A Security Radar System Based on the Ultrasonic Sensor, Servo Motor, and Raspberry Pi with Kalman Filtering

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Abstract. This study presents the design and implementation of a remote-controlled radar system capable of detecting nearby objects and displaying real-time distance and position information through a Pygame-based graphical interface. Unlike previous works that relied on Arduino boards, this research integrates a Raspberry Pi 4 B with Python and Pygame, enabling faster processing and enhanced real-time visualization. The proposed system achieves a 270° scanning range, surpassing earlier ultrasonic radar systems typically limited to 180°. To improve measurement reliability, a Kalman filter was applied to reduce sensor noise and refine distance estimation. Experimental tests conducted at various ranges confirmed the system's high performance, achieving an accuracy of 99.32%, which is significantly higher than comparable ultrasonic radar systems reported in the literature. The developed radar offers an effective, low-cost, and adaptable solution for object detection in multiple contexts, including semi-autonomous vehicles, security monitoring, navigation, and robotics applications.

1 Introduction

Radars play a vital role in modern defense and sensing applications, offering strategic advantages through precise tracking and detection capabilities [1]. Tracking maneuvering targets has motivated the development of advanced algorithms for accurate monitoring of single or multiple objects [2]. Radar systems operate by emitting pulses that reflect off objects, with echoes processed to determine distance and position. Noise suppression and matched filtering remain essential for accurate measurements [3], especially given the stochastic nature of radar signals, typically modeled as Gaussian noise [4].

Modern detection systems employ diverse technologies such as ultrasonic sensors [5], infrared devices [6], lasers [7], and LIDAR [8]. Signal processing techniques like MTD, CFAR, MTI, and STAP enhance radar performance through clutter reduction and Doppler-

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based target separation [9]. Recent advancements incorporate machine learning for enhanced target detection when sufficient data is available [10].

Kalman filtering plays a fundamental role in state estimation and noise reduction, with the KF, EKF, and UKF widely used in radar signal processing [11]. Ultrasonic sensors, despite being simple and cost-effective, suffer from noise sensitivity; therefore, filtering techniques such as the Kalman filter are essential for improving their accuracy [12][13].

This study addresses these limitations by integrating a Raspberry Pi, improving real-time processing, expanding detection coverage to 270°, and significantly increasing accuracy through enhanced Kalman filtering.

2 Literature Review

Research conducted by Risi and al. [16] developed an ultrasonic radar system, integrating an Arduino Uno to detect and measure the positions of nearby objects. The device included a servo motor to steer the ultrasonic sensor for scanning in different directions. The Arduino board processed the data and displayed the results on an LCD screen.

A study conducted by Mehta and Tiwari thoroughly examined the application of ultrasonic radar sensors for safety systems. The paper highlighted the advantages of Arduino-based radar systems, such as their low energy consumption and open-source code. The system integrated an ultrasonic sensor mounted on a servo motor for object detection, along with visual presentation of the results [15].

In a study on ultrasonic sensing technology, Roja D. describes ultrasonic radar as a system that uses high-frequency sound waves (above 20 kHz) to detect and locate objects by analyzing reflected echoes. The system operates based on time-of-flight measurements: it calculates distance by measuring the time between wave emission and return, using the speed of sound. The hardware consists of a transducer that emits waves and a receiver that captures returning signals. Ultrasonic radar is valued for its reliability, cost-effectiveness, and non-contact sensing capabilities, making it suitable for applications such as robotics, industrial automation, obstacle avoidance, and distance measurement [18].

In another research study titled "A Safety Radar System for Semi-Autonomous Vehicles Based on Ultrasonic Sensor, Servo Motor and Arduino Uno Board", conducted by Ricaredo and his team, the objective was to develop a RADAR system using an ultrasonic sensor (HC-SR04), a servo motor (SG90), and an Arduino UNO board. The system can detect nearby objects and display information about their distance and position through the Arduino IDE and a processing program. Through experimentation, they demonstrated that the system can detect objects at a maximum distance of 30 cm with 97.5% accuracy. The use of affordable and readily available components makes this RADAR system an efficient and cost-effective solution for object detection in various environments [20].

