location, and environmental conditions (Wang et al., 2020). However, these methods require tracking accuracy and behavior analysis of objects and significant computational power and memory resources. A promising and cost-effective approach that has shown great potential involves the utilization of ultrasonic sensors in conjunction with microcontrollers (Manimegalai et al., 2022). This combination will enhance object detection and analysis in surveillance systems.

To develop an ultrasonic sensor-based radar system for object detection, a combination of different sensor technologies can be utilized. The integration of ultrasonic sensors with other sensor types like thermal Infrared (IR) cameras and Frequency-Modulated Continuous Wave (FMCW) radar can enhance the detection capabilities of the radar system (Hahn, 2022). For instance, a 3D ultrasonic sensor system can be employed for short-distance object detection unaffected by temperature changes, while a thermal IR camera can be used for classifying objects like walls and stairs. Additionally, FMCW radar can provide radial distance measurements for distant objects. By fusing data from these different sensors, a comprehensive 3D visualization of multiple objects can be achieved (Rakesh et al., 2022).

Ultrasonic sensors use high-frequency sound waves beyond human hearing to determine the distance between the sensor and an object. These sensors can calculate the distance between the sensor and the object by measuring the duration for sound waves to bounce back and reflect after hitting an object (Bowler et al., 2022; Paulet et al., 2016). This principle is called" time of flight" and forms the basis of ultrasonic object detection. On the other hand, Arduino-based microcontrollers provide a versatile and accessible platform for interfacing with various peripherals, including ultrasonic sensors (Haq et al., 2021; Sainz-Raso et al., 2022). However, by combining ultrasonic sensors with Arduino, we can create a radar-like system that scans the surrounding environment, measures the distance to objects, and identifies potential obstacles. This setup allows for the real-time detection of objects and enables autonomous systems to make informed decisions based on the gathered data.

In this article, we employed a framework to establish a cost-effective and dependable method to identify individuals who try to gain access to entry points in a border area. The proposed approach utilizes an ultrasonic radar system built on the Arduino platform. This system comprises several components, such as scanning and receiving signals from objects, comparing the reflected sound waves with a predetermined threshold, and calculating three parameters to determine the object's location within the critical region precisely. Furthermore, a comprehensive scanning process ensures the object's presence within the targeted area. Various peripherals, including a servo motor, ultrasonic sensors, LCD display, LEDs, sonar GUI, alarming buzzer, and other connecting devices, were connected to the Arduino board to create the radar. In the experiment, we considered the object detector to have a critical distance of 50 cm in terms of rotational movement, with an angular distance ranging from 0 to 360 degrees.

We conducted experiments in a variety of settings and scenarios, totaling about seventeen test cases, in order to assess the performance of our Arduino-based ultrasonic sensor radar. We conducted tests with different settings to determine stability, response time, and detection accuracy. We measured detection accuracy, response time, and robustness under varying conditions. The results show that our method enhances object tracking by utilizing ultrasonic sensor data for position and distance. The system categorizes proximity using three signals: yellow for mid-range, red for high-risk, and green for mild danger, with objects outside the critical region marked as" out of range." Compared to existing methods, our system offers 360-degree coverage using dual sensors, while typical systems provide only 180-degree coverage. Although our detection range is shorter (1 cm to 50 cm) than some systems (up to 400 cm), the accuracy within this range is high, making it suitable for short-range applications. Additionally, our system is significantly more cost-effective (less than $50) and simpler to set up compared to others that are often more expensive (over $200) and complex.

Overall, this research introduces an innovative approach to object detection using microcontroller-based ultrasonic sensors. By addressing the challenges of existing methods and proposing a cost-effective ultrasonic radar solution, our study contributes to the advancement of object detection technology. However, the contribution of this article is summarized as follows:

- Introduction of a cost-effective and reliable method for identifying objects attempting to enter points in a border area.
- Utilization of an Arduino-based ultrasonic radar system incorporating various components.
- A comprehensive four-phase processing radar system that ensures accurate detection and object tracking within the targeted area.
- Ensuring 360-degree coverage for detecting objects from all directions, which is critical for applications like border surveillance where identifying unauthorized access from any direction is imperative.
- A detection system that addresses the limitations of existing methods in terms of coverage, accuracy, cost, and complexity.
- Enabling effective monitoring and surveillance of objects or entities in various industries.

The article's organization consists as follows: Section II outlines the related studies that investigated object detection using ultrasonic sensors. Then, Section III describes the proposed methodological design of the framework for detecting objects. Next, the experimental design of our work is presented and analyzed in Section IV. Finally, we draw the conclusion of this study in Section V.

2. Related Works

In the literature, numerous studies have examined different facets of object detection using ultrasonic sensors. These studies encompass a wide range of applications, including the development of location systems, detection of muscular force, implementation of hardware and software, creation of teaching aids, design of surveillance robots, utilization of radar-based detection methods, and the prevention of accidents. Researchers have made significant contributions to advancing the object detection field using ultrasonic sensors by investigating these different areas.

