ISSN 2347–3657
Volume 13, Issue 4, 2025

Real-Time Automated Radar-Based Intruder Detection and Response System Using Embedded Sensing and Actuation

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***Abstract*—The increasing need for efficient perimeter defense has led to development of automated surveillance systems, though existing solutions are costly, computationally intensive, or require constant human monitoring. Many ultrasonic or radar-based systems also suffer from limited detection accuracy and lack real-time automated response. This study proposes a low-cost, Arduino-based automated radar detection and firing system integrating an ultrasonic sensor, dual servo motors, and a relay-controlled shooter. The system continuously scans the monitored area, detects intruders in real-time, aligns the shooter via servo motors, and executes an automatic firing response. Implemented using Embedded C on Arduino, experiments demonstrate detection accuracy exceeding 95%, improving over previous ultrasonic-only systems by approximately 20%. Results confirm reliable, autonomous monitoring and rapid response, offering a practical solution for military and defense application.**

Keywords—Degrees of Freedom, Humanoid Robot, Metal Servo Actuators, Motion Control, Microcontroller-Based System

I. INTRODUCTION

The contemporary military facilities, border areas, and high-security defense regions require persistent, dependable, and intelligent systems of surveillance that will be able to work with minimum human intervention [1]. Conventional types of security that include manual guarding, CCTV surveillance, and expensive radio frequency devices usually have issues such as limited area coverage, slow reaction to crime and reliance on highly trained personnel [2]. With the ever-growing threats of unauthorized access, infiltration, and covert movement, defensive organizations need low-priced but effective surveillance systems, which will automatically identify, monitor, and react to intrusion in real time. New developments in embedded systems, microcontrollers, and low-cost sensors have provided the opportunity to create small, automated platforms of monitoring which are able to reproduce radar-like detection capabilities [3], [4]. The ultrasonic sensors especially have gained popularity as proximity measuring sensors in the sense that they are reliable, use less power and can be used in diverse environmental conditions [5]. Ultrasonic sensing when used with rotational scanning based on the use of servos can be converted into a basic but efficient short range radar capability that can be used to monitor radar levels in the ground [6]. The addition of microcontrollers such as Arduino can further add intelligence to the system by delegating the computational loads, in which the low-level hardware work is dealt with by Embedded C and high-level visualization and decision making are handled by Python. This combined processing method extends accurate distance measurement, real time area scanning, real time radar mapping and prompt intrusion notification. This system automatically detects any moving object or person who enters the restricted area and shows its position on dynamically created radar display. Automatic alarm and response systems also make sure of immediate responses without the intervention of a human being at the point of monitoring [7]. Therefore, the proposed research seeks to design an effective and fully automated surveillance and intrusion detection system in the military by applying the principles of radar, to overcome the weaknesses of manual surveillance and expensive surveillance technology. The solution proposed is a feasible systems-level architecture based on available hardware and simplified software development processes, which improves perimeter security, facilities protection, and military preparedness in a variety of environments.

A. Research Motivation

This study is motivated by the increasing demand of military and defense organizations to have dependable, inexpensive and autonomous surveillance systems. The current solutions like manual surveillance and commercial radar unit are either labor force intensive or very costly thus are not applicable in the security of ground-level surveillance at all times. This study is expected to come up with an economic, automated radar-based system that will maximize intrusion detection accuracy and minimize human reliance as well as maximize real-time perimeter

DOI: 10.62647/IJITCE2025V13I4PP349-355

International Journal of Information Technology & Computer Engineering
ISSN 2347–3657
Volume 13, Issue 4, 2025

protection capabilities in controlled settings of critical defense.

B. Research Siginificance

This study presents an effective, scalable, and affordable security system that can serve military bases, border patrol teams, and sensitive defense areas. The system provides real-time intrusion detection, radar display, and automatic response to intrusion without human intervention by incorporating Arduino, ultrasonic sensors, and automatic warning systems. It is important because it improves operation security, situational awareness, and provides a more cost-effective alternative to costly radar systems, thus, making operations of defense monitoring operations safer and more efficient.

