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Safe Perimeter: An Embedded Real-Time Blind-Spot Detection and Pedestrian Warning System for School Buses

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Abstract

Pedestrian accidents from vehicle blind spots are a significant safety issue in a number of locations, including but not limited to, campuses, school transportation, parking lots, and urban settings. Currently available proximity warning systems typically only provide an alert to the vehicle operator and/or rely on costly detection equipment. Therefore, they are prohibitively expensive for many cost-sensitive applications. This paper describes a prototype proximity warning system designed to alert both the driver and the pedestrian should there be a risk of collision between the two. The prototype consists of an Arduino Nano microcontroller, HC-SR04 ultrasonic sensors, RF transmitter–receiver modules, LEDs, and an audible buzzer to allow for continuous monitoring of proximity and to transmit mobile alerts wirelessly in both directions. The results of the experiment show that reliable object detection can be accomplished at distances of up to 1.5 m, average alert response times will be approximately 300 ms, wireless communication has been achieved at distances greater than 10 m, and false triggers occurred at very low rates in controlled testing conditions. This system should provide a very economical, scalable and energy-efficient solution for improving pedestrian safety and could serve as a starting point for developing future intelligent transportation systems and smart mobility applications.

1. Introduction

An important issue affecting many aspects of the modern transportation system is how to keep pedestrians safe around large vehicles like school buses due to the large blind spots that restrict a driver's line of sight when operating a vehicle. Many pedestrian accidents occur each year when a pedestrian is boarding or exiting a large vehicle and/or when the driver is maneuvering the vehicle and not able to see a pedestrian in a blind spot.

Children are at an especially high risk because of their smaller stature and unpredictable behaviour, which means the ability to accurately monitor blind spots is critical for pedestrian safety.

Unfortunately, these traditional safety systems, such as rear-view mirrors, warning signs, and being vigilant, cannot eliminate pedestrian accidents that result from blind spots. Advanced Driver Assistance Systems (ADAS), camera-based monitoring, radar or LiDAR technologies have significantly improved vehicle perception, but these solutions are usually expensive (look at the installation cost) and require complex processing capabilities to operate, as well as needing to be regularly maintained. As a result, ADAS have traditionally not been installed in school buses or any cost-sensitive environment.

Innovations in wireless communication and embedded devices have resulted in smaller, low-cost pedestrian detection options. Ultrasonic technology offers an economical solution for short-range object detection due to its relatively low price and power usage, as well as its ability to measure distance reliably (time of flight). Therefore, embedded microcontrollers using ultrasonic sensors can provide near real-time proximity monitors without the need for the complex images, needs, or techniques typical of traditional imaging systems.

The purpose of this study was to develop a system designed to provide real-time pedestrian proximity warnings to support improved pedestrian safety around school buses and similar vehicles, called "Safe Perimeter." The system is based on the Arduino Nano microcontroller and HC-SR04 ultrasonic sensor, which continuously measures the area around the vehicle. Once a pedestrian enters the defined "near" area, the pedestrian receives a wireless warning signal, which will be utilized by both the vehicle driver and the pedestrian to respond immediately. Furthermore, the wireless system provides enhanced flexibility in deployment at low hardware expense and requires little power.

This study's prototype system was tested in controlled laboratory testing to characterize detection capability, reaction time, and wireless communication performance. The results showed that pedestrians could be detected successfully from approximately 1.5 m away; the average time to create and send alerts for detected pedestrians was approximately 300 msec; and communications from the prototype system to either remote receivers were successful at distances of up to 10 m. Experimental tests provide evidence that using the system to provide the simultaneous alerting of drivers and pedestrians for real-time applications to increase pedestrian safety will yield viable results.

The main contributions of the study are:

- A low-cost, commercially available, wireless pedestrian proximity warning system based on commercially available, embedded technology.
- The combination of ultrasound-based detection methods and radio frequency-based communications to provide real-time simultaneous alerts.
- The project will include testing of the achieved system using controlled testing to examine its detection accuracy, response time, and communication reliability.
- A demonstration of a scalable safety system that can be utilized for other kinds of vehicles (e.g., school buses, campus vehicles) as well as catering to future developments in intelligent transportation systems.

The rest of this document is structured in the following way: literature overview in Section 2 and identifying the gap in the current research; the system methodology and hardware architecture are described in Section 3; evaluation of the experiments in Section 4 and conclusions in Section 5.

2. Literature Review

The increase in accidents involving vulnerable road users (VRUs), particularly pedestrians close to large vehicles, has led to increased research on VRU safety within intelligent transportation systems (ITSs). Conventional safety measures, such as mirrors and manual observation by the driver, do not adequately eliminate some risks associated with blind spots; this is especially true for VRUs outside the driver's field of view, such as school buses. As a result, researchers have begun to investigate the use of advanced sensing technology to improve real-time pedestrian detection and collision avoidance [1, 2].

