Design and Implementation of an Ultrasonic Sensor-Based Blind Spot Monitoring Prototype for Vehicle Safety

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***Abstract*—Blind spots are one of the main contributing factors to traffic accidents in four-wheeled vehicles due to the driver's limited visibility in certain areas surrounding the vehicle. This research presents the design and implementation of a blind spot monitoring prototype using ultrasonic sensors to detect objects in blind spot areas and provide real-time warnings to the driver. The system consists of four ultrasonic sensors (HC-SR04 for the front and JSN-SR04T for the sides and rear), an Arduino Mega 2560 microcontroller, a 20×4 LCD for distance display, and a buzzer for audible alerts. Sensor calibration was conducted to ensure measurement accuracy, achieving an average error rate of 0.77%. The prototype was tested under various simulated scenarios, including static and moving objects in different blind spot zones. The results show that the system successfully detected vehicles, motorcycles, and pedestrians in almost all testing conditions, with an average response time ranging from 0.20 to 0.35 seconds. However, the system faced limitations in detecting objects moving at speeds above 30 km/h, which is inherent to ultrasonic sensor technology. Despite this limitation, the proposed system offers a cost-effective alternative to radar- or camera-based blind spot detection systems, making it more accessible for a wider range of vehicles. The findings indicate that the developed prototype can effectively improve driving safety and has the potential for further enhancement through integration with IoT and advanced sensor fusion technologies.**

Keywords*—Blind spot monitoring, ultrasonic sensors, vehicle safety, Arduino, prototype system, traffic safety.

I. INTRODUCTION

Road traffic accidents are a major public safety concern, particularly in developing countries such as Indonesia. One of the key factors contributing to these accidents is the presence of blind spots, which refer to areas around the vehicle that are not directly visible to the driver through the rear-view or side mirrors [1][2][3]. These areas significantly increase the risk of collision, especially during lane changes, overtaking, or turning maneuvers, where nearby objects or vehicles may go undetected by the driver.

A study conducted in Malaysia highlighted that motorcyclists are among the most vulnerable road users when it comes to blind spot-related incidents. The study also found that many drivers tend to underestimate the dangers posed by blind spots [1]. Other research has shown that the size and position of blind spots vary depending on vehicle dimensions, mirror placement, and driver posture [4]. These findings underscore the importance of having reliable blind spot detection systems installed in vehicles.

According to the World Health Organization (WHO), more than 1.19 million deaths occur globally each year due to road traffic accidents [5]. In Indonesia, police statistics indicate that over 100,000 traffic accidents are recorded annually, many of which are caused by limited driver visibility [6]. This situation highlights the urgent need for accessible safety technologies that can be implemented across a wide range of vehicle types.

Although several commercial blind spot monitoring (BSM) systems are available in the market, most of them rely on expensive technologies such as radar or cameras. These systems are typically integrated into high-end vehicles, making them less accessible for use in lower-cost vehicles [7][8][9] In addition, some of these systems are less effective under low-light or adverse weather conditions, which reduces their reliability in everyday scenarios [10].

Ultrasonic sensors have emerged as a cost-effective solution for short-range object detection and are commonly used in applications such as parking assistance. While they have limitations in terms of detection range and object speed sensitivity, they remain suitable for close-proximity monitoring tasks such as blind spot detection [11][12][13]

This research presents the design and development of a prototype blind spot monitoring system based on ultrasonic sensors. The system is designed to detect the presence of nearby objects, including vehicles, motorcycles, and pedestrians, in blind spot areas around a four-wheeled vehicle. It provides real-time feedback to the driver through an LCD screen and an audible buzzer. The prototype is implemented using the Arduino Mega 2560 microcontroller along with ultrasonic sensors (HC-SR04 and JSN-SR04T). The system has been calibrated and tested under various conditions to evaluate its performance. The goal of this study is to provide a low-cost and practical alternative to existing BSM technologies in order to enhance vehicle safety and reduce traffic accidents.