Romer (R¨ omer, 2003) analyzed the Lighthouse location¨ systems, a novel laser-based location system for Smart Dust. This system allows remote dust nodes to estimate their location accurately and autonomously without additional infrastructure components, except for a modified base station device. Finally, Tanaka et al. (Tanaka et al., 2003) conducted a study on an ultrasonic sensor disk for detecting muscular force. They proposed an ultrasonic sensor disk as one of the sensor disks embedded in the sensor suit.

Bakar et al. (Bakar et al., 2017) described the low-cost hardware and software implementation for developing an ultrasonic system. Their system visualizes sound feedback through measured distance through a mobile phone. It monitors detection frequency using a real-time graph of a Java application. They utilized the RCWL 0516 sensor as the main module to detect object movement and displayed the microwave wave value on the user's gadget through the Blynk application. Aini et al. (Aini et al., 2018) focused on designing and developing a physics teaching aid based on Arduino. Using the designed learning media, they conducted a case study on free fall motion, measuring the object's height and the time needed.

Kause (Kause, 2019) also studied designing and developing a physics teaching aid based on Arduino, specifically for studying free fall motion. The author measured the object's height and the time required for free fall. Finally, Azeta et al. (Azeta et al., 2019) developed a cost-effective, sustainable surveillance robot using an Arduino microcontroller, a motor shield, and an Android smartphone running the operating system. The robot serves as a surveillance system.

Using an ultrasonic radar, Biswas et al. (Biswas et al., 2020) researched moving object detection. Their proposed method involved proper distance, direction, and object shape analysis in detecting and predicting the exact speed of the objects detected by the radar system. Y M Mohialden et al. (Mohialden et al., 2022) focused on an object detection radar prototype using an ultrasonic sensor and an IoT-based Arduino system. They aimed to prevent accidents by detecting objects in the surroundings. The system incorporates an ultrasonic sensor with IoT capabilities. Finally, Masud et al. (Masud et al., 2022) proposed an effort-saving, convenient, easy-towear object detection system.

F. Noor et al. (Noor et al., 2018) introduced a method for detecting multiple objects in a dark environment using an ultrasonic sensor. Their approach involved utilizing an Arduino microcontroller with an ultrasonic sensor mounted on a motor. By incorporating motor movement, the system enabled efficient scanning and detection of objects even in low-light conditions.

A recent study conducted by J. N. Yasin et al. (Yasin et al., 2021) introduced a collision avoidance algorithm that accurately detects and navigates around obstacles using only one ultrasonic sensor. However, while the algorithm successfully detected obstacles, it did not account for challenging environmental factors such as rough sea waves, unpredictably moving obstacles, or overcast conditions. Therefore, their research focused on creating a reliable collision avoidance system in typical scenarios.

S. U. ERCAN and M. S. Mohammed (ERCAN and¨ MOHAMMED, 2020) designed and implemented an object detection system based on XBee and an ultrasonic sensor. This system could detect stationary and moving objects, providing precise location, direction, and distance information. In addition, the integration of XBee technology enhanced the communication capabilities of the system, enabling reliable transmission of object detection data.

The radar system can be designed using Arduino, as demonstrated in (Gorkshnath et al., 2024). Arduino-based radar systems utilizing ultrasonic sensors have been effective in detecting objects. The essential components of such a radar system typically include a servo motor and an ultrasonic sensor (Rakesh et al., 2022). This setup allows for the rotation of the sensor to scan the surrounding environment and detect objects within a certain range. Furthermore, the ultrasonic sensor can be utilized for obstacle detection within specific angular ranges (Suaif and Gani, 2021). Research has shown that ultrasonic sensors can detect objects up to 40 cm away and within angular rotations ranging from 15° to 165°. This capability makes ultrasonic sensors suitable for applications like blind assistive prototypes, where they can help in detecting objects at close distances to aid navigation (Budilaksono et al., 2020). However, by combining ultrasonic sensors with other sensor technologies and utilizing Arduino-based systems, a radar system for object detection can be developed. The integration of different sensors allows for enhanced detection capabilities, while the use of Arduino provides a versatile platform for building the radar system.

Overall, the existing literature on object detection using ultrasonic radar for a region reveals several research gaps that warrant further exploration. Firstly, there is a need to investigate the integration of multiple sensors to enhance detection accuracy and robustness. Second, developing real-time tracking and localization algorithms specific to border side environments is necessary. Third, specialized algorithms for detecting specific objects or threats relevant to border security should also be improved. Fourth, rigorous performance evaluations in realistic border-side conditions and integrating ultrasonic radar systems with existing border surveillance infrastructure require attention. Finally, we need to find scalable and cost-effective solutions for deploying these systems across large border regions. Addressing these research gaps will improve the effectiveness and efficiency of object detection in border-side regions using ultrasonic radar technology.