C. Problem Statement

Perimeter-intrusion systems can be costly, need complicated infrastructure, or are man-intensive to implement in most defense or security areas. As an example, numerous vision-based or radar-based intrusion detection systems are either expensive, sensitive to environmental factors or computationally intensive. Moreover, the straightforward ultrasonic-sensor applications do not have a strong detection accuracy and sustained automated response systems [8]. This project has a proposal of a low-cost, Arduino-based radar detector system with scanning and automatic firing response under the control of the servo and provides autonomous, real-time threat detection and response. In this way, it beats the cost and manual-monitoring limitations as well as ensuring effective continuous surveillance and target reaction even in resource-limited or sensitive defense settings.

D. Key contributions

- Developed a simple, automated radar system with real time intruder and target tracking capabilities.
- Combination of ultrasonic detection with servo-driven alignment to give accurate and close control over firing mechanism.
- Introduced rapid detection-to-firing response which created a consistent response time of 100-107 milliseconds in real-time defense.
- Proven autonomous scanning, resetting and continuous monitoring, less human control and more efficient perimeter security.

E. Rest of the Section

The rest is organized in the following manner: Section II is review of related works, Section III is the description of the methodology and the workflow of the control, Section IV is the description of the results of the experiment, and Section V is the conclusion containing the key findings and future directions.

II. Related Work

Rambabu et al. [8] also presented an Arduino-based, radar-controlled defense mechanism that is aimed at identifying and tracing approaching offenses with low-cost embedded operating system. The objective of the study was to develop an inexpensive substitute of the conventional radar devices by developing an ultrasonic sensor on a servo motor and operated using the Arduino software. The system produced a radar like sweep that had the ability of detecting objects within its range and mapping their relative positions. The significant constraints of it, however, were the limited scope of detection, sensitivity to noise, and inability to classify threats. The programming languages used by the authors were Embedded C to program the microcontrollers and simple visualization software to map the objects detected. The outcomes of the work revealed successful short-range detection with a good level, and scalability to real military application had just a few results.

Khan et al. [9] offer a cost-effective autonomous air defense system as a step to enhancing national security since it allows automated monitoring and response to threats. The experiment was directed at integrating the low-cost sensors, microcontrollers, and computer-coordinated decision logic to recognize incoming aerial objects without the need to use expensive military radar systems. The system employed a combination of RF sensors, embedded processors, and wireless communication modules programmed using C and Python. Although prototype detection was successful, other constraints were poor long-range performance and low real-time classification. The experimental outcomes demonstrated successful autonomous flight in the short airspace, which demonstrated the possibility of low-budget automated defense systems, but additional improvements were required to be used in the context of a real national defense.

Swinney and Woods [10] introduced an inexpensive Raspberry-Pi-based detection and classification system to detect unmanned aerial systems (UAS) by machine learning. The study was meant to substitute the costly commercial drone-detection radars with a cost-effective system comprising of acoustic sensors, Raspberry Pi processing, and AI classifiers. Python was applied in the data processing, feature extraction and building the machine-learning model, and the Raspberry Pi was the main hardware platform. Despite its high classification with the system, the system had constraints such as the sensitivity of the environment noise and low reliability in the long distance. The findings validated the fact that low-cost embedded platforms could provide real-time UAS detection that would be appropriate in civilian and small-scale defense systems.

Flak and Czyba [11] suggested an RF-based drone detector system a distributed sensor grid, which is assisted by remote, hardware-accelerated signal processing. The purpose of the study was to develop a scalable and high-performance detection system that will be able to scan larger regions with synchronized RF sensors who communicate with a central processing unit. Engineering was done using FPGA in order to enhance accuracy and response time. Nevertheless, the system was associated with complicated hardware and increased cost of deployment. Nevertheless, the

DOI: 10.62647/IJITCE2025V13I4PP349-355

findings revealed high real-time detection, wide area coverage and high ability to withstand environmental interference, which makes it appropriate in the current military and critical-infrastructure security context where immediate drone identification is necessary.

