RESEARCH ARTICLE

AI-Powered Pothole Detection and Mapping System for Road Safety in Developing Nations

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Abstract

In underdeveloped countries, especially where the infrastructure system is not well-maintained, potholes are responsible for many road-traffic accidents and damage to vehicles. In this work, we explore the feasibility of leveraging AI and smartphone sensors to classify potholes for improving road safety and facilitating on-time repairs. Through the fusion of CNN for image classification and accelerometer data for vibration analysis, this research presents a hybrid model with a detection accuracy of approximately 92%. GPS data enables the generation of heatmaps to help pinpoint areas at the highest risk for targeted interventions. This approach presents a low-cost and scalable technique for road monitoring, particularly in resource-constrained conditions.

Keywords

Artificial Intelligence, Pothole Detection, Road Safety, Smartphone Sensors, Convolutional Neural Networks.

Introduction

Potholes are a common source of road accidents and vehicle destruction in developing countries, where infrastructure maintenance is poorly done. In India, for example, pothole-related road accidents resulted in 5,626 deaths between 2018 and 2020.[1] In Ethiopia, potholes are the most severe distress for paved roads, especially during and after the rainy season.[2] Conventional practice for road inspection is expensive and inefficient. Road traffic deaths in low and middle-income countries contribute to 90% of the total number of global traffic fatalities, though such countries are estimated to have only 54% of all vehicles globally.[3] This contrast highlights the timely requirement of unconventional measures to improve road safety.

Thanks to the development of AI and mobile devices, road monitoring is now capable of a complete transformation, considering that smartphone sensors are now everywhere. Researchers have shown the potential of detecting road anomalies using smartphone accelerometers, with some systems achieving detection accuracy up to 92%.[4] Furthermore, some applications of AI and map visualization in Sensing systems for real-time pothole detection have been designed as a potential solution to the infrastructure monitoring problem.[5]

In this research study, we assess the potential of integrating data collected from accelerometers and a computer vision CNN-based image classifier for the real-time detection and mapping of potholes. Through the integration of these technologies, the goal of this research is to develop a low-cost and sustainable platform for road monitoring to enhance road safety in developing countries.

Numerous studies have explored various methodologies for pothole detection. Mednis *et al*.[6] demonstrated the feasibility of using smartphone accelerometers to detect road anomalies. However, their method had limitations in accuracy-Liu *et al*.[7] improved detection accuracy by employing CNNs on vibration signals. Arya *et al*.[8] utilized image models for road damage detection, but their approach faced challenges under varying weather conditions. More recently, Sahoo *et al.*[9] developed iWatchRoad, integrating YOLO image detection with real-time GPS mapping. Yurdakul *et al.*[10] enhanced pothole detection system by incorporating depth cameras, achieving superior detection performance. This study builds upon these advancements by combining accelerometer data with CNNs to detect and map potholes effectively.

Methods

Data Collection

For this experimental research work, we gathered data through a smartphone connected to the guided bike handlebars. We collected data from the accelerometer and the GPS sensor by using the Physics Toolbox app during some rides along different road sections; real-time data from the smartphone sensors allowed for standardized, precision measurements. In addition, while accelerometer data was collected, images of potholes and smooth roads were photographed with the smartphone camera to provide supplementary feature information. We extracted the above.