3. Methodology

The section describes the methodological design of an object detection system for surveillance purposes in a region's border. It outlines the various segments involved in the design, which are depicted in Figure 1. The first segment involves scanning the area and receiving signals emitted by the objects. The reflected sound waves are compared to a threshold limit in the second segment. Next, we calculate three parameters to pinpoint the object's location in a crucial area. Finally, deep scanning confirms the object's presence within the targeted area.

A. Scanning and Receiving Signals

The first phase of this segment is object scanning, which follows three tasks, including setting up the trigger for ultrasound generation, creating a short ultrasonic burst cycle, and waiting for the reflected sound wave for a fixed amount of time. These steps will continue repeatedly. Then, the object detector is mounted on a motor to provide rotational movement from 0° to 180°. The motor can rotate a full 360° because it has two detectors on opposite sides of its arms. When one detector is rotating from 0° to 180°, the other detector simultaneously rotates from 180° to 0°. So, the two detectors together can cover the entire 360° range. The detector has a transmitter (e.g., trig pin) and a receiver (e.g., echo pin). To initiate scanning, set the trig pin to high for a brief period of 10µs. The transmitter will then emit multiple pulses of ultrasonic bursts at 40 KHz. These pulse patterns are organized especially so that the receiver distinguishes the transmitted pulses from ambient ultrasonic noise. These pulses travel through the air away from the transmitter, as shown in Figure 2. Meanwhile, the receiver goes HIGH right away after the eight ultrasonic bursts and waits for the reflected sound wave to travel back to the receiver, as depicted in Figure 3 (Zhmud et al., 2018).

B. Comparison of Reflected Sound Wave

The receiver waits for the sound wave to reflect from the object back to itself for about $threshold_{limit}$ milliseconds(ms). If the pulses are not reflected within the specified time limit, the receiving signal will time out and go low after $threshold_{limit}$ms. Thus, a pulse of $threshold_{limit}$ms indicates no obstacle found within the range of the detector. However, after the receiver goes into the time-out state, the detector again starts object

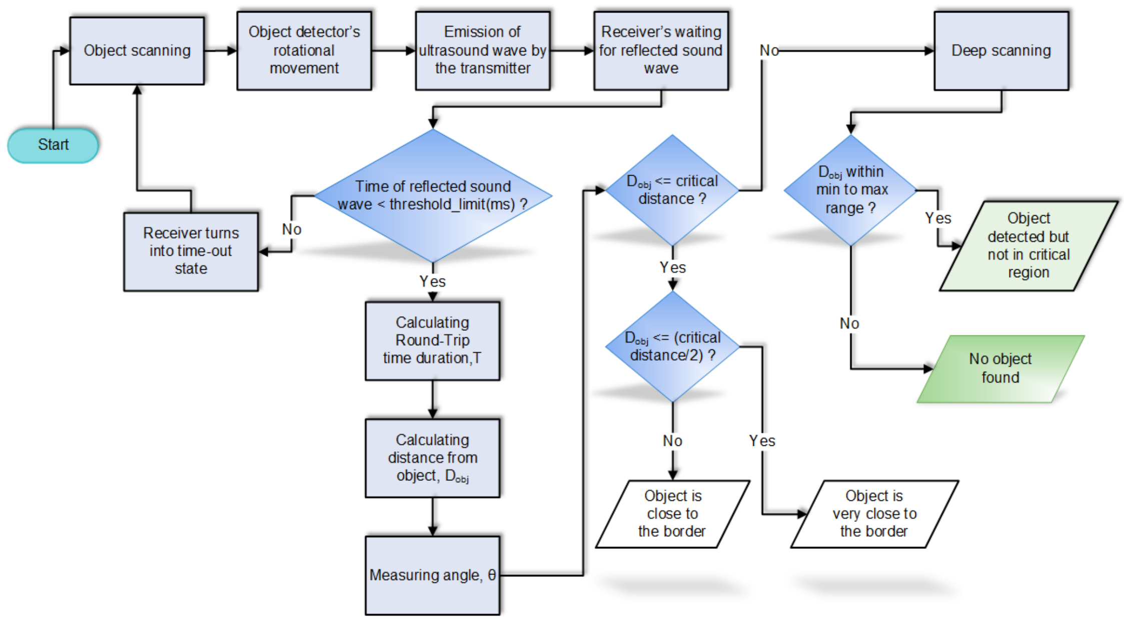

Fig. 1. Overall architectural workflow design for the object detection system.

scanning. Again, if the pulses are reflected within the time limit of $threshold_{limit}$ms, the receiver will immediately go low upon receiving the signal. When the signal is received, it produces a pulse that changes in width from 150μs to 25ms—the pulse width changes depending on the time it takes to receive the signal.

C. Locating Object within Critical Region

The detector uses three measurements to determine the detected object's round-trip time duration, distance, and angle. These measurements depend on the pulse width and the duration it takes to detect the reflected sound wave. The equations used for calculating the round-trip time and distance are shown in equation 1 and equation 2. In these equations, T represents the round-trip time, t_1 represents the time for the sound wave travels from the transmitter to the obstacle, t_2 represents the time for the sound wave to travel from the obstacle to the receiver, and D_{obj} represents the distance from the object.