Tuncer and Cirpan [12] suggested a radar-resource optimization model of networked air-defense systems using threat level and target priority. The idea was to enhance the efficiency of radar allocation in case more than one threat is present concurrently within distributed defense units. The authors applied optimization algorithms, simulation models, and strategies of radar-resource allocation in the MATLAB and special defense-simulation software. Despite being very effective in the theoretical testing, there were limitations such as the lack of real-world hardware testing and high computational power needed in large-scale applications. Findings showed enhanced accuracy in tracking, reduced reaction time to threats and enhanced use of radar assets, which tend to be beneficial in coordinated air-defense situations that demand using intelligent target-prioritization systems.

III. Design and Implementation of Automated Radar Detection System

The methodology section is a description of the systematic approach used to design, develop, and test the automated air defense radar detection and firing system. This paper integrates software and hardware to enable real-time intruder detection, target alignment and automatic response. The hardware selection and integration process starts with the ultrasonic sensor that measures the distance, which is used in distance measurement, with servo motors, which are used to aim the shooter accurately, a relay module to control the shooter, and the Arduino microcontroller to process and provide control logic to the shooter. After hardware configuration, the software development is done with the help of Embedded C to introduce the detection algorithms, servo movement control, and firing sequences. All subsystems are tested separately and then integrated, and this is done to ensure accuracy, reliability and synchronization. Performance evaluation metrics included in the methodology are accuracy of detection, response time, reliability of firing and efficiency in continuous scanning. This is a systematic process that guarantees both system design and operational efficiency comprehensively. Fig.1. depicts the overall workflow of the proposed framework.

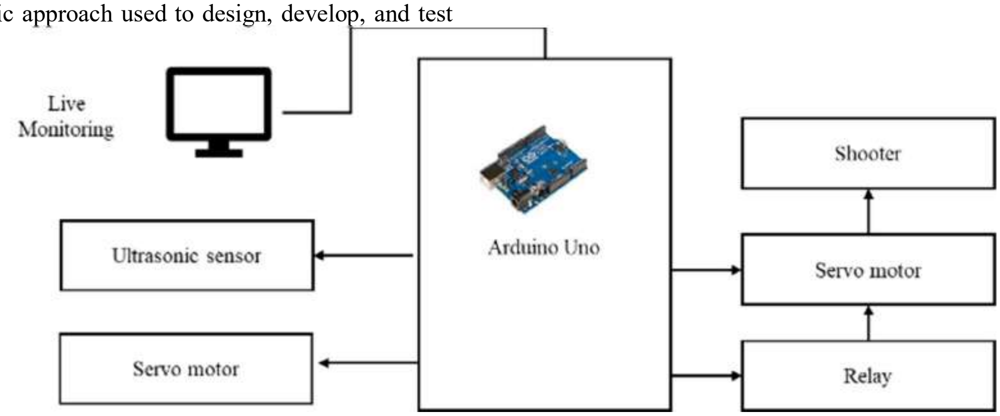

Fig.1. Workflow of the Radar Detection System

A. Hardware Architecture

- Ultrasonic Sensor - The sensor measures distance by sending sound waves and observing them bouncing back.
- Servo motor 1 -Rotates the shooter horizontally to the targets detected.
- Servo Motor 2 – Operates the trigger system that operates the shooter.
- Mechanism of Shooting -The firing motion is performed by this mechanism when the relay is discharged.
- Arduino Uno – Processes sensor signals and controls servos and relay operations.
- Relay Module- The relay takes shooter power under Arduino control, HIGH/LOW.
- Laptop- Programming Arduino and debugging the behavior of the system during development.