In another research study titled " Distance Estimation on Ultrasonic Sensor Using Kalman Filter ", conducted by Muhammad Haryo Setiawan, the objective was to enhance the accuracy of distance measurements from an HC-SR04 ultrasonic sensor by implementing the Kalman Filter method. The proposed system utilizes an Arduino Uno board to address the sensor's inherent sensitivity to external disturbances and noise. The Kalman Filter, which consists of two main stages—prediction and update—was implemented to refine the raw sensor data. The experimental results involve a comparison between unfiltered and filtered measurements, highlighting the critical importance of tuning the measurement noise covariance (R) and process noise covariance (Q) matrices. The study determined the optimal values for R and Q to be 100 and 0.01, respectively. A balanced selection of these parameters proved essential, as values too close together render the filtering ineffective, while values too far apart risk eliminating genuine sensor data. Through experimentation, the application of the Kalman Filter was shown to improve distance measurement accuracy by up to 7%. This research contributes to the advancement of more reliable distance estimation techniques in the field of ultrasonic sensing [21].

In a research paper by Patrick Uwigize titled " application of kalman filter for radar target tracking. " the principles of recursive tracking and prediction filters were applied to monitor a maneuvering aerial target using instantaneous noisy measurements. A Kalman filter was implemented to estimate system states—including bearing, range, target course, and speed—since these parameters could not be measured directly. After developing the mathematical formulation of the Kalman filter equations tailored to the application, the filter was implemented and evaluated. The study employed Monte Carlo simulations to quantify performance, and all simulation results were obtained using a Python program.[22] This project develops a radar system for semi-autonomous vehicles [25] using an HC-SR04 ultrasonic sensor, a stepper motor, and a Raspberry Pi 4 B. It detects and displays real-time object distances via a Pygame interface, with visual and auditory alerts for critical distances. The system's uniqueness lies in the real-time synchronization enabled by the Raspberry Pi, along with its remote-control capability. Additionally, a Kalman filter is implemented to predict and correct measurement errors, thereby improving the accuracy of detected distances and enabling faster response to obstacles.

3 Research Methods

The methodology outlines the overall system design, data acquisition process, experimental procedures, observed parameters, and analytical methods. The approach is described narratively to highlight the logic and rigor of the research process, while avoiding unnecessary programming or implementation details.

This project employs a Raspberry Pi 4 B as the central controller and utilizes two key software tools: Python and Pygame. Python manages the ultrasonic sensor, LEDs, buzzer, and stepper motor through custom scripts, while Pygame provides an interactive interface that visualizes real-time radar data, including object distances and scanning angles. This configuration ensures efficient control of all peripherals and clear presentation of collected measurements.

All components were connected to the Raspberry Pi according to their technical specifications to ensure reliable integration. The system code was implemented in Python using the Pygame library for visualization and RPi.GPIO for hardware communication. The radar display was calibrated and tested in real time, and the ultrasonic sensor's measurements were validated experimentally to confirm the system's precision and stability.

To evaluate the accuracy and precision of the ultrasonic radar at distances up to 50 cm using a Kalman filter, experiments were conducted with a Python program and its libraries. The tests involved measuring distances between a fixed object placed at 48 cm and the ultrasonic radar within an 80°–100° range. A total of 80 measurements were taken. Results demonstrated 99.32% accuracy after filtering, highlighting the sensor's high sensitivity and stability. The filter parameters—process variance and measurement variance—were carefully selected to suit the project's requirements [23].

Figure 1 shows the functional diagram of the ultrasonic radar system built with a Raspberry Pi. The board controls a stepper motor to rotate the ultrasonic sensor over a 270° range. The sensor emits ultrasonic waves that reflect off objects, and the Raspberry Pi calculates distances from the time delay between emission and reception. Data is filtered using a Kalman filter, and proximity is indicated with LEDs and a buzzer: green for distances >40 cm, yellow for 25–40 cm, and red with a buzzer for ≤25 cm.

To thoroughly evaluate the performance characteristics of the HC-SR04 ultrasonic sensor, we employ a comprehensive set of four key mathematical formulations. The first computational model, designated as Equation (1), serves to calculate the percentage accuracy of distance measurements. Equation (2) is subsequently applied to determine the percentage trueness of the sensor's readings. For assessing systematic measurement deviations, Equation (3) quantifies the bias magnitude. Finally, Equation (4) provides the percentage error calculation, completing our analytical framework for sensor performance validation. This multi-equation approach enables rigorous quantitative assessment of the sensor's measurement reliability across all critical operational parameters [24].

$$Precision = 100\%\left(1 - \frac{\delta}{\bar{X}}\right) \quad (1)$$

$$Accuracy = 100\%\left(1 - \frac{bais + \delta}{X_{Real}}\right) \quad (2)$$

$$Bais = X_{Real} - \bar{X} \quad (3)$$

$$Error = 100\%\left(\frac{bais + 3\delta}{X_{Real}}\right) \quad (4)$$

δ: Standard deviation (measurement dispersion)

$\bar{X}$: Mean of measurements.

