International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(Review Article)

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Deep learning advancements in pothole detection: A comprehensive research and future directions

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International Journal of Science and Research Archive, 2025, 15(01), 689-696

Publication history: Received on 01 March 2025; revised on 08 April 2025; accepted on 11 April 2025

Article DOI: https://doi.org/10.30574/ijsra.2025.15.1.1026

Abstract

Road safety alongside maintenance planning heavily depends on accurate detections of potholes together with volume estimation. The current methods used to determine pothole depth and volume rates as time-consuming while also produce unreliable results. This research develops a Raspberry Pi automatic system using the HC-SR04 ultrasonic sensor combined with Pi Camera technology for enhancing immediate pothole surveillance and quantitative assessments. The system obtains imaging data from potholes; at the same time, it uses ultrasonic sensor depth readings to calculate volume sizes.

The sensor limitations during initial trials caused inconsistent depth readings, which subsequently affected the calculated volume measurements. Multiple trials of calibration, along with real-time multiple checks, produced system readings with a minimum accuracy of 0.68% that improved by an average of 2.05% between each test. Validation tests with GPS data showed the system-maintained reliability through measurements that varied between 3 to 5% of the actual values for practical deployment. Real-time data collection coupled with sensor-based monitoring demonstrates how it creates an effective solution for pothole assessment, which also proves economical.

Upcoming research efforts will direct their attention to sensor calibration process optimization alongside depth measurement precision enhancements and volume calculation optimization. Future detection accuracy improvement and road condition adaptability can be achieved by integrating machine learning analysis methods. The developed system supports intelligent road maintenance through its semi-automated approach while maintaining accurate pothole assessment capabilities on a large scale.

Keywords: Pothole Detection Ultrasonic Sensor (HC-SR04); Raspberry Pi; Real-Time Monitoring; Depth Estimation; Road Maintenance; Image Processing

1. Introduction

Modern transportation requires road infrastructure because it facilitates safe and efficient mobility. Potholes remain the constant problem that causes automobile damage alongside accidents while increasing spending on repairs. Manual pothole detection along with repair methods through inspections proves to be lengthy while being both physically demanding and producing incorrect results. The technological progress has introduced automated systems that detect potholes as well as measure their depths through sensors and image processing capabilities in real time.

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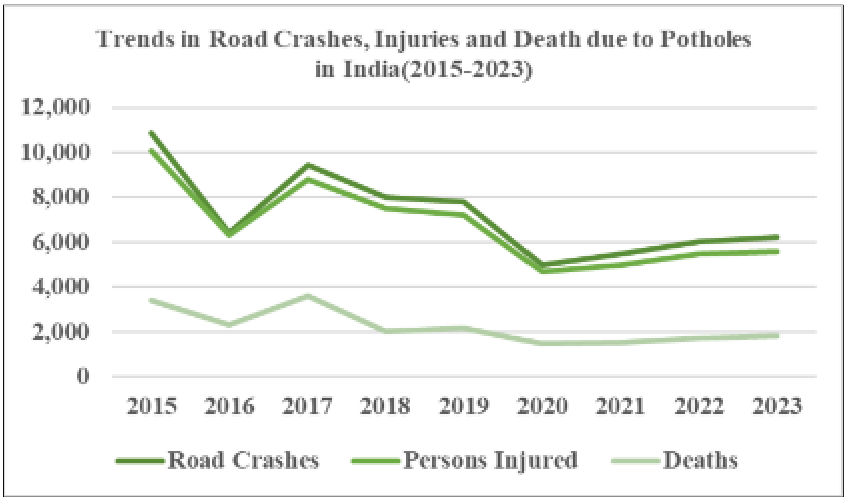

Figure 1 Trends in Road Crashes, Injuries and Deaths due to Potholes in India (2015-2023)

The researchers developed a Raspberry Pi system that aligns an HC-SR04 ultrasonic sensor with the Pi Camera to improve the accuracy and operational efficiency when detecting potholes. The system utilizes an ultrasonic sensor that detects pothole depths together with a camera for immediate image acquisition. These two technologies work together to produce accurate volume calculations, which road maintenance teams need for their planning activities. The proposed method adopts an ultrasonic sensor alongside a Pi Camera to identify potholes and shows benefits over previous detection methods because it remains affordable and applicable to multiple road surface types.