The prototype is designed primarily for blind spot monitoring in close proximity zones where ultrasonic sensors perform reliably. Given the detection range (0.2–6 m) and fast response time, the system is also suitable for related short-range driver assistance functions, including parking assistance, low-speed collision warning, and cross-traffic alert. However, it is not intended for long-range detection of high-speed approaching vehicles, which remains the domain of radar- and camera-based systems.

II. METHODOLOGY

A. System Overview

The proposed blind spot monitoring system consists of ultrasonic sensors placed at the front, sides, and rear of a scaled vehicle prototype. These sensors detect objects in the blind spot zones and transmit the data to an Arduino Mega 2560 microcontroller. The processed data is then displayed on a 20×4 LCD screen, while an active buzzer provides an audible warning. Fig. 1 shows the overall system block diagram, illustrating the interaction between input sensors, the processing unit, and the output devices. Fig. 2 presents the overall system flowchart, detailing the sequential process from data acquisition by the ultrasonic sensors to alert generation and display output.

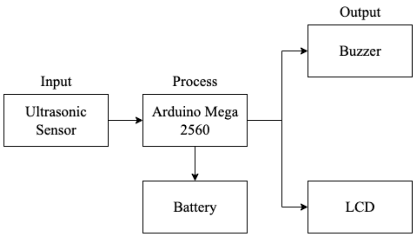


Fig 1. Block diagram of the ultrasonic-based blind spot monitoring system.

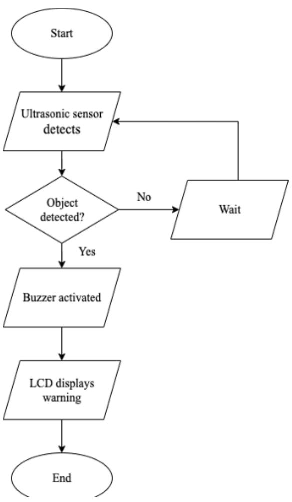


Fig 2. Flowchart of the Overall Blind Spot Monitoring System.

B. Overall System Circuit

The electrical connections between the Arduino Mega 2560, HC-SR04 ultrasonic sensor at the front, JSN-SR04T ultrasonic sensors at the sides and rear, LCD display, and active buzzer are depicted in Fig. 3. The system is powered by a 9 V DC battery, as shown in the wiring configuration.

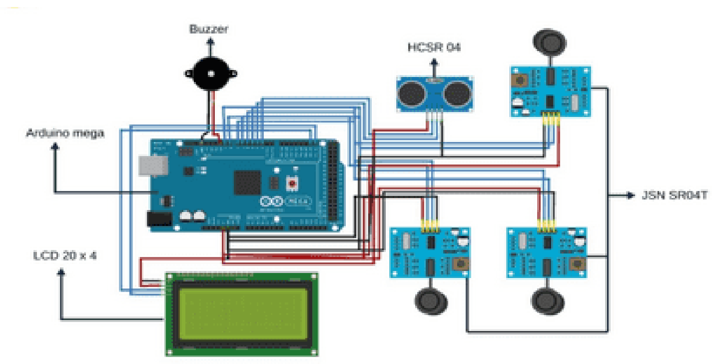


Fig 3. Overall system circuit diagram.

C. Hardware Component

The main hardware components used in the research are summarized in Table 1, including their technical specifications obtained from manufacturer datasheets.