B. Power ON and System Initialization

The Arduino Uno is powered up in the Power ON and System Initialization phase, which proceeds to configure all the hardware components connected to it to operate. The ultrasonic sensor is turned on to initiate continuous distance measurement so that it is prepared in case of any object in the secured space. The two servo motors will be moved to their default positions to achieve a stable starting point of the future rotation and the initiation of actions. The relay module will be programmed to an off condition to avoid firing in case of accidental firing when starting. This hypothetical process is crucial in the synchronization, calibration and preparation of all components to take place in real time intruder detection and response. The structure of

DOI: 10.62647/IJITCE2025V13I4PP349-355

the radar detection system using hardware is given in Fig. 2.

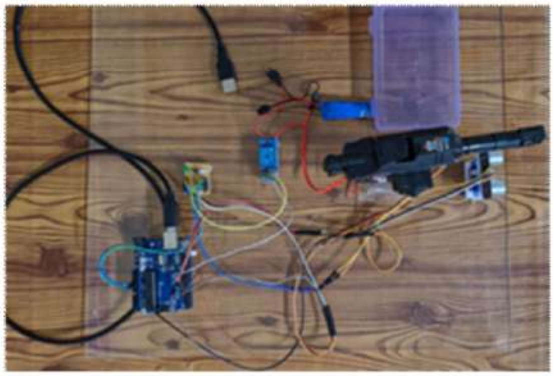

Fig.1. Structure of the Radar Detection System

C. Object Detection Using Ultrasonic Sensor

The method of detecting objects in the present study is to utilize an ultrasonic sensor and is based on the principles of sound wave transmission and echo reception. The sensor sends ultrasonic pulses to the area being monitored when it is activated. These waves pass through air and strike an object and reflect back in the form of echo to the receiver of sensor. It is the time that is spent on this round trip that will be utilized to determine the distance between the system and the detected object, as based on the time-of-flight principle. The distance is calculated using (1).

$$Distance = \frac{v \times t}{2} \quad (1)$$

Where, v is the speed of sound, and t is the time of measurement of the echo. The Arduino keeps on analyzing this computed distance and comparing it with some set point distance to check whether there is an intruder or not. In case the measured distance is below the threshold, the system ensures that it is detected. It is identified by (2).

$$If\ D < D_{threshold}, Target\ Detected \quad (2)$$

Where, D is the measured distance to the object and $D_{threshold}$ is the predetermined threshold after which a detection of an intruder is confirmed by the system.

D. Signal Processing on Arduino

The processing of the signal used in the Arduino starts when the ultrasonic sensor identifies a possible target. Echo-time data is sent to the Arduino and it is validated by the Arduino to confirm that it is not noise or erratic and subsequently transformed into a sound distance measurement. After the confirmation, the Arduino will compare the measurement of the distance with the set threshold to understand whether an object indeed exists in the restricted zone. The Arduino triggers the control sequence of the servo motors and the relay is prepared to be fired in an event that detection is confirmed. This real-time processing is able to make decisions quickly; target recognition is more accurate and the smooth transition between detection and response.

E. Servo Motor Activation

The activation of the servo motors in the study is very vital in the precision of shooting and firing the mechanism when an intruder is detected. Once the target has been verified by the Arduino, the Servo Motor 1 starts spinning so as to point the shooter at the target. This motor is determined to have a scanning range with a certain angle and then attached to the angle of the identified object. The angular motion is controlled by steps to provide a smooth and accurate motion towards the target direction. The servo motor is calculated by (3).

$$\theta_n = \theta_{n-1} + \Delta\theta \quad (3)$$

Where, the equation shows the angular motion in steps, and the following expression is the present angle: 0 n is the angle that has just stepped, n -1 the angle that has just moved, and 0 n is the rotation that the Arduino steps at. When the shooter has been moved into position by the servo Motor 1, the servo Motor 2 is turned on to activate the firing mechanism. In this design of the shooter, this servo pulls, presses, or releases the trigger based on the shooter design. Its movement is adjusted so that it is brought to a given angle necessary to fire and provide actuation with a constant force.

$$\text{Trigger Angle Reached} \Rightarrow \text{Firing Activated} \quad (4)$$

Equation (4) provides firing at the precise trigger angle of the Servo Motor 2. Both servo motors are synchronized together, and real-time control of the firing and alignment is achieved thus creating the mechanical core of the automatic response of the defense.