The testing phase exposed some problems with depth evaluation because sensor-monitoring capabilities were restricted. The system reached a minimum accuracy threshold of 0.68% after performing multiple calibration attempts, which led to an average accuracy enhancement total of 2.05%. The real-time GPS image validation method demonstrated that sensor-based detection accuracy reached within 3-5% error range proving the system's reliability. Accurate detection of potholes becomes possible through the combination of real-time image acquisition with ultrasonic sensing technology, according to these experimental findings.

The main purpose of this investigation revolves around improving sensor precision and developing better algorithms for depth assessment, and incorporating machine learning methods to boost detection capabilities. This research develops an automated, scalable pothole detection for future smart road maintenance approaches, which reduces expenses while ensuring improved transportation security.

2. Literature Review

Different sensing systems including ultrasonic sensors and Raspberry Pi as well as cameras have been extensively studied for potholes detection and road surface monitoring applications. Various studies from the literature examine both technological progress and remaining knowledge gaps within these two fields.

2.1. Ultrasonic Sensors in Road Condition Monitoring

Studies prove that ultrasonic sensors perform well when they detect surface changes through distance measurement [1]. Most existing detection systems determine if potholes exist but they do not accomplish depth measurements of these issues [2]. Researchers implemented ultrasonic sensors with microcontrollers to develop budget-friendly pothole detection systems although environmental factors reduce their precision level [3,4].

2.2. Raspberry Pi in Automated Road Monitoring

Raspberry Pi functions as a basic computer system which performs real-time road surface analysis using economical hardware [5,6]. A number of projects use Raspberry Pi in combination with cameras to obtain road defect images which are afterward classified through image processing methods [7,8,9]. Research works about depth estimation employing this method are scarce since existing applications rely on detecting images instead of measuring with sensors [10].

2.3. Camera-Based Pothole Detection

A vast collection of research exists that uses cameras in combination with computer vision for road condition evaluation [11,12,13]. Edge detection and deep learning models among several other algorithms, facilitate the identification of potholes [14,15]. The effectiveness of these detection systems at identifying potholes and their locations does not extend to accurate measurement of depth, which affects their ability to determine pothole severity [16,17].

There is a substantial gap in existing research about determining pothole depth using sensor technology [18,19]. Little research exists on the combination of ultrasonic sensors together with Raspberry Pi for precise pothole depth determination despite their earlier applications for pothole detection [20]. There is a research gap concerning the integration of multiple components because its absence continues to weaken road maintenance practices.