Researchers have investigated a range of technologies, including camera-based systems, radar-based systems, and laser (LiDAR)-based system, for the purpose of detecting pedestrians from vehicles, improving driver awareness of the environment, and enhancing vehicle safety. These systems combine computer vision, machine learning, and the fusion of multiple sensors to provide accurate object recognition and to detect objects at long ranges. However, these systems typically require expensive hardware, a high degree of computational power, and significant calibration complexities, making them less suitable for low-cost transportation applications [3]–[6].

Ultrasonic sensor technology is low-cost, simple, and accurate for short-range pedestrian detection because of the principle of measuring distance through the time it reaches sound waves to travel to an object and be back (TOF). Embedded systems that contain ultrasonic sensors and host microcontrollers perform satisfactorily for many uses (including obstacle detection, parking assistance, and blind-spot monitoring), while consuming low amounts of power and requiring little processing. The characteristics of ultrasonic sensor technology make it especially well-suited for compact, real-time safety system applications. [1, 7]

Wireless communications also improve the functionality of pedestrian safety systems by allowing warning signals to be transmitted rapidly from sensors to alerting devices. RF (radio frequency) communications are low-latency, have low power use, and are straightforward to implement in short-range safety applications. Wireless communications combined with proximity detectors in embedded systems provide simultaneous alerts to drivers and pedestrians, decreasing response time and reducing the chance of collisions. [9, 10]

Although pedestrian detection has greatly advanced with intelligent systems, there is still a high demand for low-cost and scalable safety systems that utilize real-time sensors and wireless alert mechanisms. This need is especially significant for school transportation and regions where the deployment of lower-cost hardware, ease of installation, and highly reliable performance is typically seen as an everyday occurrence. [2, 12]

While existing pedestrian detection systems provide high accuracy with cameras, radars, and LiDAR devices, the hardware is typically costly, places heavy demands on the processing ability of the detection hardware, and is difficult to install. Some systems currently in use exist primarily to alert the vehicle driver and only rarely provide near-instant alerts to the pedestrian as well. A low-cost, embedded wireless proximity warning system that would effectively provide vehicle drivers and pedestrians with reliable and real-time alerts would meet the needs of both school bus applications and other public safety-related applications.

3. System Design and Methodology

3.1 Overall System Architecture

The Safe Perimeter system was created to use real-time wireless detection of pedestrian proximity and warn drivers as a means of improving safety around school buses and other similar vehicles. This system utilizes an HC-SR04 ultrasonic sensor to provide continuous monitoring of areas surrounding the vehicle and detects pedestrians who enter predefined safety zones. The measured distance from the ultrasonic time-of-flight (ToF) method is processed by an Arduino Nano microcontroller, which determines a warning level when a pedestrian enters the warning or critical zone. Once a pedestrian is detected, the controller wirelessly transmits an alert signal to the receiver unit; once received, the receiver unit activates visual and audible warnings. The driver and nearby pedestrians receive notifications in parallel without employing many hardware components and using little energy.

3.2 Working Principle

An Arduino Nano and ultrasonic sensor begin to function after being powered on; the ultrasonic sensor will measure the distance from vehicles and pedestrians by sending out ultrasonic waves. The distance measured will be compared against defined safety thresholds to determine whether an alert should be triggered. Any time a pedestrian enters the warning zone or critical zone an appropriate alert will immediately be activated. The execution of this process will result in continuous monitoring and quick response while the devices are operational.

Equation (1)

D=(v*t)/2

where

D = Distance between sensor and object (m)

v = Speed of sound in air (343 m/s)

t = Echo travel time (s)

3.3 Hardware Configuration

The two main components of the prototype are the alert unit and sense unit. The sensing unit is made up of three electronics; a microcontroller (Arduino Nano), an ultrasonic sensor (HC-SR04), and an RF transmitter. The sensing unit will sense the pedestrian and send a wireless signal. The alert unit consists of an RF receiver, an Arduino (Arduino Nano), LED’s to show when to alert, and a piezoelectric buzzer that generates an alert sound for the pedestrian. All the elements were selected based on cost; low power consumption, and ability to be integrated into a small low-cost pedestrian safety system.

Table 1
Hardware components used in the proposed Safe Perimeter system.