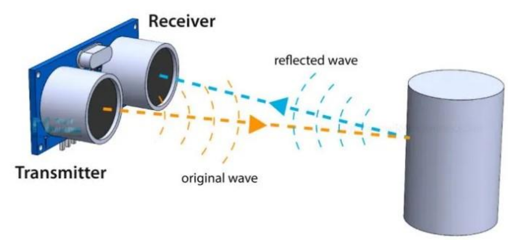

Fig. 2. Sending and receiving signal using ultrasonic sensor (Zhmud et al., 2018).

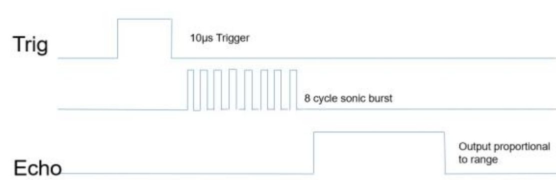

Fig. 3. Timing diagram of ultrasonic sensor.

$$T = t_1 + t_2 \quad (1)$$

$$D_{obj} = Speed \times Time \quad (2)$$

Let us consider an example of measuring the distance between an object and a sensor or detector shown in example 1.

***Example 1**:* Consider the receiver pulse duration time= 1.5*ms* and speed of sound is = 340*m/s*, then we use the following procedure to find the distance:

$$Distance = \frac{Speed \times time}{2}$$

$$speed = 340\ m/s$$

$$= \frac{(340 \times 100)cm}{1000\ ms}$$

$$= 34\ cm/ms$$

$$Distance = \frac{34\ cm/ms \times 1.5\ ms}{2}$$

$$= 25.5\ cm$$

The purpose of measuring these parameters is to detect and receive the reflected radar signals from objects within a certain distance. The distance is defined as the critical distance when the object is 'p cm' away from the borderline of the region or country. In order to fully comprehend the object's characteristics, like its features, surfaces, or components, we establish a critical distance that is half of the measured distance, expressed as $\frac{p}{2}cm$. Scanning the object closer allows for a thorough inspection and analysis, facilitating the identification of defects, anomalies, or intricate details that may not be easily observable from a distance.

However, we proceed with a double-checking procedure to determine the object's location using the measured values: T, D_{obj}, and θ. Suppose the intruder crosses the threshold of 'p cm' (i.e., the distance from the radar to the intruder, $D_{obj} \leq p$), we then examine whether the intruder also crosses the threshold of $\frac{p}{2}$ cm (i.e., $D_{obj} \leq \frac{p}{2}$). Suppose the intruder does cross the $\frac{p}{2}$ cm threshold. In that case, the radar positioned at the checkpoint near the border line will trigger a danger alarm, indicating that the intruder is close to the border. On the other hand, if the intruder only crosses the 'p cm' threshold but not the $\frac{p}{2}$ cm threshold, the radar will emit a mild danger alarm, indicating that the intruder is close to the border.

D. Deep Scanning

In addition to detecting objects at the critical range, the radar can also detect objects outside the critical range. If the distance from the object, D_{obj}, is outside the critical distance" p cm" (i.e., $D_{obj} > p$), then the radar goes into the deep scanning stage. In this stage, the radar checks whether the object is within the radar's max range (shown by the" max" parameter in Figure 1). Suppose the object is within the radar's maximum detectable range (i.e., $p < D_{obj} \leq$ max), the radar does not produce any alarm, which indicates that the object is well outside the critical region. However, the radar can detect the object as it is within the radar's maximum detectable range and show the red dots as proof of detection. Otherwise, if the object is outside the radar's maximum detectable range defined by the" max" parameter (i.e., D_{obj} > max), then the radar declares that" No object found" within its sight.

E. Detecting Unauthorized Entity Access

As part of the proposed methodology for border surveillance, a crucial aspect involves detecting unauthorized entity access. The provided Algorithm 1 aims to detect unauthorized entity access using an Arduino board and an ultrasonic sensor module. It outlines the steps involved in monitoring the distance measured by the sensor and comparing it to the authorized access threshold. The algorithm starts by initializing the hardware components and defining the authorized and unauthorized access thresholds. Then, in a continuous loop, the algorithm reads the ultrasonic sensor data and converts it to distance. An alert is triggered if the measured distance exceeds the authorized access threshold, indicating unauthorized access. Otherwise, the system continues monitoring for any access attempts. The algorithm ensures the real-time detection of unauthorized access and facilitates prompt response.