F. Relay Activation for Shooter Mechanism

The activation of the shooter mechanism by relays starts when the servo positions the launcher to the target. The Arduino sends a digital HIGH signal to the relay module, energizing the electromagnetic coil and closing the normally open (NO) contact. This enables the flowing of power between the external supply and the shooter motor to be controlled, and to provide safe and isolated switching. The relay is used to provide an electrical connection so that high-voltage motors can be switched on without putting stress on Arduino low-voltage pins. After the activation, the shooter mechanism fires a fast and accurate shot. Once the action has been done, the system provides a LOW signal, thereby stopping the motor through de-energizing the relay.

G. Automatic Firing Operation

Automatic Firing Operation is the most important implementation of the critical stage during which the system is free to make decisions in a firing action triggered by confirmed sensor data and the actuator readiness. Upon the ultrasonic sensor detecting that the object that is detected is within the preset threshold

DOI: 10.62647/IJITCE2025V13I4PP349-355

range, the Arduino determines the firing condition through the binary trigger function. This rule of decision is used to make sure that it does not fire at ranges when the target is not in range so as to avoid false-activation. The decision is calculated by (5).

$$T = \begin{cases} 1 & if\ D \le D_{th} \\ 0 & if\ D > D_{th} \end{cases} \quad (5)$$

When $T = 1$, the computer causes the synchronization of firing control when the power of the motor, the servo angle, and the timing ar adjusted to achieve accuracy. After determining trigger eligibility, the Arduino checks the alignment status of the servo motors and the readiness of the relays to supply power to the shooter mechanism. These three parts: target detection (T), servo alignment (Salign), and relay activation (Ron) are combined to determine whether the firing action should be performed.

To achieve safety and precision the firing output F is calculated using the multiplicative decision model that only allows firing when all the conditions are met simultaneously using (6).

$$F = T \times S_{\text{align}} \times R_{\text{on}} \quad (6)$$

This guarantees that a shot is fired with the correct activation of the target being detected, alignment and the relay being activated permits a stable and controlled firing operation.

H. Reset and Continuous Scanning

The reset and continuous scanning process is followed to maintain the system in its default position following every firing action and it is in that position to deal with the next target. After the mechanism of shooter has been triggered, internal flags on the Arduino like target detection, servo alignment status and relay activation state are reset. Servo motors are brought back to a neutral position and the next detections are guaranteed to be at the same position. This sensor which operates on ultrasonics then returns to continuous distance scanning with a constant time interval, which allows continuous tracking of the environment. This scanner is based on loop and thus enables real time tracking of objects, and quick reaction to new objects. In case the distance measured is more than the threshold, the system keeps in idle mode and proceeds with the scan. As a new object comes into the sensing range, the detection-to-firing workflow automatically restarts in a seamless manner, which guarantees autonomous efficient functioning.

Algorithm 1. Automated Radar Control Logic

```
BEGIN
  Initialize Arduino, UltrasonicSensor, Servo1, Servo2, Relay
  Set default servo positions
  Set Dth = threshold_distance
  LOOP forever
    D = UltrasonicSensor.readDistance()
    IF D <= Dth THEN
      T = 1
      Servo1.alignToTarget()
      Servo2.prepareTrigger()
      Salign = 1
      Relay.ON()
      Ron = 1
      F = T * Salign * Ron
      ActivateShooter()
    ELSE
      T = 0
      Salign = 0
      Ron = 0
      F = 0
      Servo1.reset()
      Servo2.reset()
    ENDIF
  ENDLOOP
END
```