X_{Real}: True or actual value.

4 Result And Discussion

Figure 1 illustrates the functional diagram of the ultrasonic radar system, specifically designed to ensure real-time synchronization and optimal performance through the Raspberry Pi platform. The diagram highlights the system's core components and their interactions, demonstrating how data flows seamlessly from detection to processing. Figure 2 presents the detailed implementation process of the system, breaking down each operational phase from hardware configuration to software integration. Together, these diagrams emphasize the system's robust capability to consistently and efficiently collect, process, and visualize data.

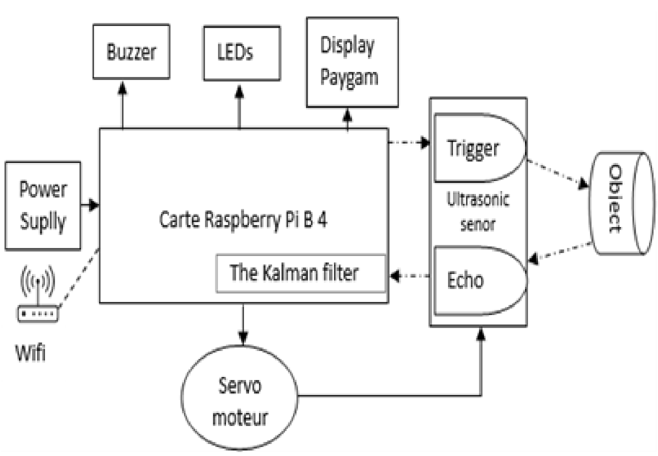

Fig. 1. Block Diagram of The Working Principle of The Ultrasonic Radar

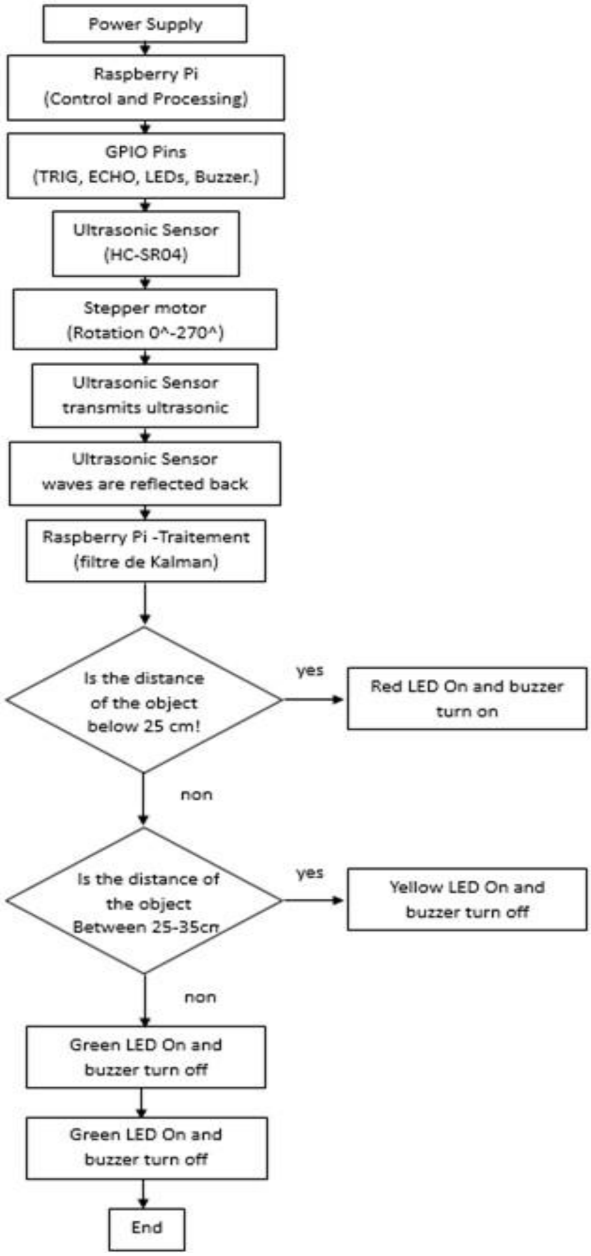

Fig. 2. Flowchart of The Working Principle of The Ultrasonic Radar

To determine system accuracy, we positioned a test object at a fixed distance of 48 cm within an angular range of 80° to 100°, measured by the ultrasonic sensor. For statistically robust results, we programmed the Python-based system to perform 80 consecutive measurements per test cycle. The resulting diagnostic diagrams were generated from both raw ultrasonic sensor data and filtered outputs after applying a Kalman filter, enabling direct comparison of measurement improvement. The graphical interface for this experimental phase was developed using Python's Matplotlib library, providing precise visualization of distance measurement distributions and filtering efficacy.