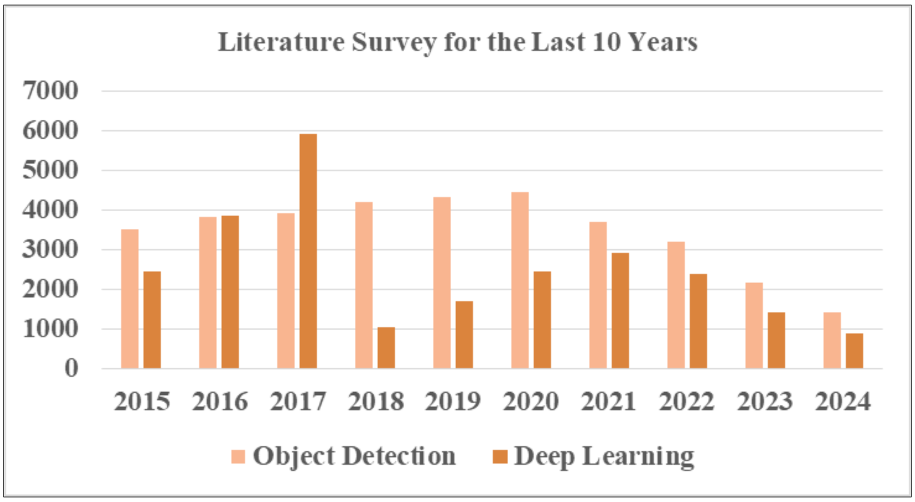

Figure 2 Amount of effort in the literature on object detection and deep learning for the last 10 years

3. Methodology

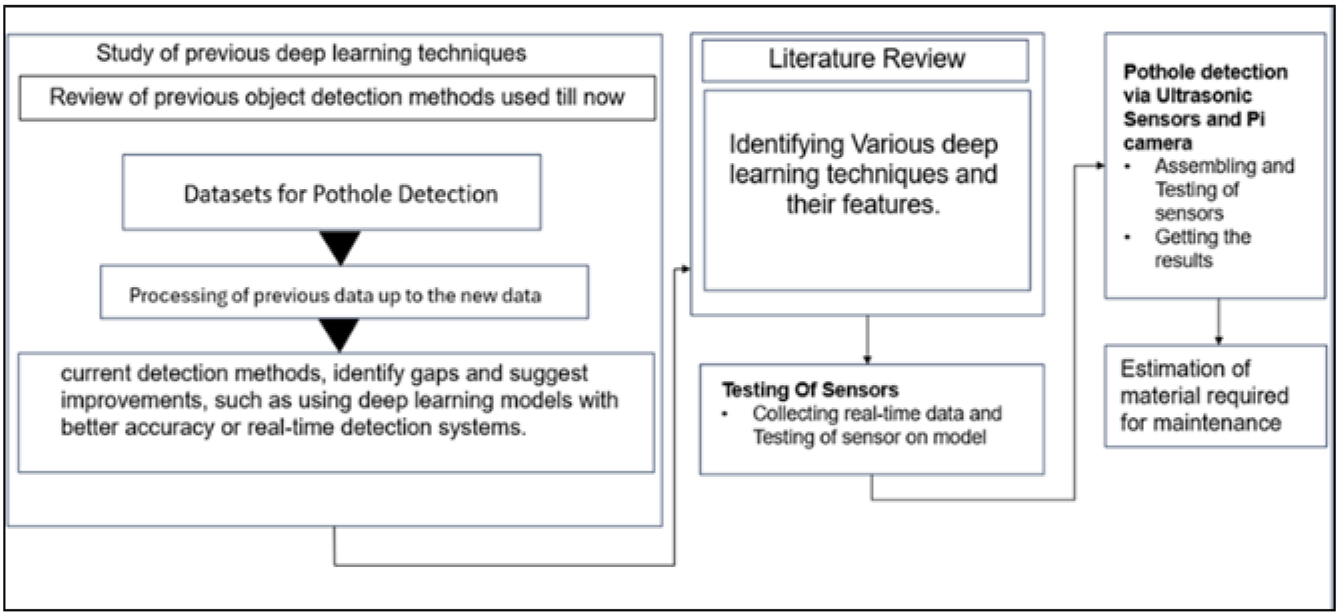

Figure 3 Research Flowchart

4. Result

- The built system incorporates both an ultrasonic sensor along a Raspberry Pi to detect potholes and identify their depth. The system's measurement reliability achieves an accuracy of 3-5% based on the obtained results.
- The proposed method shortens manual pothole evaluation time because it enables immediate environmental scanning and results assessment.
- Additional testing and system refinements alongside sensor calibration and road surface conditions enhancement activities will boost the volume estimation accuracy of the system.