Algorithm 1. shows the entire operational process of the real time air defense radar detection system. First, the Arduino becomes autonomous and initializes all the hardware connected with it, such as the ultrasonic sensor, servo motors, and relay and provides default positions to achieve precise scanning. The system constantly analyzes the distance measured by the ultrasonic sensor in a bid to detect any intruders. Then when an object of interest falls within the specified threshold the first servo rotates the shooter, and the second servo cocks the trigger system. At the same time, the relay also triggers the shooter to carry out the firing mission. In case of no object being detected, all the components are set back to default and the sensor starts scanning continuously again. The loop provides a prerequisite to autonomous, reliable and real time threat detection and response.

IV. Result and Discussion

The results of this study present a comprehensive analysis of the performance of the implemented system, highlighting its efficiency, accuracy and practical applicability in real-world scenarios. Key findings are organized based on the objectives of the study, allowing clear comparisons between expected and observed outcomes. Quantitative metrics, system behavior, and user-level improvements are systematically reported to demonstrate how the proposed framework enhances reliability, responsiveness, and overall effectiveness in its intended application environment.

TABLE I. Servo Response Analysis Across Rotation Angles

Angle (°)	Normalized Range	Performance
0	1.000	0.00
30	0.866	-2.50

DOI: 10.62647/IJITCE2025V13I4PP349-355

ISSN 2347–3657

Volume 13, Issue 4, 2025

60	0.500	-12.04
90	0.000	-200
120	0.500	-12.04
150	0.866	-2.50
180	1.000	0.00

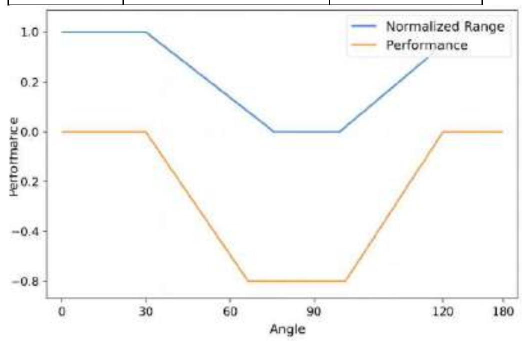

Fig.3. Servo Meter Performance Vs Voltage

Fig. 3. and table I demonstrate the change in the Normalized Range and Performance with the increase in the angle (0 to 180) and indicates a symmetric trend around the angle of 90. The Normalized Range decreases regularly between 1.000 at 0 o and the minimum of 0.000 at 90 o then continues increasing back to 1.000 at 180 o, a V-shaped trend. The same sympathy has a more pronounced series of drops, in performance: which starts with 0.00, descends to -2.50 at 30, to -12.04 deepest at 60 and 120, and to -200 lowest at 90. Beyond the midpoint, the values once more increase to 0.00 at 180. Comprehensively, both measures decrease to the center angle and achieve the worst results and shortest range at 90, then equally to both extremes.

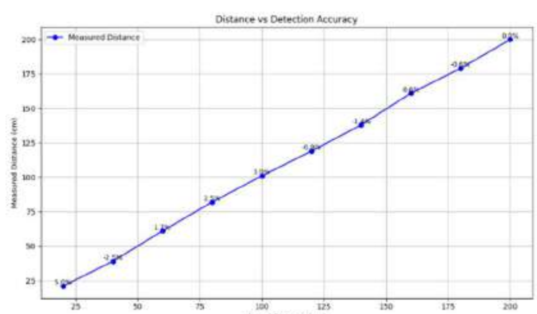

Fig.4.. Robot Walking Speed Vs Battery Voltage

Fig. 4. illustrates the correlation between the actual distance and the distance that the ultrasonic sensor in the radar system detected. The range of data points is 20cm to 200cm. An example would be that at 20 cm, the measured value of the distance is 21 cm, error of 5.0 percent and at 100 cm, the distance will be 101 cm, error of 1.0 percent. The graph draws a line which has markers to join the points and annotations to show the percentage error presented above the point so that the values do not overlap. In general, the sensor is highly accurate in its entire range of detection with error margins that are mostly less than 5 percent, which indicates that the sensor has good distance measurements when used in intruder detection in real-time.