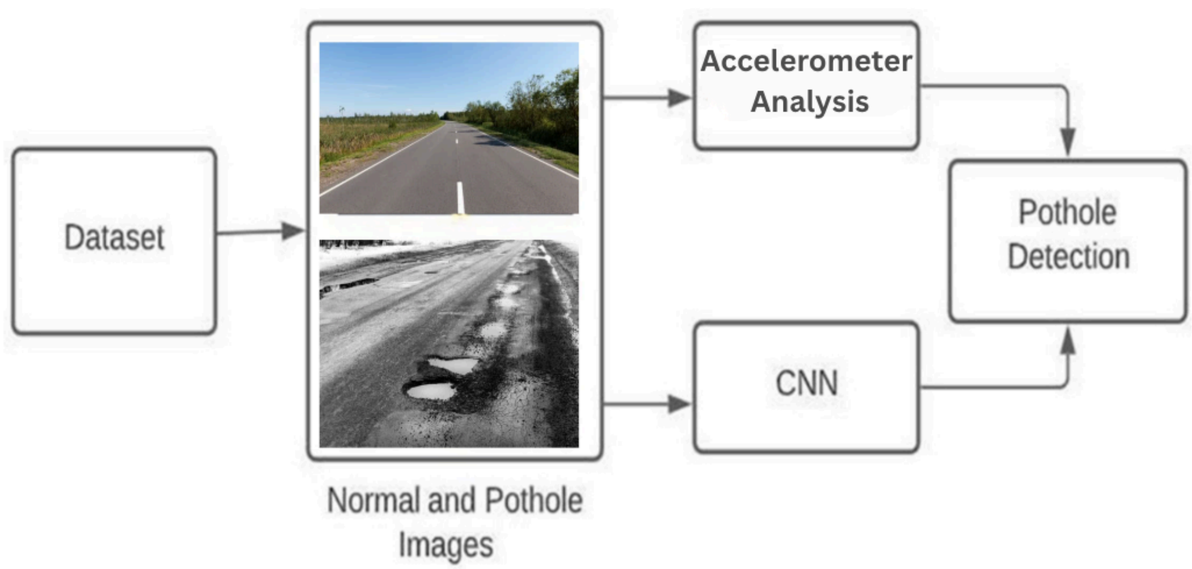

Figure1. Block diagram of proposed methodology. This figure shows the overall process of the proposed pothole detection system. It combines accelerometer data and CNN-based image classification to improve detection accuracy and reliability.

Image Classification

A Convolutional Neural Network (CNN) image classifier was trained using the Teachable Machine platform. The model was trained for classifying pothole and non-pothole images. The trained CNN model was tested on the test set to evaluate its performance. We achieved 85% accuracy scores, which shows how well the model classifies potholes from smooth road surfaces.

Accelerometer Analysis

Accelerometer data were analyzed to detect spikes that are indicative of potholes. These spikes were characterized by a sudden and significant increase in the Z-axis acceleration values, typically resulting from impacts caused by road irregularities. A threshold of 0.25g was established to classify significant accelerations as potential pothole events. This threshold was based on preliminary tests and ensured that only substantial accelerations, indicative of potholes, were considered for further analysis.

Data Fusion

For increased stability in pothole detection and to minimize false positives, a model fusion took place between both accelerometer and image data. Pothole events were verified when both the accelerometer and image model indicated that there was a pothole. This combination of two data sources, with the exploitation of their advantages, considerably reduced the false alarm probabilities and enhanced system reliability. A block diagram of the proposed methodology is presented in Figure 1.

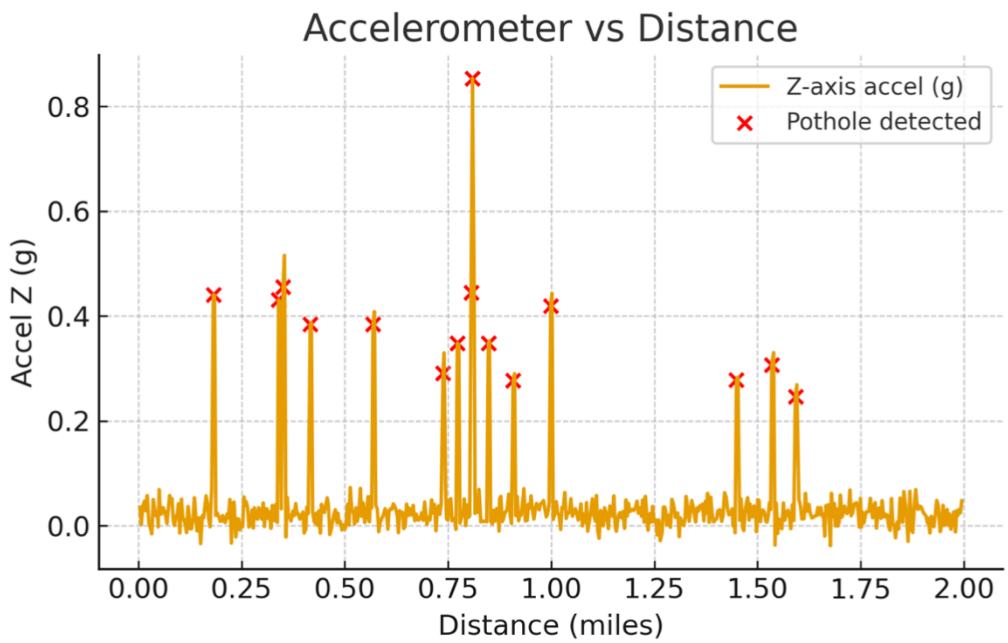

Figure 2. Accelerometer Z-axis vs distance (miles). The plot shows significant acceleration spikes at pothole locations, illustrating how accelerometer data can be used to reliably identify potholes from road surface vibrations.

Mapping

Spatial heatmaps were created with the Kepler.gl visualization tool. The map with heatmaps creates a graphical representation of relative pothole density for various sections of the roads, using warmer colors to represent higher concentrations of identified potholes. The use of this mapping approach focuses repairs where they are most needed and will be most effective, allowing city planners to prioritize road work.

Results

The accelerometer-only model, trained with the information given by the smartphone accelerometer, provided an accuracy of 70%. The distance-based accelerometer data, plotted in Figure 2, also presents the clear spikes due to potholes; additionally, it features the inherent noise of accelerometry. Through these spikes, we could detect potential potholes, but false positives had an impact on the overall results.