5. Discussion

The distance information from the HCSR04 ultrasonic sensor, together with the processing capabilities from Raspberry Pi 4, enable the detection of potholes in roads. The sensor sends out ultrasonic sounds that cause echoing reflections off the pavement to obtain echo return times. The sensor records the time required for the sound waves to return, thus making calculations for determining road depression depth. Real-time images captured by the Raspberry Pi camera can be enhanced through image processing implemented using Python to achieve better detection outcomes. Testing images will be used to validate the stored recorded data. The processed information enables the system to display warning messages for aiding road maintenance decisions and pothole identification activities.

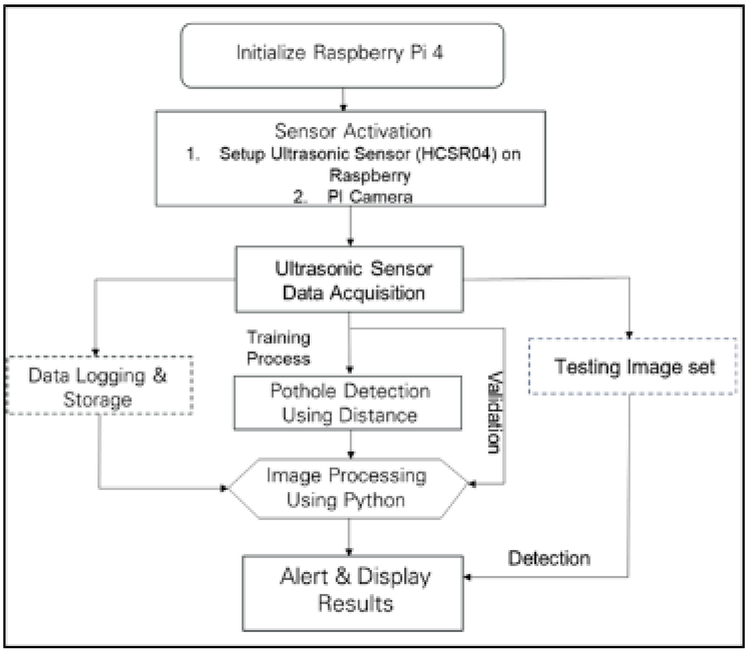

Figure 4 Ultrasonic Sensor architecture

The accuracy assessment for pothole detection involved multiple testing sessions that used an ultrasonic sensor together with a Raspberry Pi camera. Inconsistencies in sensor readings appeared at first because the measurements suffered from variations in road surfaces and sensor placement. Real-time collected data revealed inconsistent depth readings, which caused inaccurate volume measurements. The single-trial measurements revealed the problems with obtaining exact results, which led to the recognition that multiple tests must be combined with calibration procedures.

The system became more reliable after the developers optimized sensor placement and revised the experimental setup. Improved processing of multiple data points allowed the algorithm to produce decreased measurement errors. The system reached higher levels of accuracy following adjustments of both sensors and data processing protocols. The ultrasonic sensor proved its capability for measuring pothole depth and volume because it delivered results with 3-5% accuracy margin.