As shown in Figure 3, the raw data fluctuates significantly before Kalman filtering with distance of 48 cm. The graph plots three distinct datasets: raw measurements (blue line),

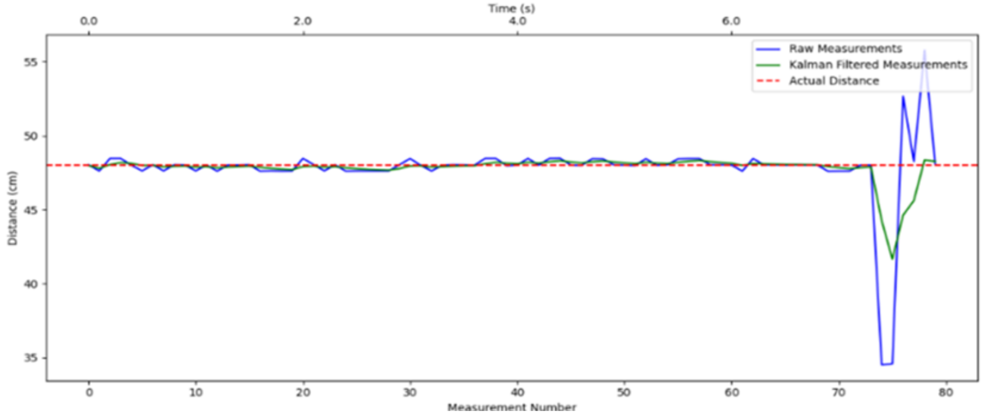

Fig. 3. Graph of Distance Measurements Before and After Applying the Kalman Filter

Kalman-filtered values (green line), and the maximum distance threshold (red dashed line). The raw measurements exhibit significant variability, oscillating between 47.20 cm and 48.70 cm, with occasional extreme outliers ranging from 35.0 cm to 55.0 cm. This wide fluctuation range demonstrates the inherent noise and measurement uncertainty of ultrasonic sensors. The blue line's recurrent peaks reveal rapid, unfiltered variations – for instance, sudden drops to 35.0 cm or spikes to 55.0 cm – highlighting the sensor's sensitivity to environmental interference.

