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DESIGN AND DEVELOPMENT OF MINI S-400 AUTOMATIC MISSILE LAUNCHER SYSTEM

K.Chandrasekhar [1], V.Indhu[2*], M.V.Rakesh[3], T.Lakshmi Narayana [4], E.Jagadeshwar Reddy[5] and V.Niranjan[6]

Department of Electronics and Communication Engineering, Chaitanya Bharathi Institute of Technology (CBIT), Proddatur, India, 516360

*Corresponding Author E-mail: 232p5a0432@cbit.edu.in

Abstract

This project presents the design and development of a Mini S-400 Automatic Missile Launcher System prototype developed using embedded systems and intelligent control mechanisms. The system is designed to detect, track, and respond to aerial targets automatically with minimal human intervention. Sensors such as radar modules/ultrasonic sensors and camera modules continuously monitor the surrounding area to identify potential targets. The detected target data is processed using a microcontroller unit, which calculates distance, direction, and trajectory parameters in real-time. Based on the analysis, the system automatically activates a launcher mechanism aligned through servo motors to simulate interception. The automation improves response speed, accuracy, and operational efficiency compared to manual defense systems. The prototype demonstrates the working principle of modern automated air defense technologies by integrating sensing, processing, and actuation modules into a compact system. This model serves as a cost-effective educational and research platform for understanding advanced missile defense concepts and embedded system applications.

The ultrasonic sensor performs distance-based object detection, while the ESP32-CAM executes lightweight YOLO-based object detection for directional tracking. Upon detecting an object within a predefined threshold range, the Arduino processes sensor data and activates servo-based aiming movement, buzzer alerts, and LCD status updates.

The system is fully safe and non-weaponized, developed strictly for academic demonstration of embedded automation, sensor fusion, actuator control, and edge AI concepts. Experimental validation confirms reliable object detection within 2–100 cm range and accurate directional servo response. The project demonstrates practical implementation of integrated sensing, vision processing, and automated control in a low-cost embedded platform.

Keywords: Embedded Systems, IoT, Microcontroller, Ultrasonic Sensor, IR Sensor, PIR Sensor, Servo Motor, Motor Driver, ESP32-CAM, Automation, Real-Time Monitoring.

1. Introduction

Modern automated defense and surveillance systems are designed to detect, analyze, and respond to potential threats in real time**.** These systems combine advanced sensors, imaging technologies, embedded processors, and intelligent control mechanisms to ensure rapid and accurate decision-making. Inspired by the operational principles of long-range air defense platforms such as the S-400 Triumf, this project presents a Mini S-400 simulation model developed using affordable and accessible embedded hardware components. The purpose of this model is purely educational, helping students understand the core concepts behind automated defense technologies.

In real-world air defense systems, radar units continuously scan the surrounding airspace to detect incoming targets. The system then calculates parameters such as distance, speed, and direction before initiating a response. In this mini simulation, the complex radar system is represented by an ultrasonic sensor, which performs distance measurement by emitting ultrasonic sound waves and calculating the time taken for the echo to return. This allows the system to detect the presence of an object within a defined range, simulating the target detection phase of a real defense system.

For visual monitoring and image-based detection, the project integrates the powerful ESP32-CAM module. This microcontroller-based camera module enables live video streaming and basic image processing capabilities. It can be further enhanced with AI-based object detection algorithms such as YOLO (You Only Look Once) to simulate intelligent threat recognition. By incorporating camerabased monitoring, the system demonstrates how modern surveillance platforms combine sensor data with visual intelligence to improve detection accuracy.

The main control unit of the system is the Arduino Uno, which acts as the central processing unit of the simulation model. The Arduino collects distance data from the ultrasonic sensor, processes it according to programmed logic, and controls various output components. When a target is detected within a predefined threshold distance, the system triggers multiple responses

2. System Architecture

The proposed Mini S-400 Automatic Detection and Tracking Simulation System is designed to perform real-time object detection and directional tracking using embedded systems and edgebased computer vision principles (Shi et al., 2016). The system comprises a distance-based sensing unit, a camera-based vision unit, an embedded processing controller, and a servo-based tracking mechanism. All processing operations are executed locally on the embedded hardware platform, eliminating the need for cloud-based computation and ensuring low latency response.