Component	Specification	Function
Arduino Nano	ATmega328P, 16 MHz	Embedded controller
HC-SR04 Ultrasonic Sensor	2–400 cm	Distance measurement
RF Transmitter (433 MHz)	ASK Modulation	Wireless data transmission
RF Receiver (433 MHz)	ASK Modulation	Wireless data reception
LED Indicator	5 V	Visual warning
Piezoelectric Buzzer	5 V	Audible warning

3.4 Safety Zone Classification

The measured distance is categorized into three levels of safety to determine the correct level of warning to be provided. Objects that are sensed beyond the monitoring threshold of the system are considered safe. As pedestrians enter the warning zone and critical zone the level of warning increases with the level of alert to the pedestrian. This thresholded classification reduces the chance of false alarms being triggered by the pedestrian while providing timely notification of an impending hazard.

Table 2
Proximity-based safety zone classification and corresponding alert mechanisms.

Distance Range	Safety Zone	Alert Mechanism	System Response
> 100 cm	Safe	None	Continue monitoring
50–100 cm	Warning	LED + Buzzer	Notify pedestrian
≤ 50 cm	Critical	LED + Buzzer + Vibration	Notify pedestrian and driver

4. Experimental Setup and Performance Evaluation

4.1 Experimental Setup

To develop an Arduino nano microcontroller proto-type for the Safe Perimeter project, we used an HC-SR04 ultrasonic sensor, a set of RF transmitter and receiver modules, LED indicators, a piezoelectric buzzer, and a regulated power supply. An illustration of the completed prototype is provided in Fig. 5. The testing occurred in a controlled laboratory environment, where multiple items were placed at set distances from the ultrasonic sensor. During each test, each item’s distance was measured, wireless communications functionality was assessed, response time was measured, and an alarm was sounded on each trial to provide an overall level of assurance for the system as a whole. A number of varieties of trials were conducted to assess the reproducibility and dependability of the prototype.

4.2 Performance Evaluation

The developed prototype was able to successfully detect pedestrians entering the monitored area and send out simultaneous warning alerts via the wireless communication link. During experimental testing, the prototype worked consistently through multiple tests and trials. The HC-SR04 ultrasonic sensor used in the prototype was able to reliably detect objects up to 1.5 m from the sensor, while the RF communication module used in this system was able to maintain stable wireless communications with good reliability up to approximately 10 m away from the vehicle. The average alert response time was approximately 300 ms, which permitted an alert to be received by both the person driving the vehicle and the pedestrian as quickly as possible. In addition, the prototype had a very low false trigger rate, thus providing a reliable threshold-based decision-making process while tested in a controlled laboratory environment. The results of this prototype demonstrate that the proposed architecture is appropriate for the short-range pedestrian safety application for which it was designed.

Table 3
Experimental Results

Parameter	Target	Achieved
Detection Range	150 cm	150 cm
Alert Response Time	< 500 ms	~ 300 ms
RF Communication Range	10 m	~ 10 m
Driver Alert	On Detection	Working
Pedestrian Alert	On Detection	Working
False Trigger Rate	Minimal	Low

4.3 Comparative Discussion

The Safe Perimeter system illustrates how a low-cost embedded hardware solution can deliver reliable pedestrian safety without being dependent on computationally expensive sensing techniques (cameras and LiDAR). This proposed architecture results in low implementation costs, lower power usage, and less complicated installations, while providing adequate short-range detection performance. Conversely, many of today's blind-spot monitoring systems simply warn a driver of an impending collision; however, this developed solution allows both the pedestrian and the driver to receive simultaneous notifications via wireless communications, providing both the pedestrian and the driver increased situational awareness while reducing the potential for a collision to occur between them.

The prototype's performance during controlled laboratory evaluations will differ from that in actual outdoor conditions. Specifically, the high level of precipitation, uneven surfaces in the real world, and unpredictable moving objects may all affect how well ultrasonic sensing works. To increase robustness

in detecting objects in more complex outdoor environments, future implementations will use camera or radar sensors, employing sensor fusion methodologies to create a more reliable overall solution.

Table 4
Comparison with Existing Systems

Feature	Camera-Based	LiDAR-Based	Proposed Safe Perimeter
Real-Time Detection	✓	✓	✓
Low Cost	☒	☒	✓
Low Power Consumption	☒	☒	✓
Wireless Alerts	Partial	Partial	✓
Driver Warning	✓	✓	✓
Pedestrian Warning	Partial	Partial	✓
Easy Deployment	Moderate	Difficult	✓

4.4 Limitations

Through the process of ultrasonic-sensor testing in a purposely-built finished prototype. The following are some of many environmental conditions that can potentially affect detection accuracy: heavy rain, reflecting on irregular-shaped objects like chairs, as well as pedestrians walking about. Continued research and development will allow for more development/testing to support additional sensor technologies such as camera/radar fusion methodologies, which will further develop and improve detection accuracies; thereby making final prototypes available for testing.