TABLE II. . SERVO RESPONSE ANALYSIS ACROSS ROTATION ANGLES

Trial No.	Detection Time (ms)	Servo Alignment Time (ms)	Relay Activation Time (ms)	Total Response Time (ms)
1	35	45	**20**	100
2	38	47	**22**	107
3	36	44	**21**	101
4	37	46	**20**	103
5	35	45	**22**	102

The table II is a manifestation of the detection to firing response time of the automated radar system on a variety of trials. It describes three successive steps: the detection time that the ultrasonic sensor requires to sense the presence of an object, the servo alignment time that the shooter requires to control the servo to point at the object, and the relay activation time, which commences the firing. These three stages add together to make the total response time, which reflects the speed of response of the system. The results indicate that the timing is constant in all the trials and the range of total response times is 100-107ms. This proves the capability of this system to work in real-time and provide quick and faithful detection of the target and automatic shooting without human intervention.

A. Discussion

This study has been discussed with an emphasis on the effectiveness and reliability of the Arduino-based automated radar detection system. The ultrasonic sensor showed a high level of real-time measurements of distances with less error within a 20-200_{cm range making it precise in detecting intruders. Angular alignment was smooth with the help of servo motors, which meant that the shooter was focused on objects correctly, and this was proven by the similarity of the performance curve between 0 and 180 degrees. The firing mechanism and relay system worked on a regular basis with a total detection to rate of responding to the firing ranging between 100-107ms, which demonstrated that this system had great real-time potential. There were constant scanning and reset, which guaranteed continuous monitoring. All in all, these findings confirm the system as a cheap, effective, and autonomous way of military surveillance, with detection, alignment, and reaction being a solid and dependable automatic defense mechanism.

V. CONCLUSION AND FUTUREWORK

The analysis managed to design a real time air defense radar detection and firing system based on an Arduino based microcontroller, ultrasonic sensor, servo motors and a relay-controlled shooter mechanism. The system was found to be precise in the identification of objects within a specific threshold and the ultrasonic sensor was found to be reliable in the distance sensor

DOI: 10.62647/IJITCE2025V13I4PP349-355

ISSN 2347–3657

Volume 13, Issue 4, 2025

and low error at the range tested. The precision of the shooter was achieved by the use of servo motors to maintain a constant targeting movement and the firing operations were safely and controlled by the relay module. The time taken to detect and fire was found to be 100-107 ms, which implies that the system can operate in real-time and very fast. The scanning and reset could go on continuously which ensured that the system could automatically scan, track and react on intruders without human intervention. The findings validate the effectiveness of this low-cost system as an efficient and practical low-cost system, which can be used in military and perimeter security systems as an alternative to the more expensive traditional electronic surveillance technologies.

To work on this in the future, it is possible to explore several improvements to achieve the better performance and versatility of the system. First, the use of several ultrasonic sensors or the combination with infrared or LIDAR technology might help achieve higher detection and accuracy of larger or more intricate locations. Second, the use of AI-based algorithms to identify targets and classify them as a threat can be implemented to provide a selective response to the various types of intruders to decrease the number of false alarms. Third, the servo motors and shooter mechanism can be improved in order to increase speed, range, and precision of the fire. Lastly, remote supervision and analytics may be added through the inclusion of a wireless monitoring interface, the provision of real-time alerts, and the recording of data. Such advancements will not just make the system stronger and more stable, but also increase its use in various defense, security, and autonomous surveillance conditions. This study forms a base on autonomous, inexpensive, and scalable defense systems, and illustrates how small elements and smart control logic can offer real life and work solutions to the security issues of today.

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