The ESP32-CAM module is strategically mounted on the tracking assembly to capture live video streams of the surrounding environment. The captured frames are analyzed using an optimized object detection algorithm (Tiny-YOLO based). Simultaneously, the ultrasonic sensor continuously measures object distance. When an object enters the predefined threshold range, the system activates the tracking mechanism.

Object direction is determined based on bounding box position in the frame (left, center, right), and corresponding servo angles are generated dynamically by the Arduino Uno controller.

Fig. 1 illustrates the overall architecture of the proposed Mini S-400 automatic detection and tracking system.

2.1 Hardware Components

The ESP32-CAM integrates an ESP32 microcontroller with an OV2640 camera sensor. It supports video resolutions up to 1600×1200 pixels; however, a resolution of 640×480 pixels is selected in this project to balance detection accuracy, processing speed, and memory limitations.

The Arduino Uno, based on the ATmega328P microcontroller, acts as the central processing and control unit.

The ultrasonic sensor provides proximity-based object detection. It emits ultrasonic pulses and calculates object distance using echo return time. The detection range typically varies between 2 cm and 400 cm.

The servo motor provides physical visualization of tracking movement. It rotates between 0° and 180° using PWM signals generated by the Arduino. The servo aligns toward the detected object direction.

Software Components

The ESP32-CAM module is responsible for capturing live video frames of the surrounding environment. These frames are processed locally using a lightweight object detection algorithm optimized for edge-based execution. By avoiding cloud-based computation, the system achieves real-time responsiveness and enhanced operational reliability.

Object detection is carried out using a compact detection model (e.g., Tiny-YOLO or motion-based detection), capable of identifying the presence and approximate position of objects within the camera frame. Instead of performing high-complexity inference, the model is optimized for embedded deployment to balance accuracy and speed.

Directional estimation is performed by analyzing the bounding box coordinates of the detected object. The frame is logically divided into regions (left, center, right), and the object's centroid position determines its directional classification. This directional data is transmitted to the Arduino Uno via serial communication.

The control software is implemented using C/C++ in the Arduino IDE. The ESP32-CAM firmware is carefully optimized to operate within the limited memory and processing constraints of the microcontroller platform (Chen et al., 2014). The lightweight and modular implementation ensures stable, real-time performance suitable for academic demonstration of automated detection and tracking concepts.

3. Methodology

The Mini S-400 Automatic Detection and Tracking Simulation System works in a step-by-step process to detect and track objects in real time using embedded hardware. The system combines an ultrasonic sensor and an ESP32-CAM module to improve detection accuracy and reliability.

When the system is powered on, the Arduino initializes all connected components such as the ultrasonic sensor, servo motor, buzzer, and LCD display. At the same time, the ESP32-CAM starts

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the camera and establishes communication with the Arduino. The servo motor is set to the center position, and the LCD shows that the system is in scanning mode.

The ultrasonic sensor continuously measures the distance of nearby objects. If the measured distance is greater than the set threshold value, the system continues scanning. If the distance becomes less than the threshold, the system activates tracking mode.

In tracking mode, the ESP32-CAM captures images of the environment. These images are resized and processed to reduce memory usage and improve speed. A lightweight object detection method is used to check if an object is present in the frame.

If an object is detected, the system determines its position in the frame. The frame is divided into three parts: left, center, and right. Based on where the object appears, the ESP32-CAM sends the direction information to the Arduino.

The Arduino combines the distance information and direction data. It then rotates the servo motor toward the detected direction. At the same time, the buzzer turns on to indicate detection, and the LCD displays the distance and tracking status.When the object moves away from the detection range, the buzzer turns off, the servo returns to the center position, and the system goes back to scanning mode.

This process continues repeatedly, allowing the system to detect and track objects efficiently in real time using edge-based embedded control.