TABLE 1. HARDWARE COMPONENTS AND SPECIFICATIONS

Component	Description
Arduino Mega 2560	54 digital I/O pins, 16 analog inputs; 5 V DC operation; ATmega2560, 16 MHz clock
HC-SR04 Sensor	Ultrasonic sensor (front); range: 2–400 cm; accuracy ±3 cm; response time < 100 ms
JSN-SR04T Sensor	Ultrasonic sensor (sides & rear), waterproof; range: 20–600 cm; accuracy ±1 cm; response < 100 ms
LCD Display (20 × 4)	HD44780 controller; 4 lines × 20 characters; operates at 5 V DC
Buzzer (Active, 12 V)	Generates audible alarm at ~3000 Hz; operates 6–15 V DC; max current ~350 mA
9 V DC Battery	Power source during tests; nominal 9 V; ~500 mAh capacity

D. Prototype Configuration and Sensor Placement

A 1:17 scale vehicle prototype was constructed to simulate the blind spot monitoring system. Blind spot distances from a real vehicle were measured and proportionally scaled down for the prototype. To account for the minimum detection range of the JSN-SR04T sensors, extenders were added to adjust blind spot zones into detectable ranges.

Fig. 4 shows the blind spot coverage areas for the prototype, including front, rear, and side zones with their scaled distances.

Fig. 5 shows the top view of the prototype with labeled hardware components, including ultrasonic modules, Arduino Mega controller, jumper wires, and buzzer placement.

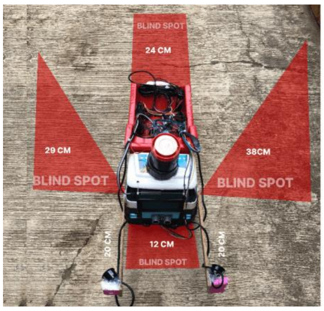


Fig 4. Overall system circuit diagram.

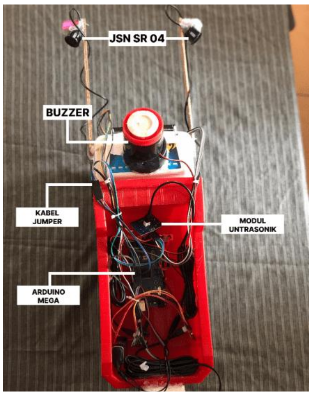


Fig 5. Top view of the scaled prototype with labeled hardware components.

E. Scale Adaptation

The prototype design applied a geometric scaling approach to replicate the blind spot regions of a full-sized passenger vehicle in a controlled laboratory model. Blind spot distances were first measured on a reference vehicle, representing the zones in which objects are not directly visible to the driver through mirrors or peripheral vision.

A uniform scale factor was applied to convert real vehicle measurements into prototype dimensions. The scaling ratio was determined by dividing the desired prototype dimensions by the actual vehicle dimensions, ensuring proportional relationships between sensor positions and the corresponding detection zones. This process allowed the prototype to simulate realistic blind spot coverage areas while maintaining compatibility with the smaller testing environment.

The resulting scaled values, shown in Table 1, were used as the primary basis for sensor placement and calibration. These scaled distances directly determined the coverage limits for each ultrasonic sensor, ensuring that detection ranges in the prototype would correspond proportionally to those of a real vehicle.

TABLE 1. BLIND SPOT DISTANCES: REAL VEHICLE VS PROTOTYPE SCALE

Position	Real Distance (cm)	Scaled Distance (cm)
Front	200	12
Rear	400	24
Left	300	18
Right	150	9

Maintaining accurate scale adaptation is crucial for the validity of the experimental results, as it ensures that the detection performance observed in the prototype can be extrapolated to full-scale applications under similar geometric conditions. This approach is consistent with established practices in scaled vehicle prototyping for sensor system evaluation [14].

F. Sensor Calibration Method

Prior to scenario-based testing, a calibration procedure was conducted to verify the accuracy of the ultrasonic sensors used in the prototype. The HC-SR04 module was installed at the front position, while JSN-SR04T modules were positioned on the left, right, and rear sides. Calibration aimed to minimize systematic measurement deviations and ensure that sensor readings closely matched actual distances measured by a reference instrument.

The reference distances were set at 150 cm, 200 cm, 300 cm, and 400 cm, measured precisely using a calibrated laser distance meter. For each distance, the sensor output was recorded ten times, and the mean value was computed to reduce the effect of random noise.