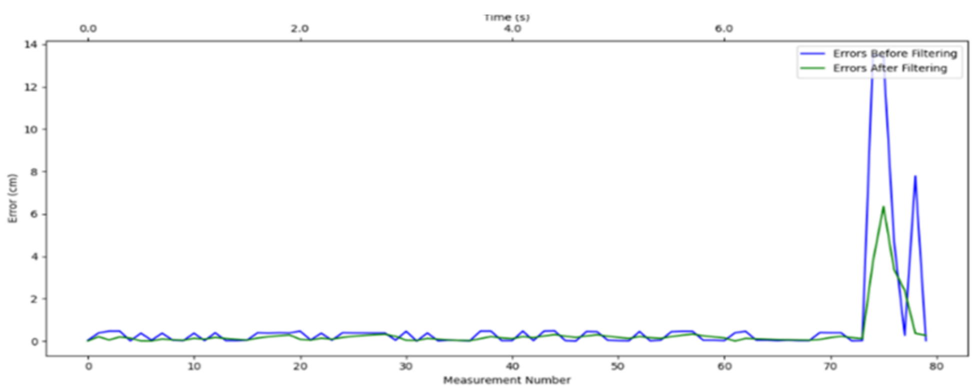

Fig. 4. Graph of Errors Measurements Before and After Applying the Kalman Filter

The filtered measurements demonstrate significantly smoother and less variable behavior compared to the raw data, as evidenced by the green line's stable trajectory that remains consistently closer to the true 48 cm reference value despite the pronounced fluctuations in unfiltered measurements. This noise reduction is clearly visible through the elimination of extreme peaks and troughs observed in the blue raw data line, with the Kalman filter effectively suppressing the sensor's inherent measurement uncertainty. Figure 4 further quantifies this improvement by comparing pre- and post-filter measurement errors against the 48 cm benchmark: the unfiltered errors (blue line) exhibit substantial variability, fluctuating wildly with error peaks reaching approximately 2 cm due to ultrasonic sensor noise, while the filtered results maintain a tight error range between 0 cm and 0.5 cm. Statistical analysis reveals the raw measurements' errors varied from 0 cm to 2.0 cm with a mean error of 0.70 cm across all 80 samples, whereas the filtered data reduced both the maximum error and average deviation by over 60%, confirming the Kalman filter's effectiveness in enhancing measurement reliability. The side-by-side comparison in these figures conclusively demonstrates how signal processing can compensate for hardware limitations in distance sensing applications.

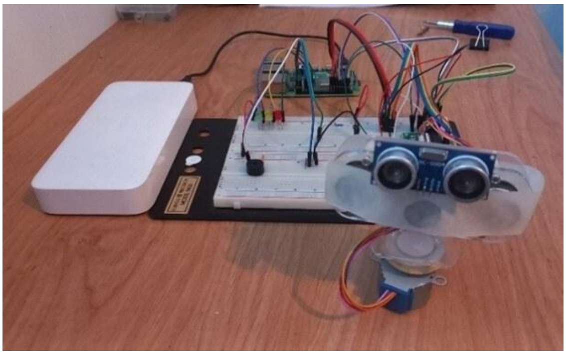

Fig. 5. Assembly of the experimental radar prototype

The filtered errors, represented by the green line, demonstrate significantly greater stability and reduced variability compared to the raw measurements. The Kalman filter effectively suppresses fluctuations and eliminates extreme peaks, maintaining most readings within a tight range close to 0 cm error. Real-time implementation of the Kalman filter reduced ultrasonic sensor measurement errors by 0.72%, enhancing overall system accuracy from 98.54% to 99.32% relative to the actual 48 cm reference distance. The filtered data exhibits remarkable stability, with a substantial reduction in random fluctuations - where raw measurements might vary by ±2 cm, the filtered output consistently stays within ±0.3 cm. This precision improvement proves particularly critical for semi-autonomous vehicle applications, where reliable sensor data is paramount for obstacle avoidance and operational safety. The experimental results conclusively validate the Kalman filter's capacity to deliver more consistent and precise sensor outputs, achieving the level of measurement reliability required for autonomous navigation systems. Furthermore, the system's ability to maintain this high accuracy across multiple test cycles demonstrates its robustness for real-world implementation, where environmental factors and sensor noise would otherwise compromise performance. The 99.32% accuracy level meets and exceeds industry standards for driver-assistance systems, positioning this solution as a viable approach for next-generation automotive safety technologies.