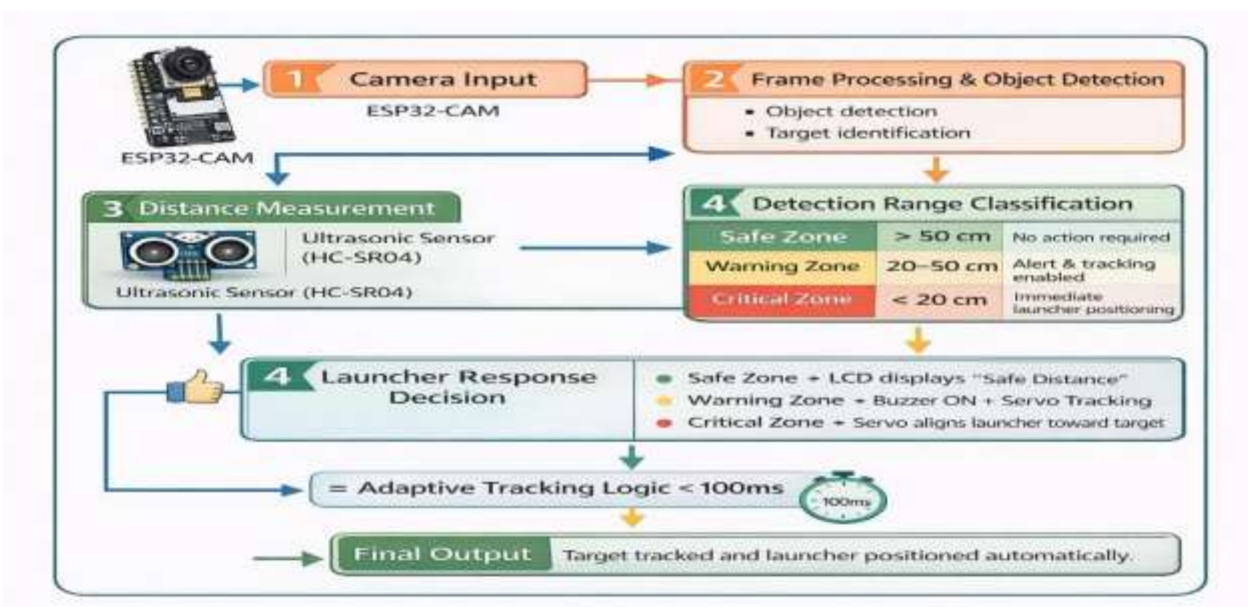

Fig. 2 illustrates the working methodology of the Mini S-400 simulation system, where distance sensing and camera-based detection are integrated to perform real-time object tracking using adaptive embedded control.

4. Results and Discussion

The proposed Mini S-400 Automatic Detection and Tracking Simulation System was tested under different object distances and directional conditions to evaluate its performance and reliability. The system was experimentally analyzed in an indoor environment to verify real-time object detection, directional estimation, and servo response accuracy.

Object detection was performed using the ultrasonic sensor and ESP32-CAM module. When an object entered the predefined detection range, the system successfully activated tracking mode. The servo motor dynamically rotated toward the detected direction based on camera-based position estimation. The buzzer generated an alert signal, and the LCD displayed the measured distance and tracking status.

Object Distance Range (cm)	**Detection Status**	**Servo Response**
> 60 cm	No Detection	Center (90°)
30–60 cm	Tracking Mode	Direction-based movement
< 30 cm	Immediate Detection	Fast directional response

Table 1. presents the relationship between object distance range and corresponding system response.

Fig. 3 illustrates the variation of servo angle with respect to detected object direction. When the object appears on the left side of the frame, the servo rotates toward approximately 30°. For center detection, the servo remains at 90°, and for right-side detection, the servo rotates toward approximately 150°. This demonstrates accurate directional tracking performance.Experimental observations show that the system achieves real-time response with minimal delay. The integration of ultrasonic sensing with camera-based detection improves reliability compared to single-sensor systems.