4. Experiment and Result Analysis

Our goal for this study was to create a dependable and affordable system to detect objects access to entry points within a specific area. To achieve this, we utilized an ultrasonic radar based on Arduino technology. The experiment was conducted to assess the effectiveness of the proposed system

Algorithm 1 Detection of Unauthorized Entity Access

Require: Arduino board, ultrasonic sensor module
Initialize the hardware components
Define authorized and unauthorized access thresholds
while true **do**
    Read ultrasonic sensor data
    Convert sensor data to distance
    if distance exceeds authorized access threshold, **then**
        Trigger unauthorized access alert
    else
        Continue monitoring
    end if
end while

authorities promptly. The setup involved the deployment of ultrasonic sensors strategically positioned at entry points, such as gates or doors, coupled with an Arduino microcontroller for data processing and analysis. The system was calibrated and tested using various scenarios simulating authorized and unauthorized access attempts. The results were analyzed to evaluate the system's accuracy, sensitivity, and performance in detecting entities. The findings of this experiment can improve a country's security infrastructure by offering an effective and affordable solution to prevent unauthorized entry into sensitive areas.

A. Experimental Setup

The experimental procedure for detecting entity access to entry points in a region (i.e., a country's border) using an Arduino-based ultrasonic sensor involves several steps. First, the hardware components are initialized, which includes setting up the Arduino board and connecting the ultrasonic sensor module. Next, threshold values for authorized and unauthorized access are defined based on distance measurements.

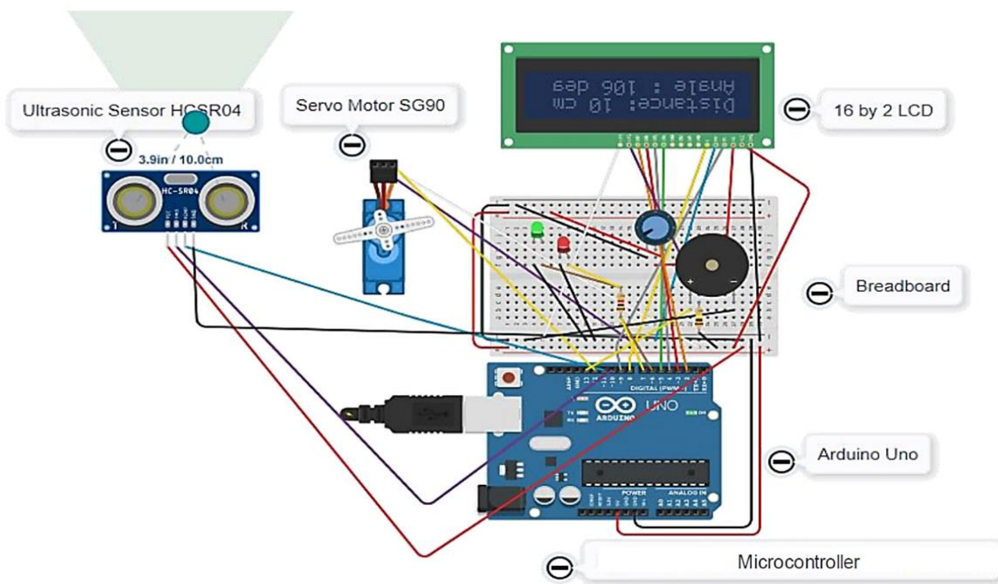

Fig. 4. Block diagram of the system providing a high-level overview.

The main program loop is then started, where the ultrasonic sensor data is continuously read, converted into distance measurements, and compared against the authorized access threshold. Monitoring for unauthorized access attempts continues if the measured distance falls within the authorized range. However, an alert or notification indicates unauthorized access if the measured distance exceeds the authorized threshold. Afterward, the system calibrates using data from authorized access points and continuously monitors the distance measured. Finally, we conducted experiments to evaluate the system's performance, and the collected data was analyzed to calculate metrics such as detection accuracy. The experimental configuration, code, and outcomes are extensively recorded, and based on the analysis and feedback, the system design and code are iterated upon for improvement.

However, following the procedure and algorithm (as shown in Algorithm 1) mentioned, we have designed a comprehensive block diagram of the proposed system, as shown in Figure 4. This detailed representation exhibits the interconnections between various components and their electrical connections, providing a comprehensive and technical view of the system or circuit. Furthermore, to provide a higher-level overview of the system, we have also created a block diagram representation. This diagram focuses on the functional relationships between components rather than intricate details, utilizing simplified block-shaped representations to depict the major components or subsystems of the proposed radar. By incorporating both the schematic and block diagrams, we demonstrate a comprehensive understanding of the system, providing different peripherals with a complete picture of the proposed radar system.

B. Result Analysis

We conducted experiments using an Arduino-based ultrasonic sonar sensor as a radar for object detection. The setup included LEDs, an LCD screen for displaying detection actions, and a Sonar GUI for real-time monitoring (Figure 4). This design ensured 360-degree coverage, allowing the sensor to detect objects from all directions.

The radar system's comprehensive coverage allowed it to identify and track objects accurately within its range. Figure 5 shows the initial scanning results, with green lines indicating no objects detected and red patterns indicating the presence of an object.