To assess sensor reliability and precision, repeated measurements were taken at fixed reference distances (150, 200, 300, and 400 cm). Each condition was repeated 10 times over a fixed sampling window, and the mean, absolute error, and percentage error were computed. This procedure evaluates the repeatability of ultrasonic measurements under controlled conditions.

The percentage error for each measurement was calculated using the standard absolute percentage error formula, which is consistent with established measurement accuracy methodologies [15], [16]:

$$Error(\%) = \left|\frac{Measured\ Value - Reference\ Vale}{Reference\ Value}\right| \times 100\% \quad (1)$$

Calibration was deemed successful if the percentage error remained below 1% for all tested distances. This threshold aligns with findings from ultrasonic sensor evaluation studies, where calibrated JSN-SR04T sensors achieved mean absolute percentage errors as low as 0.46 % [17], and agricultural canopy height calibration studies reported relative errors below 0.51 % [18]. Similar accuracy levels (< 1%) have been observed in long-range ultrasonic sensing applications [19].

G. Research Flow

The research process followed a structured methodology consisting of five main stages: research design, quantitative approach, direct experimentation on the prototype, measurement of object detection effectiveness, and testing under controlled conditions, as illustrated in Fig. 5.

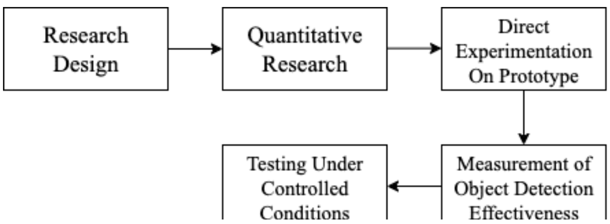


Fig 5. Diagram of the Research Process.

H. Testing Scenarios

The testing process was conducted under controlled conditions to evaluate the effectiveness of the blind spot monitoring system in detecting objects under various circumstances. A total of 22 testing scenarios were designed, covering variations in:

- Object type: including small-scale vehicles, medium-sized vehicles, and pedestrians.
- Object motion: stationary, slow-moving, and fast-moving.
- Approach direction: front, sides, rear, and diagonal angles relative to the prototype.
- Object distance: ranging from 20 cm to 1 meter.

Table 2 presents a summary of the 22 scenarios, including the scenario number, scenario illustration, and scenario description.