5. Conclusion and Future Work

5.1 Conclusion

Safe Perimeter is a low-cost, wireless pedestrian detection and warning system designed to provide real-time alerts of pedestrian traffic in school bus and other transportation environments. It consists of an Arduino Nano microcontroller, an HC-SR04 ultrasonic sensor, and RF communication modules that allow continuous monitoring of pedestrian proximity and produce simultaneous warnings (using ultrasonic distance measurement and wireless bidirectional alerts) to both pedestrians and drivers.By combining these two methods of detecting pedestrians, Safe Perimeter provides an effective solution for reducing accidents and collisions due to driver blind spots, while keeping hardware requirements, power consumption, and cost to a minimum.

The effectiveness of this prototype was demonstrated by evaluating its performance in an experimental setting. Results showed that the system achieved reliable object detection up to 1.5 m, produced an average alert response time of approximately 300ms, displayed stable wireless communication up to 10

m, and had a low false alarm rate when tested in identical conditions.Thus, the experimental test results provide evidence that the proposed system will work for real time applications involving pedestrian safety. Overall, this prototype has demonstrated that a low cost embedded architecture is capable of providing an effective and scalable long-term solution to pedestrian safety issues for school buses and other campus vehicles as well as for any other type of low-speed transportation system.

5.2 Future Work

The future of this project is to improve the functionality and durability of the achieved results through the use of advanced sensor and intelligent processing technologies. By replacing the ultrasonic sensor for human detection with a camera-based approach using the ESP32-CAM and lightweight deep learning models such as TensorFlow Lite, a human-specific detection option will be available while reducing false alarms. The sensor system of ultrasonic, visual, and radar technologies can enhance the accuracy of detection in a variety of adverse environmental conditions.

Additionally, future enhancements of this system will include support for multiple tracks and vehicles, IoT (Internet of Things) connectivity for remote monitoring and data logging, and large-scale field testing in real-world traffic conditions. These enhancements will enhance the Safe Perimeter System's scalability and reliability, furthering its potential use in next-generation intelligent transportation systems and smart mobility applications.

Declarations

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Ethics, Consent to Participate, and Consent for Publication

Not applicable.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Author Contribution

V.S.R. conceptualized the study, designed the system architecture, coordinated the project, developed the hardware and software modules, performed experiments, analyzed the data, prepared the figures,

and wrote the original manuscript draft. C.U.R. contributed to the system design, literature review, hardware implementation, experimental validation, data collection, data analysis, manuscript writing, and editing. H.S. contributed to sensor integration, embedded system development, experimental setup, testing, result interpretation, manuscript review, and editing. S.M.S. contributed to software development, wireless communication implementation, data processing, visualization, performance evaluation, manuscript editing, and proofreading. S.H. contributed to methodology development, experimental verification, result validation, manuscript formatting, critical review, language editing, and final proofreading. All authors discussed the results, reviewed the manuscript, approved the final version, and agreed to be accountable for all aspects of the work.