For different danger levels, we set the distance thresholds to 10 cm and 20 cm. If the distance was between 10 cm and 20 cm, it triggered a medium danger alert with a yellow LED and a 2 KHz buzzer (Figure 6). Distances below 10 cm triggered a high danger alert with a red LED and continuous buzzer (Figure 7). Distances above 20 cm activated the green LED, indicating a mild danger level (Figure 8).

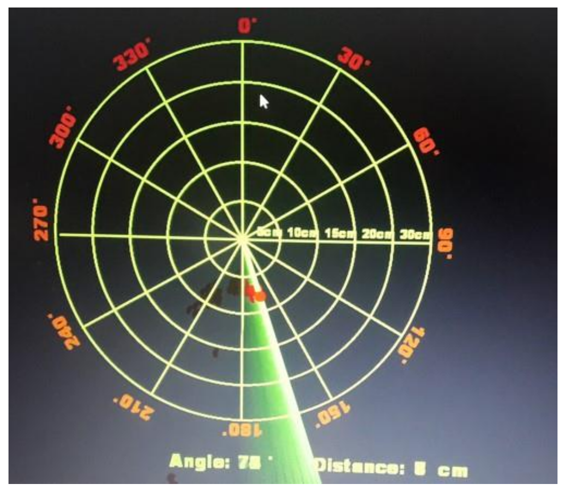

Fig. 5. Successful object detection in the initial scanning.

In deep scanning mode, the system accurately detected objects within a 50 cm range. Objects within 30 cm and an angle between 90° and 120° were marked (Figure 9). Anomalies in the 180° to 240° region were detected at 208° and 32 cm (Figure 10). Objects beyond 50 cm were not detected, as shown in Figure 11.

We tested the system in various scenarios to simulate both authorized and unauthorized access. Table I summarizes the test cases, showing successful object detection within the specified ranges. Objects closer than 1 cm or farther than 50 cm were not detected, illustrating the sensor's limited range despite its design to detect distances up to 400 cm.

We used two sensors rotating from 0° to 180° and vice versa, ensuring comprehensive 360° coverage. This setup guarantees detection of objects within the entire angle range. The test cases provided valuable insights into the system's performance, limitations, and angle coverage.

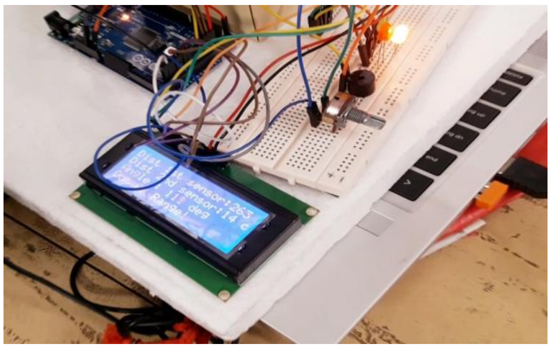

Fig. 6. Yellow signal and buzzer activation when the distance is between 10 cm and 20 cm.

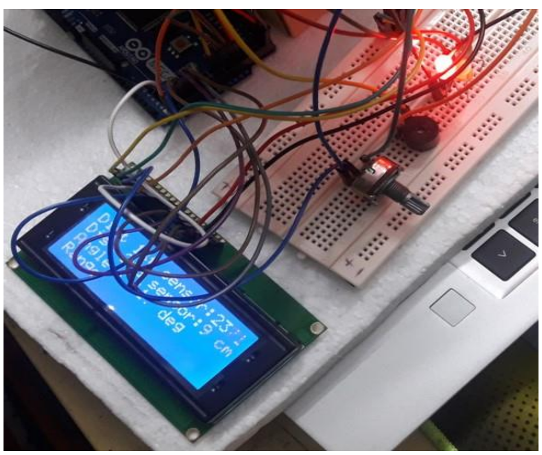

Fig. 7. Red alarming when the distance is below 10 cm.

C. Comparative Analysis

To evaluate the performance of our Arduino-based ultrasonic radar system, we compared it with existing object detection systems. The comparative analysis focused on key parameters such as coverage, detection range, accuracy, cost, and complexity. Table II summarizes the comparison.

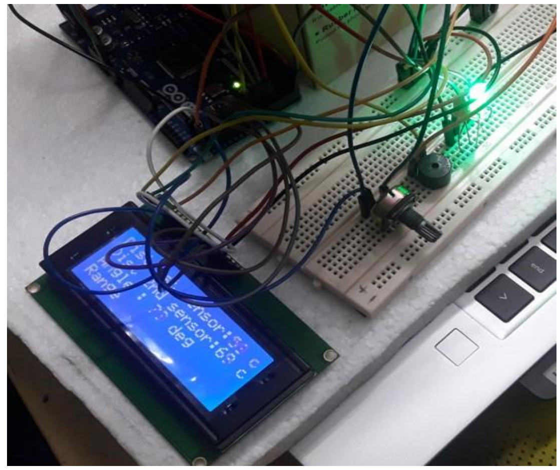

Fig. 8. Activation of Green LED when the distance is greater than 20 cm.