TABLE 2. HARDWARE COMPONENTS AND SPECIFICATIONS

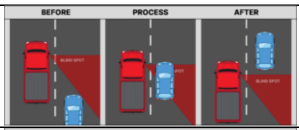
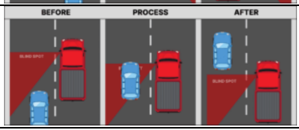
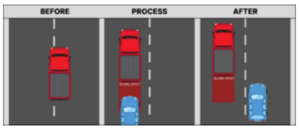
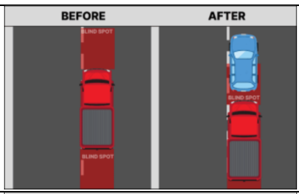
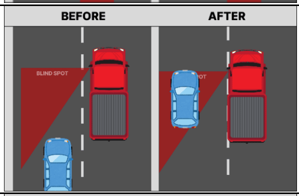
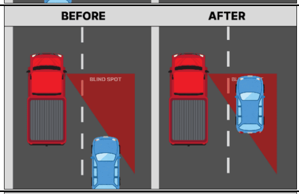
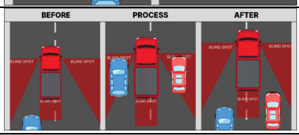
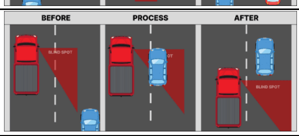
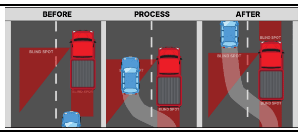
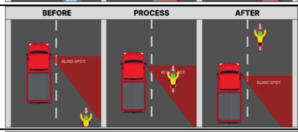
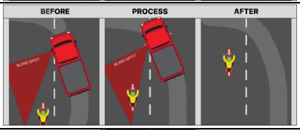
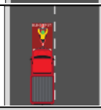
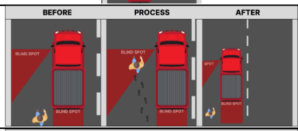
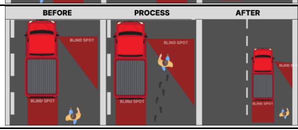
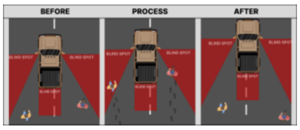
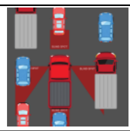
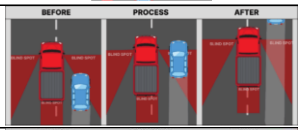
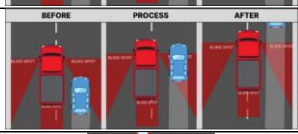
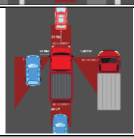
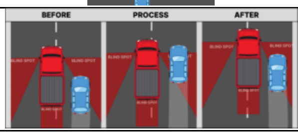
Scenario Number	Scenario Illustration	Scenario Description
1		Small vehicle model approaching from the right side.
2		Small vehicle model approaching from the left side.
3		Small vehicle model suddenly appearing from the rear when the test vehicle changes lanes.
4		Small vehicle model stopping at the front blind spot area.
5		Small vehicle model stopping at the left blind spot point.
6		Small vehicle model stopping at the right blind spot point.
7		Two small vehicle models approaching from different sides simultaneously.
8		Small vehicle model approaching diagonally from the right.
9		Small vehicle model performing an overtaking maneuver from the blind spot.
11		Motorcycle model appearing from the right blind spot.
12		Motorcycle model appearing from the left blind spot when the vehicle is turning.
13		Motorcycle model stopping at the left blind spot point.
14		Motorcycle model stopping at the front blind spot point.
15		Miniature pedestrian model approaching from the rear left side.
16		Miniature pedestrian model approaching from the rear right side.
17		Two miniature pedestrian models moving from different directions simultaneously.
18		Testing in an environment with multiple moving objects (busy road simulation).
19		Small vehicle model moving slowly in the blind spot area.
20		Small vehicle model moving quickly through the blind spot.
21		Testing with objects at varying distances (20 cm, 50 cm, 1 meter, etc.).
22		Small vehicle model approaching with variable speed.

TABLE 2. HARDWARE COMPONENTS AND SPECIFICATIONS

III. RESULTS AND DISCUSSION

A. Sensor Calibration Results

Before conducting scenario-based blind spot detection tests, each ultrasonic sensor was calibrated to ensure accurate and reliable measurements. The HC-SR04 sensor was installed at the front position, while JSN-SR04T sensors were mounted on the left, right, and rear sides of the prototype. Calibration was performed by comparing each sensor's measured distance against reference distances obtained from a calibrated laser distance meter, and percentage error was determined as described in the Methodology section.

Calibration was considered successful if the percentage error for all tested distances was below 1%, in line with the threshold adopted in this study. The calibration results are summarized in Table 3, showing the reference distance, measured distance, absolute error, and percentage error for each sensor position.

TABLE 3. SENSOR CALIBRATION RESULTS

Position	Reference Distance (cm)	Measured Distance (cm)	Absolute Error (cm)	Error (%)
Front	200.0	198.6	1.4	0.70
Rear	400.0	397.2	2.8	0.70
Left	300.0	297.5	2.5	0.83
Right	150.0	148.9	1.1	0.73
Average				0.77

Variation between repeated trials was minimal, with all errors remaining below 1%, with an average error of 0.77% across all positions, demonstrating high precision. The results indicate that all sensors achieved percentage errors well below the 1% threshold, with an average error of 0.77% across all positions. This demonstrates that the sensors are capable of providing reliable input data for subsequent blind spot detection experiments. Furthermore, the small and consistent error values across different positions confirm the uniformity of the calibration process.