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Figures

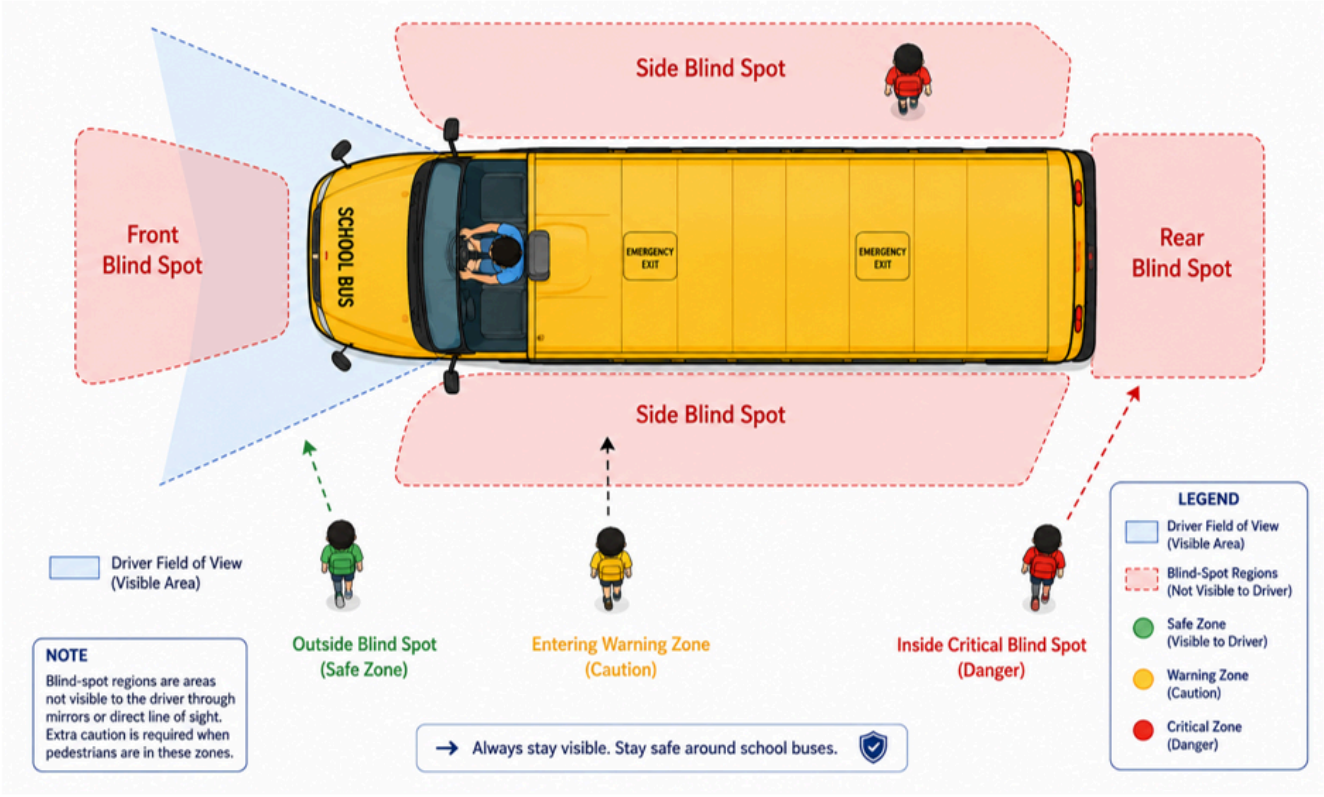

Figure 1

Blind-spot regions around a school bus and the associated pedestrian collision risk.