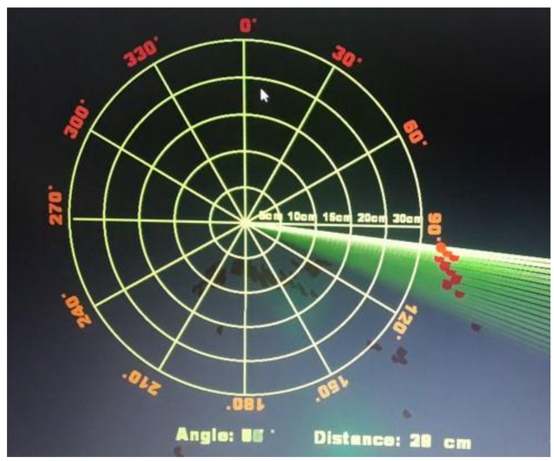

Fig. 9. Object detection at an angle of 92° and a distance of 29 cm.

Existing object detection systems typically employ a single sensor, providing up to 180 degrees of coverage (Tanaka et al., 2003), (Paulet et al., 2016). In contrast, our system uses two sensors, each covering 180 degrees and rotating in tandem, ensuring a complete 360-degree coverage. This extensive coverage is crucial for applications that require monitoring from all directions, such as border surveillance and environmental monitoring.

While some existing systems can detect objects up to 400 cm (Bakar et al., 2017), (ERCAN and MOHAMMED, 2020), our system's effective detection range is between 1 cm and 50 cm. This limitation is primarily due to the rotational movement of the motors, which affects the reflection of sound waves. However, within this range, our system performs reliably and accurately, making it suitable for short-range applications.

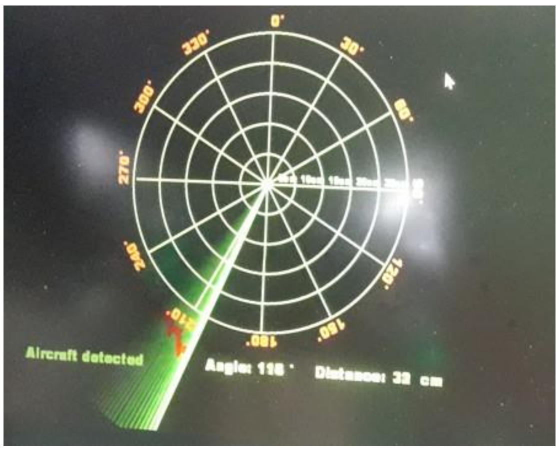

Fig. 10. Object detection at an angle of 208° and a distance of 32 cm.

Fig. 11. No object detected at a distance greater than 50 cm.

Our system demonstrated high accuracy within the 1 cm to 50 cm range. The multi-level alert system (green, yellow, and red LEDs) effectively categorized danger levels based on distance, providing clear and prompt notifications. Existing systems vary in accuracy, often depending on the type of sensors used and their calibration (Biswas et al., 2020), (Suaif and Gani, 2021). Our system's precise detection within its effective range highlights its reliability for short-range detection tasks.

Our Arduino-based system is significantly more cost-effective, with a total cost of less than $50, compared to existing systems that can exceed $200 (Azeta et al., 2019), (Gorkshnath et al., 2024). This cost advantage makes our system accessible for a wide range of applications, especially in resource-constrained environments.

The setup of our system is relatively simple, involving basic components such as ultrasonic sensors, LEDs, an LCD screen, and an Arduino board. This contrasts with many existing systems that require advanced calibration and complex configurations (Aini et al., 2018), (Kaur and Singh, 2022). The simplicity of our system's design ensures ease of deployment and maintenance.

D. Discussion

The results from our experiments highlight the capabilities and effectiveness of the Arduino-based ultrasonic radar system in object detection, with a focus on coverage, detection range, and accuracy.

The system provides comprehensive 360-degree coverage using two ultrasonic sensors, each rotating from 0° to 180° and back. This dual-sensor setup ensures full-angle detection, which is crucial for applications requiring extensive area surveillance, such as environmental monitoring and security systems. The complete coverage eliminates blind spots, thereby enhancing the system's reliability in detecting objects from all directions.

The ultrasonic radar system effectively detects objects within a range of 1 cm to 50 cm. Different danger levels were set at specific distance thresholds of 10 cm and 20 cm, triggering appropriate alerts through LEDs and a buzzer. Objects within this range were consistently detected, as demonstrated by the test cases presented in Table I. Although the ultrasonic sensor is designed to detect up to 400 cm, our system's practical detection range was limited to 50 cm due to the motor's rotational movement, which impacts the reflection of sound waves back to the sensor.

TABLE I

OBJECT DETECTION AT VARIOUS RANGES.