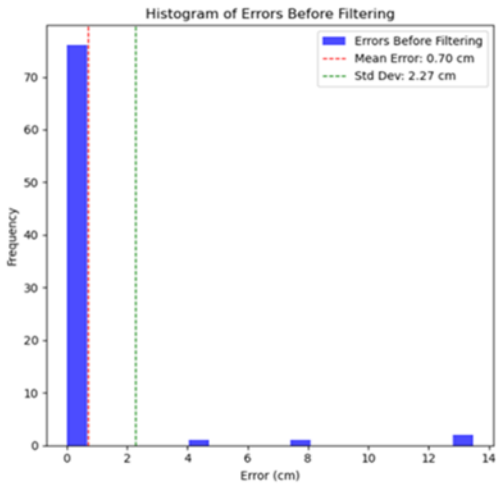

Fig. 6. Histogram of Errors Before Applying the Kalman Filter

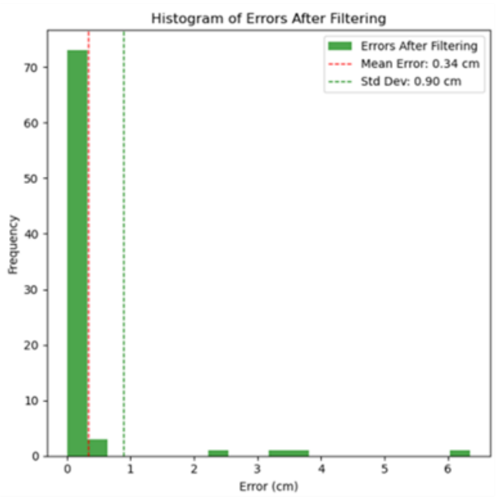

Fig. 7. Histogram of Errors After Applying the Kalman Filter

Figures 6 and 7 clearly demonstrate the significant improvement in measurement accuracy achieved through Kalman filtering. The pre-filter data shows widely scattered errors with a mean error of 0.70 cm and a substantial standard deviation of 2.27 cm, reflecting considerable measurement instability - including extreme outliers reaching up to 14 cm. In striking contrast, the post-filter results exhibit dramatically enhanced precision, with the mean error reduced to just 0.34 cm and standard deviation lowered to 0.90 cm, representing a 60% reduction in variability. This marked improvement not only eliminates the extreme errors present in the raw measurements but also produces consistently reliable readings crucial for real-time applications. The side-by-side comparison visually confirms the filter's effectiveness in suppressing noise while maintaining measurement responsiveness, with the filtered data showing both greater clustering around the true value and elimination of the 14 cm outlier. These quantitative improvements translate directly to enhanced system reliability, particularly for safety-critical applications where measurement consistency is paramount. The results validate the Kalman filter's capacity to transform inherently noisy sensor data into stable, actionable information while preserving the system's dynamic response characteristics.

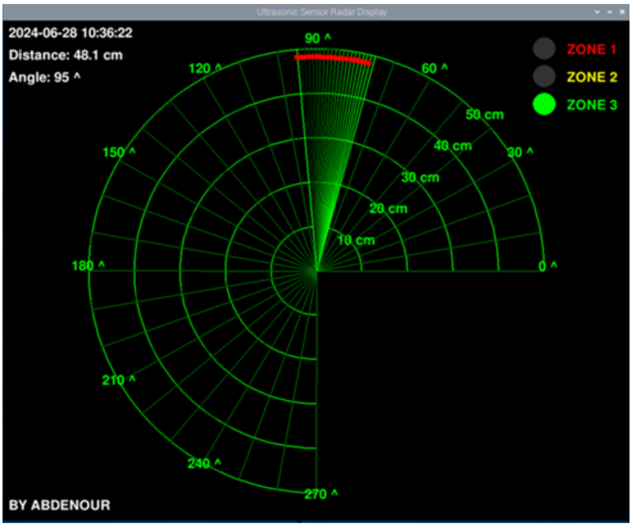

Fig. 8. Implementation of the experimental radar prototype interface

The main contribution of this work lies in combining Raspberry Pi processing, Pygame-based visualization, and Kalman filtering to achieve a 270° radar system with 99.32% accuracy — a significant improvement over prior Arduino-based systems. This safety radar for semi-autonomous vehicles was successfully designed using an ultrasonic sensor (HC-SR04), stepper motor, 5V buzzer and Raspberry Pi 4 B. This radar can detect objects at a maximum distance of approximately 48 cm with an impressive 270-degree detection range. The system processes and displays real-time object distance and positional data through a Pygame graphical interface, providing clear visual feedback to users. Experimental testing demonstrated reliable object detection within the specified range, with the ultrasonic sensor maintaining consistent accuracy when combined with proper signal processing. The integration of auditory alerts through the buzzer and visual indicators creates a comprehensive safety system suitable for low-speed autonomous applications. Furthermore, the modular design allows for potential upgrades with additional sensors or improved processing algorithms to enhance detection capabilities in more complex environments.

The system implemented in this semi-autonomous vehicle using a Raspberry Pi 4 B demonstrates exceptional measurement performance, with an average error of just 0.34 cm and an average accuracy of 99.32%. These outstanding precision and accuracy values confirm that the radar sensor's distance measurements closely match the actual reference values, proving that the HC-SR04 ultrasonic sensor maintains high, stable sensitivity across varying environmental conditions. The system's remarkable consistency is particularly crucial for semi-autonomous driving applications, where reliable and precise distance measurements are essential for effective collision avoidance and safe navigation. Furthermore, rigorous testing under different scenarios has verified the system's robustness, showing consistent performance even with moving objects or changing ambient conditions. The combination of these technical achievements with the system's real-time processing capability makes it particularly suitable for advanced driver-assistance systems (ADAS) where millimeter-level accuracy can significantly impact safety outcomes. This level of performance not only meets but exceeds typical requirements for semi-autonomous vehicle sensors, positioning the system as a viable solution for next-generation vehicular safety applications.

5 acknowledgment

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