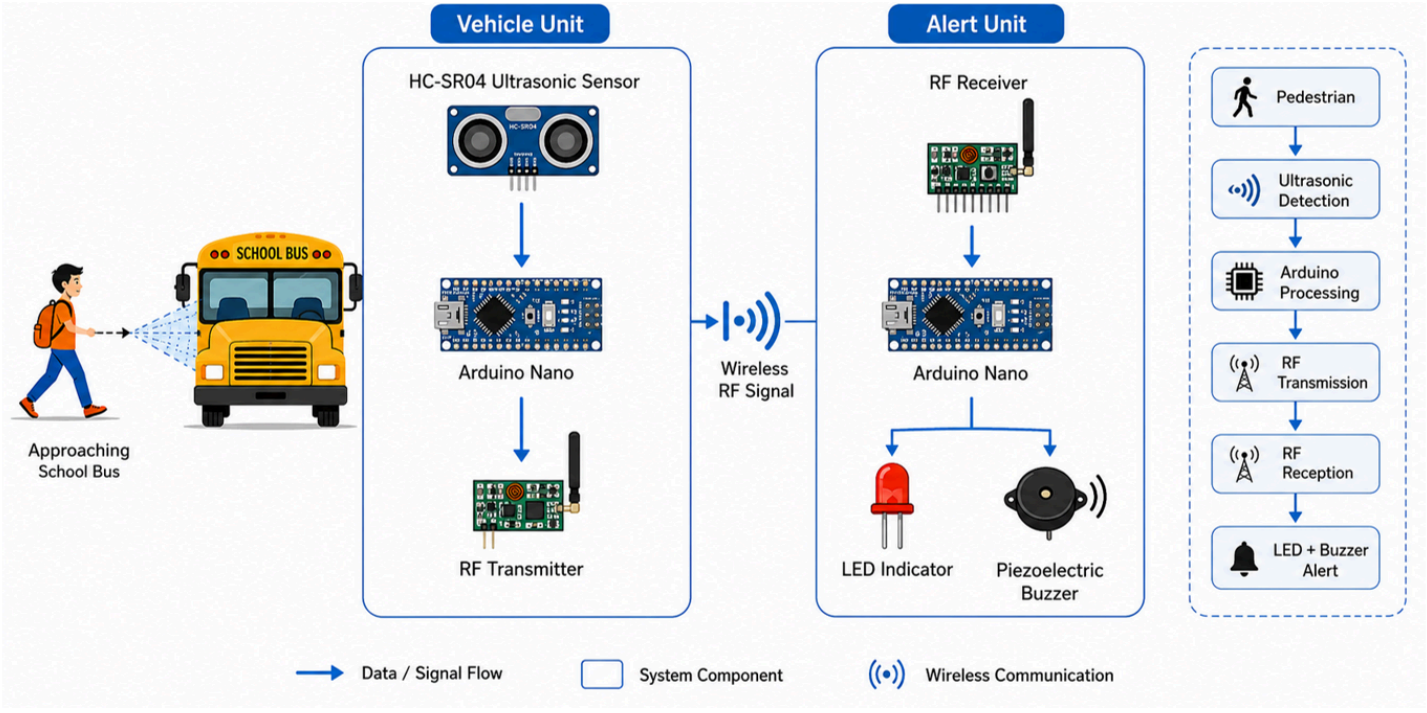

Figure 2

Overall architecture of the Safe Perimeter wireless pedestrian warning system.

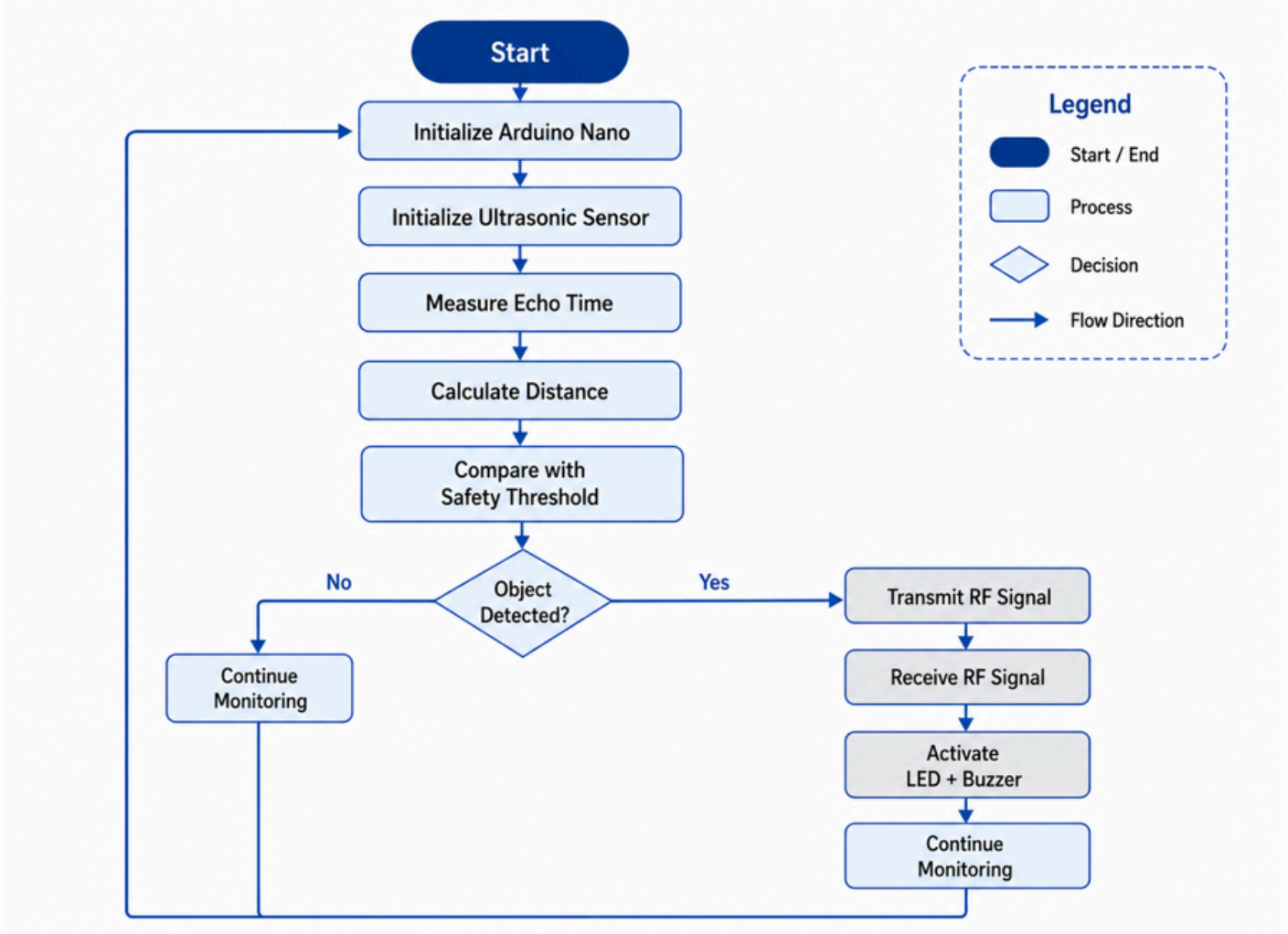

Figure 3

Operational workflow of the Safe Perimeter system.