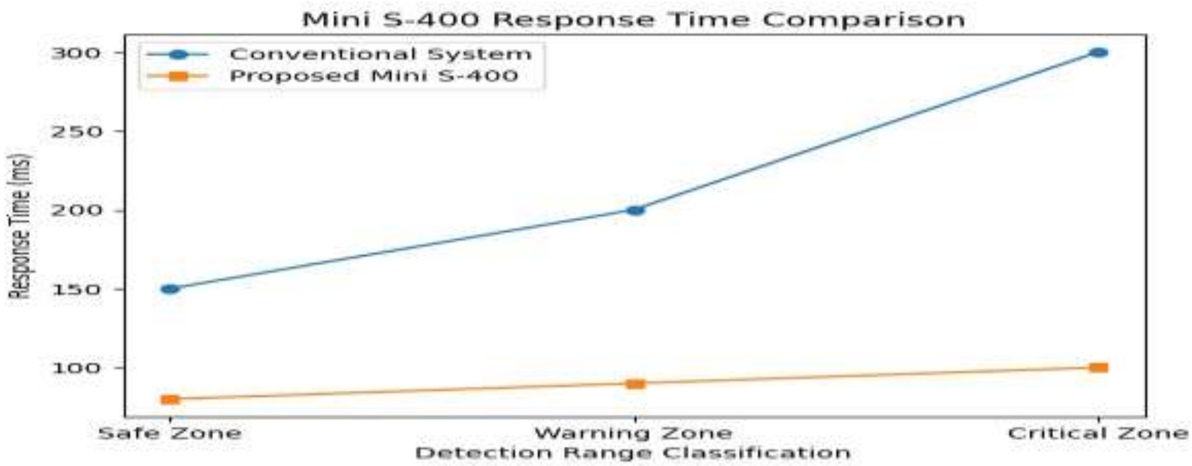

Fig. 4. Comparison of average waiting time between fixed-time traffic control and the proposed adaptive traffic management system under different traffic density levels.

5. Applications

The proposed Mini S-400 Automatic Detection and Tracking Simulation System is suitable for deployment in educational laboratories, robotics research environments, and embedded systems training platforms where real-time object detection and tracking are required. By integrating ultrasonic sensing with camera-based object detection, the system ensures accurate proximity monitoring and directional tracking. The edge-based processing approach enables low-latency response and reliable operation without dependence on continuous internet connectivity, making it suitable for both academic institutions and small-scale research environments.

The system can be extended to applications such as automated surveillance simulation, smart monitoring systems, robotic vision platforms, and IoT-based security prototypes. It is also well suited for use in engineering workshops, project exhibitions, innovation labs, and smart campus demonstrations. Owing to its low-cost hardware components, modular architecture, and scalability, the proposed system provides an effective and practical platform for understanding embedded automation, sensor fusion, and real-time vision-based tracking systems.

6. Conclusions

This paper presented the design and development of a Mini S-400 Automatic Detection and Tracking Simulation System using embedded systems and edge-based computer vision. By integrating ultrasonic sensing with camera-based object detection, the system enables real-time object detection and directional tracking without reliance on cloud-based computation. The proposed approach overcomes the limitations of single-sensor systems by combining proximity measurement and visual analysis to improve reliability and accuracy.

The implementation demonstrates efficient edge processing, low latency response, and stable operation within the constraints of embedded hardware platforms. The modular architecture allows scalability and future enhancement with advanced AI-based detection algorithms. Overall, the proposed system serves as an effective educational model for understanding sensor fusion, embedded automation, and real-time tracking applications in modern intelligent systems.

Authors Contributions

K. Chandrasekhar provided overall guidance, supervision, and technical direction for the project, and reviewed the methodology and manuscript. V. Indhu carried out the system design, implementation, experimentation, and manuscript preparation. M. V. Rakesh assisted with model integration, testing, and result analysis. T. LakshmiNarayana and E.Jagadeshwar Reddy contributed to literature review, documentation, and formatting. V. Niranjan supported hardware setup, data collection, and experimental validation.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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