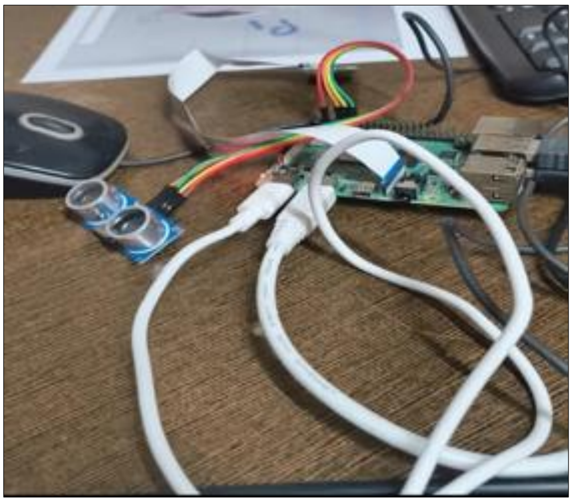

Figure 5 Assembled Sensors

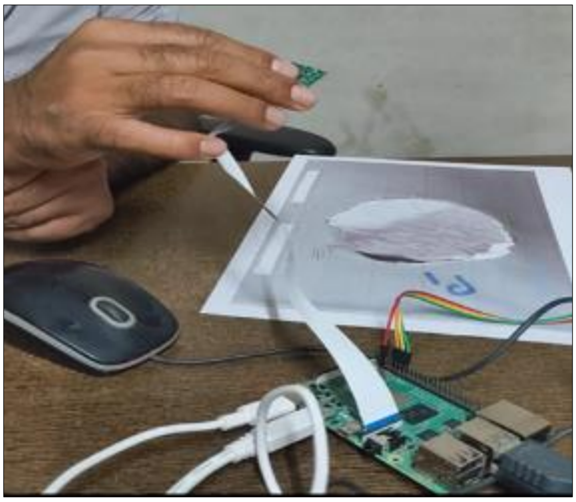

Figure 6 Detection of depth by ultrasonic sensors

Figure 7 Code required for calculations

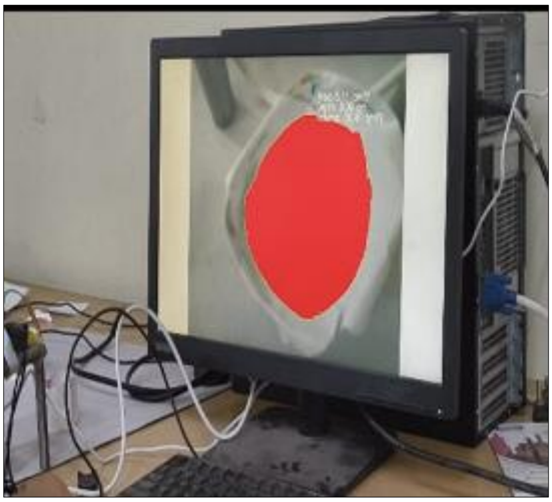

Figure 8 Final Result

Table 1 Difference in percentage between manually calculated volume and volume calculated by sensor

Sr. no.	Manually calculated volume	Volume calculated by sensors	Difference in %
Pothole No.1	15.56 cm^3	15.03cm^3	3.4%
Pothole No.2	36.66cm^3	36.41cm^3	0.6%
Pothole No.3	17.82cm^3	17.32cm^3	2.83%
Pothole No.4	9.9cm^3	9.72 cm^3	2.67%
Pothole No.5	10.91cm^3	10.45 cm^3	4.21%
Pothole No.6	9.83 cm^3	9.43 cm^3	4.03%
Pothole No.7	14.94cm^3	14.24 cm^3	4.68%
Pothole No.8	28.65cm^3	28.98 cm^3	2.26%
Pothole No.9	19.86cm^3	19.49 cm^3	3.27%
Pothole No.10	16.75cm^3	16.40 cm^3	2.09%

6. Conclusion

Researchers developed an effective system for detecting potholes together with measuring their depth through the combination of ultrasonic sensors and Raspberry Pi devices. The system displayed an error precision of 3-5% after performing several trials and adjustments, which established it as an effective solution for practical applications. Sensor data integration with image processing techniques delivers precise volume calculations that improve road maintenance planning. This proposed method offers a budget-friendly automated solution that improves the present pothole evaluation framework for better road safety and infrastructure management.

Future Scope

Investigations need to incorporate machine learning programs for improving data precision when measuring potholes and determining their classification types. Real-time monitoring through IoT brings additional benefits for data collection accuracy alongside predictive maintenance improvements. Extending the model's exposure to various road materials, coupled with multiple driving conditions, will improve its operational reliability. Researchers need to perform a financial assessment of this system alongside large-scale deployment studies for effective highway and urban road management.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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