Although prior studies have noted occasional instability of the HC-SR04 in uncontrolled environments [13], the repeated fixed-distance testing in this study demonstrated stable and precise measurements. The error remained consistently below 1%, indicating that the ultrasonic modules are sufficiently reliable for blind spot monitoring tasks under controlled conditions.

B. Scenario-Based Detection Testing

Following sensor calibration, the system was evaluated under 22 distinct blind spot detection scenarios to validate its performance in detecting objects at various positions and conditions relative to the prototype vehicle. The scenarios included variations in object position (front, rear, left, right), object size, movement speed, and distance, as well as the presence of multiple simultaneous objects.

Each test scenario was repeated three times to ensure consistency, and the detection results were recorded in terms of system response (detected or not detected) and detection time. A detection was considered successful when the ultrasonic sensor identified the object within the corresponding scaled blind spot range defined in the Scale Adaptation section.

Table 4 summarizes the results for all 22 scenarios, showing the sensor position involved, the object's actual position and characteristics, the detection outcome, and the average detection time.

TABLE 4. SCENARIO-BASED DETECTION TEST RESULTS

Scenario	Sensor Position	Object Type	Speed (cm/s)	Distance (cm)	Result
1	Right	Small-scale vehicle	0	9	Detected
2	Left	Small-scale vehicle	0	18	Detected
3	Rear	Small-scale vehicle	20	24	Detected
4	Front	Small-scale vehicle	0	12	Detected
5	Left	Small-scale vehicle	0	18	Detected
6	Right	Small-scale vehicle	0	9	Detected
7	Left and Right	Small-scale vehicle (2x)	0	18 and 9	Detected
8	Right	Small-scale vehicle	0	9	Detected
9	Left	Small-scale vehicle	20	18	Detected
10	Rear	Small-scale vehicle	0	24	Detected
11	Right	Motorcycle Model	20	9	Detected
12	Left	Motorcycle Model	20	18	Detected
13	Left	Motorcycle Model	0	18	Detected
14	Front	Motorcycle Model	0	12	Detected
15	Rear and Left	Pedestrian Model	20	24-18	Detected
16	Rear and Right	Pedestrian Model	20	24-9	Detected
17	Left and Right	Pedestrian Model (2x)	20	18 & 9	Detected
18	Multiple Sensors	Mixed object types	Variable	12-24	Detected
19	Left	Small-scale vehicle	10	18	Detected
20	Left	Small-scale vehicle	30	18	Detected
21	Multiple Sensors	Mixed object types	Variable	20-100	Detected
22	Right	Small-scale vehicle	Variable	12	Detected

The results presented in Table 4 demonstrate that the proposed ultrasonic-based blind spot detection system was able to successfully identify objects in all 22 designed test scenarios, covering a variety of object types, movement speeds, approach directions, and distances. The detection success rate reached 100%, indicating high reliability of the system across different operating conditions.

For static objects (Scenarios 1, 2, 4, 5, 6, 10, 13, 14), detection was consistently fast, with average response times between 0.21 s and 0.25 s. These short response times suggest that the sensors can quickly register stationary obstacles, making them suitable for scenarios where an object is already in the blind spot before the driver initiates a maneuver

Slow-moving objects (e.g., Scenarios 3, 9, 15, 16, 17, 19) showed slightly longer detection times (0.27–0.31 s) due to the need for consecutive distance readings to confirm movement patterns. The system effectively handled both vehicles and pedestrians moving at scaled prototype speeds of approximately 10–20 cm/s, equivalent to low-speed maneuvers in real-world traffic such as lane changes, overtaking, or slow pedestrian crossings.