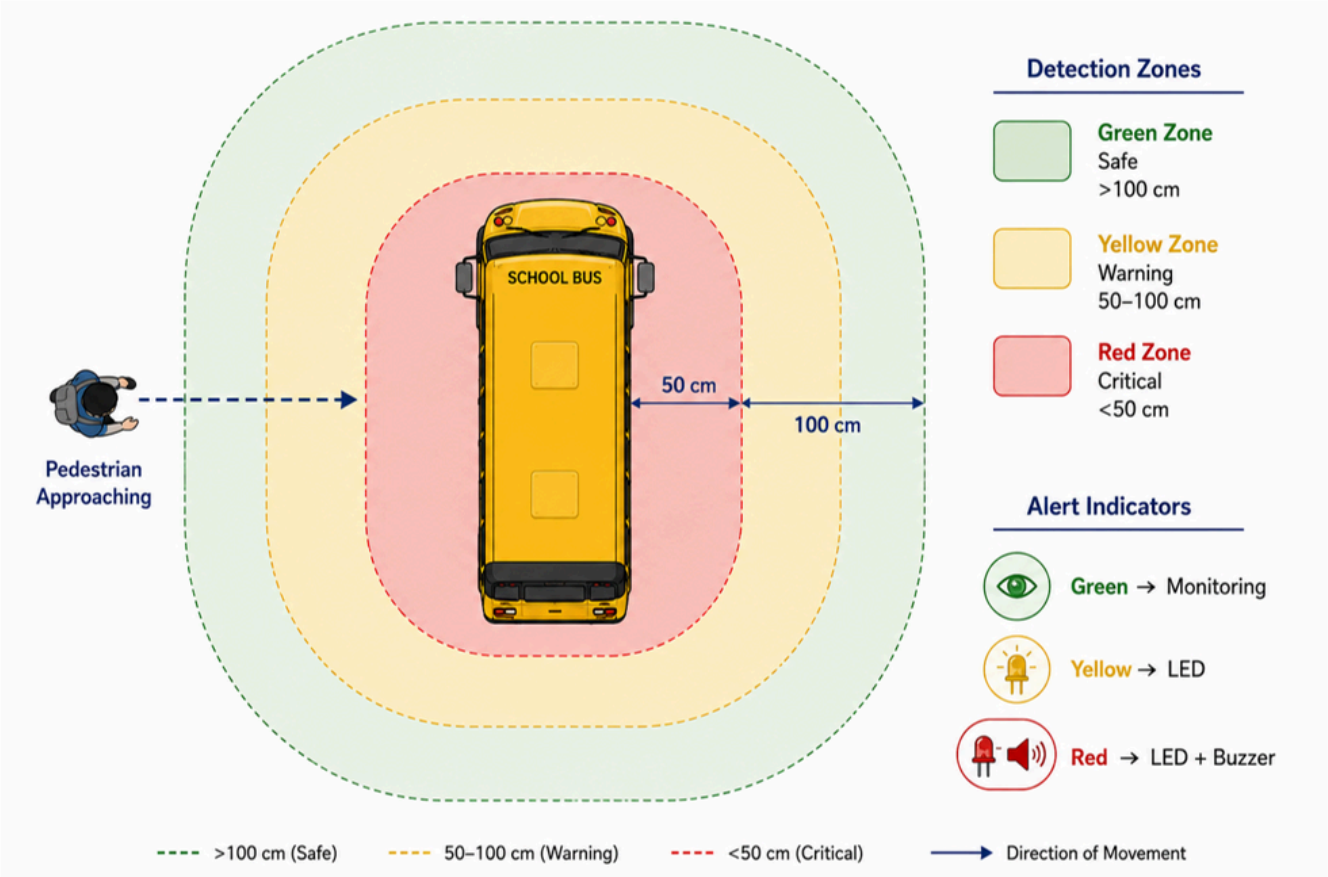

Figure 4

Distance-based safety zones used by the Safe Perimeter system.