Test ID	**Distance (d) – cm and Angle (a) - degrees**	**Object detection (YES/NO)**
1	(d) 1	NO
2	(d) 2	YES
3	(d) 3	YES
4	(d) 4	YES
5	(d) 5	YES
6	(d) 10	YES
7	(d) 15	YES
8	(d) 20	YES
9	(d) 25	YES
10	(d) 30	YES
11	(d) 35	YES
12	(d) 40	YES
13	(d) 45	YES
14	(d) 50	YES
15	(d) 50>	NO
16	(a) 0 to 360°	YES
17	(a) <0 to 360°>	NO

The system's accuracy in detecting objects within the specified range was high. Detailed scanning results confirmed the system's precision, as the multi-level alert system (green, yellow, and red LEDs) effectively categorized danger levels based on distance, providing clear and prompt notifications. Figures 5, and 9 illustrate the system's ability to accurately detect and indicate object positions.

TABLE II

COMPARATIVE ANALYSIS OF OBJECT DETECTION SYSTEMS

Parameters	**Existing Systems**	**Our System**
Coverage	180 degrees (single sensor) (Tanaka et al., 2003), (Paulet et al., 2016)	360 degrees (dual sensors)
Detection Range	Up to 400 cm (Bakar et al., 2017), (ERCAN and MOHAMMED, 2020)	1 cm to 50 cm
Accuracy	Moderate, depends on sensor type (Biswas et al., 2020), (Suaif and Gani, 2021)	High within 1-50 cm
Cost	High (>$200) (Azeta et al., 2019), (Gorkshnath et al., 2024)	Low (< $50)
Complexity	High (advanced calibration) (Aini et al., 2018), (Kaur and Singh, 2022)	Low (simple setup)

The dual-sensor configuration rotating in tandem ensures that objects within the entire 360-degree range are detected. This comprehensive coverage is crucial for applications like border surveillance, where detecting unauthorized access from any direction is imperative. Additionally, the setup's ability to provide real-time monitoring through the Sonar GUI further enhances its practical utility in various surveillance scenarios.

E. Challenges and Limitations

We incorporated ultrasonic sensors into our study for their cost-effectiveness, simplicity, non-contact sensing capabilities, suitability for short to medium-range measurements, low power consumption, and effectiveness in safety applications. However, it is essential to acknowledge their inherent limitations, which may introduce potential sources of error:

- Ultrasonic sensors are less effective for longer distances due to their limited range.
- Interference from other sources may cause false readings, including reflections off non-metal objects.
- Ultrasonic sensors have relatively slow response times compared to other distance measurement devices, such as infrared sensors.
- Ultrasonic sensors struggle to detect high-density materials, extreme temperatures, and small target surfaces, leading to underestimation of measurements.

Multipath interference is a potential issue, where sound waves take multiple paths due to obstacles or reflective surfaces, leading to inaccurate distance measurements. This complexity can affect the precision of our measurements, despite accounting for various factors like short to medium range distances and 360-degree coverage.

Several possible solutions to address multipath interference include:

- Using narrow beam sensors to reduce the likelihood of multiple reflections.
- Implementing signal filtering techniques to discard inconsistent echoes.
- Setting appropriate thresholds and range validation to reject out-of-range readings.
- Averaging multiple readings for more stable measurements.
- Applying dampening materials to surfaces causing reflections.
- Combining multiple sensor technologies (e.g., ultrasonic with infrared or laser) for cross-validation.

While these measures can significantly reduce multipath interference, complete elimination may not be feasible in all scenarios. Therefore, we will interpret our results with caution and discuss the potential influence of multipath interference on our findings in future research.

5. Conclusion

This article introduces a cost-effective and reliable method for detecting unauthorized access at border entry points using an Arduino-based ultrasonic radar system. The proposed system integrates various components, including a servo motor, ultrasonic sensors, LCD, LEDs, a sonar GUI, and an alarming buzzer, connected to an Arduino board to create a comprehensive radar system. This system operates in four phases: scanning and receiving signals, comparing reflected sound waves with a predefined threshold, calculating parameters to determine object location, and deep scanning to confirm object presence within the targeted area. The experiments, conducted across seventeen different test cases with varying distances and angles, demonstrated the system's effectiveness. The results showed that our approach could accurately detect objects within the critical range and classify their proximity using color-coded signals: green for mild danger, yellow for mid-range, and red for high-risk regions. We marked objects outside the critical range as" out of range" and identified hidden objects through deep scanning. Moreover, our system addresses existing research gaps in coverage, accuracy, cost, and complexity, enhancing security and risk management in surveillance applications across various domains.

While the current system shows promising results, further refinement of algorithms, integration of advanced signal processing, and machine learning techniques could enhance accuracy and reliability. Future work will focus on extending the radar's range and sensitivity by utilizing different sensor models and improving the signal-to-noise ratio. We also plan to implement this system for refugee surveillance along Bangladesh's border.

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Declarations

- Competing interests: The authors declare no competing interests.
- Authors' contributions: We acknowledge that both Authors contributed equally to this work.

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