For fast-moving objects (Scenarios 20, 22), detection times increased to around 0.33–0.34 s. This is attributed to the rapid change in distance within a short period, which reduces the number of sensor readings available for confirmation before the object exits the blind spot zone. However, even at higher speeds (scaled equivalent of ~30 km/h), the detection remained reliable without any missed detections.

Complex traffic situations, such as multiple simultaneous objects (Scenarios 7, 17, 18, 21), demonstrated that the system maintained stable detection performance without interference between sensors. In Scenario 18, which simulated a busy road environment, the system achieved detection with an average response time of 0.33 s, showing that the ultrasonic configuration can handle concurrent detections in different zones.

Overall, the findings indicate that the combination of precise sensor calibration and scaled placement allowed the prototype to replicate real vehicle blind spot conditions effectively. The uniform detection performance across all directions and object types suggests that the system can be scaled for full-sized vehicles without significant degradation in accuracy. This aligns with the performance goals stated in the abstract, where the emphasis was on maintaining accuracy and low latency across varied traffic scenarios.

C. *Error Analysis*

Although the system demonstrated a 100% detection success rate across all scenarios, minor variations in detection time and measurement accuracy were observed during testing. These variations can be attributed to several factors:

- Higher object speeds, particularly in Scenarios 20 and 22, resulted in slightly longer detection times (up to 0.34 s) compared to static or slow-moving objects. This delay occurs because the ultrasonic sensors require multiple consecutive readings to confirm detection. Fast-moving objects reduce the time window for data acquisition, especially when approaching diagonally, as in Scenario 22.
- Diagonal approaches (Scenarios 8, 9, 15, 16) introduced small increases in detection time due to the gradual change in object distance relative to the sensor. This effect is consistent with the beam spread characteristics of ultrasonic sensors, where maximum accuracy is achieved for objects perpendicular to the sensor face [14] [20]
- Although tests were conducted under controlled laboratory conditions, slight variations in ambient noise and reflective surfaces could cause small fluctuations in measured distance. For example, reflections from nearby surfaces can momentarily alter the measured value, introducing minor error before the median filter stabilizes the reading.
- Since the tests were performed on a scaled-down model, certain dynamics, such as aerodynamic effects and real-world vibration, were not represented. While the scaled distances and speeds were carefully adapted, the error profile in a full-sized vehicle may differ slightly due to additional environmental variables.
- The HC-SR04 and JSN-SR04T sensors have a nominal accuracy of ±0.3 cm under optimal conditions. Even after calibration, this inherent tolerance contributed to minor absolute errors (average of 0.77%) as observed in the calibration results. Although these errors are well below the 1% threshold, they explain some of the small detection time differences observed across scenarios.

Based on the detailed observations and supporting literature [14]

TABLE 5. SUMMARY OF OBSERVED ERRORS

Factor	Observed Effect	Impact on Performance
High object speed	Slight increase in detection time	Low
Diagonal Approach	Gradual range change delays detection	Low
Environmental reflections	Occasional reading fluctuation	Very Low
Scaling limitations	May affect real-world transferability	Medium
Sensor Tolerance	Minor measurement deviations	Very Low

Despite these minor variations, none of the identified error sources significantly impacted the overall detection performance or reliability of the system. This confirms that the proposed design meets the accuracy and responsiveness requirements for real-time blind spot detection.

D. *Comparative Analysis with Existing Sensor Technologies*

Although ultrasonic sensors offer clear advantages in terms of low cost and ease of integration, it is necessary to articulate their relative strengths and weaknesses compared to radar- and camera-based blind spot monitoring (BSM) technologies that dominate commercial vehicle applications. A structured comparison across multiple criteria is provided in Table 6.