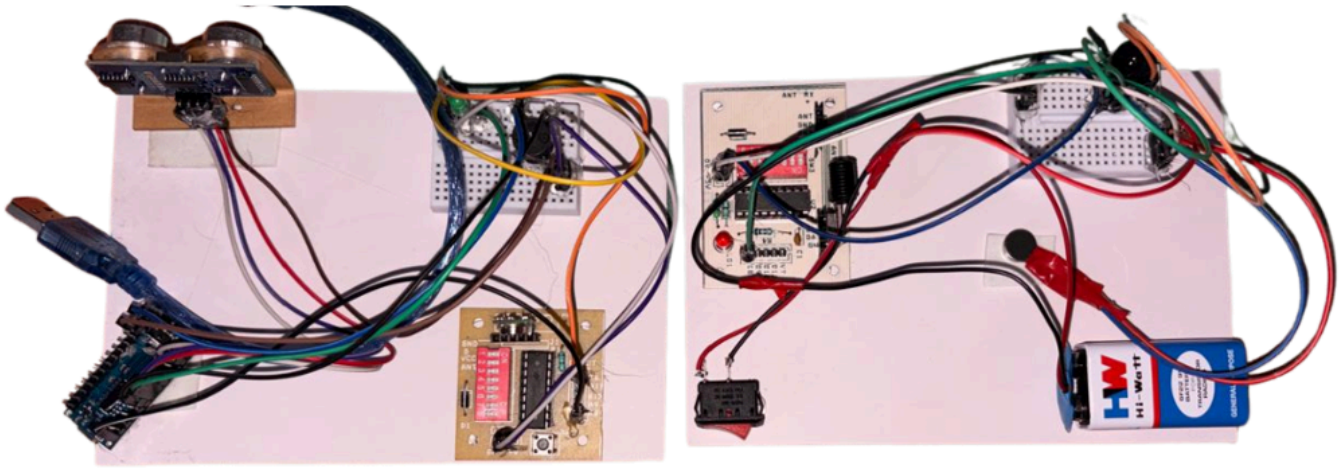

Figure 5

Developed Safe Perimeter Prototype

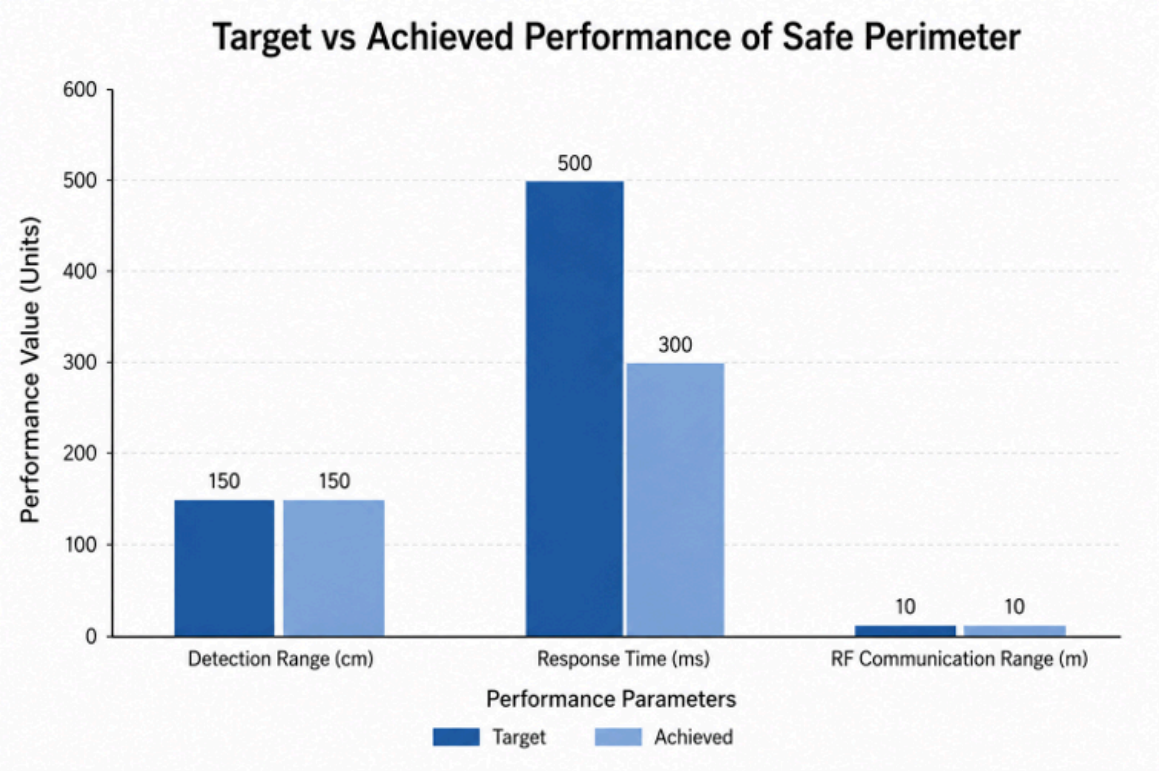

Figure 6

Comparison of target and experimentally achieved system performance.