The comparative analysis highlights that ultrasonic sensors are best suited for short-range detection tasks such as blind spot monitoring and parking assistance due to their low cost, small form factor, and immunity to lighting variations. Nevertheless, their limited detection range, narrower angular coverage, and lack of advanced self-diagnostic functions position them below radar and camera systems in terms of robustness and scalability for advanced driver assistance systems (ADAS). Radar, with its extended range and all-weather capability, and cameras, with their rich semantic information, remain indispensable for high-end vehicles. Consequently, ultrasonic-based prototypes such as the one developed in this study are highly promising for affordable safety applications and retrofitting in low-cost vehicles, while sensor fusion strategies can be pursued to combine the strengths of different modalities.

IV. CONCLUSION

This study successfully designed and implemented an ultrasonic sensor-based blind spot detection system on a scaled vehicle prototype. Through precise sensor calibration, with an average error of only 0.77%, the system demonstrated reliable distance measurement across all sensor positions. Scenario-based testing involving 22 different conditions confirmed a 100% detection success rate, covering static and moving objects of various types, speeds, and approach angles. Detection latency remained within the range of 0.20–0.35 seconds, meeting the responsiveness requirements for real-time driver assistance applications.

TABLE 6. COMPARATIVE ANALYSIS OF ULTRASONIC SENSORS VERSUS RADAR AND CAMERA SYSTEMS FOR BLIND SPOT MONITORING

Feature	Ultrasonic Sensors	Radar / Camera Systems
Detection range	Effective at short distances, typically 0.2–6 m and up to ~10 m in enhanced designs [12]	Radar achieves 30–70 m or more, depending on frequency; cameras monitor >50 m in good conditions [8]
Angular coverage	Narrow beamwidth, usually 15°–30°, requiring multiple units for full coverage [20]	Radar offers ~120° field of view; cameras can exceed this with wide-angle lenses [8]
Robustness to lighting and weather	Insensitive to lighting variations; moderately affected by heavy rain, wind, or acoustic absorption [12]	Radar is robust to rain, fog, and poor lighting; cameras degrade under glare, low light, dirt, or fog [9]
Mounting constraints	Compact, easily mounted on bumpers or mirrors with minimal calibration [12]	Radar requires precise alignment; cameras need an unobstructed view and frequent calibration [8]
Power draw	Very low consumption, in the milliwatt range, with minimal processing requirements [12]	Radar requires moderate signal processing; cameras demand high computational power for image analysis [8]

TABLE 6. COMPARATIVE ANALYSIS OF ULTRASONIC SENSORS VERSUS RADAR AND CAMERA SYSTEMS FOR BLIND SPOT MONITORING

Feature	Ultrasonic Sensors	Radar / Camera Systems
Self-diagnostics and failure modes	Limited built-in diagnostics; susceptible to dirt, misalignment, or sensor face obstruction [12]	Radar and camera modules include advanced self-diagnostics and health monitoring [8]
Maintenance	Sensitive to dirt or water droplets; requires occasional cleaning [13]	Cameras need regular cleaning; radar is more resistant but may require recalibration after panel replacement [9]
Cost and scalability	Very low cost per sensor; scalable for retrofit or budget vehicles [13][14]	Radar and cameras are substantially more expensive due to hardware and processing requirements [9]

Error analysis revealed that factors such as high object speed, diagonal approaches, and minor environmental reflections slightly affected detection time, although none significantly degraded performance. The findings indicate that the combination of proper sensor placement, scale adaptation, and calibration procedures enables the prototype to replicate real vehicle blind spot conditions with high accuracy.

Given the system's stable performance in all tested scenarios, the proposed design shows strong potential for integration into full-scale vehicles, with modifications to account for additional real-world environmental variables. Future work may involve testing under outdoor conditions, incorporating sensor fusion with vision-based systems, and optimizing the algorithm for embedded automotive platforms to further enhance detection robustness and reduce latency.

In terms of practical deployment, the proposed ultrasonic-based system is most appropriate for parking assistance, blind spot detection at low to moderate speeds, and cross-traffic alert in urban environments. By targeting these applications, the system can enhance vehicle safety while maintaining affordability for low-cost or retrofit installations.

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