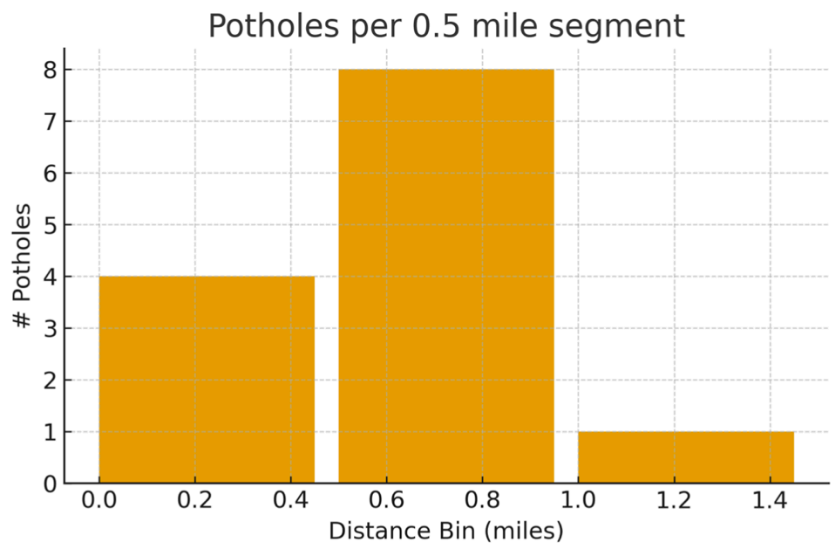

Figure 3. Pothole counts aggregated by 0.5-mile bins. This distribution shows how potholes are concentrated along different road segments, revealing clusters where road conditions deteriorate most severely.

Our CNN-only model, which is trained to classify whether an image represents potholes or non-potholes, reaches an accuracy of 85%. The AI detection model outputs the image with bounding boxes that are drawn around the detected potholes in images from the test. This model increased the degree of accuracy by relying on visual information about the road conditions, but some false classifications are still made, especially in unclear or partially obstructed images. The model integrating accelerometer and image produced much higher detection accuracy, 92%. This model showed a significant enhancement of reliability due to fewer false positives and accurate pothole detection when the accelerometer spikes coincided with image detections. The distribution of pothole counts binned at 0.5-mile intervals provides further evidence for the superior accuracy of fusion over different road segments displayed in Figure 4.

Apart from the correctness of detection, heatmaps based on GPS were also generated, in which hotspots at places with higher concentrations of potholes were displayed. These heatmaps, as depicted in Figure 4, illustrate areas with the greatest number of potholes, which can be optimized for maintenance and repair on a priority basis. Mapping pothole density is essential for urban planning in resource allocation and proactive management of road safety by the local authorities.

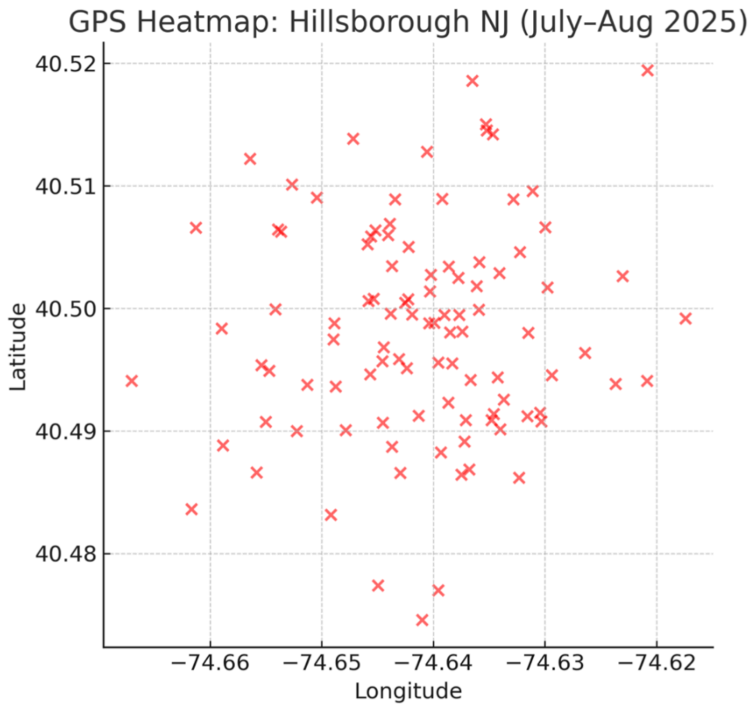

Figure 4. GPS density heatmap of Hillsborough, NJ hikes (July–August 2025). The heatmap visualizes the spatial distribution of potholes, highlighting high-density areas that can help city planners prioritize maintenance and repairs.

Discussion

In this proposed research, the idea of combining accelerometer data with CNN results in a significant improvement in results. The results show that the combined results outperform the individual results of both methods. The applicability of smartphone sensors for road anomaly detection, the accelerometer model alone achieves an accuracy of 70%. However, the signal noise of accelerometers, e.g., spikes in Fig. 2, tended to generate false positives, especially in areas with few issues of road irregularities. The accuracy of the CNN model based on image classification was only 85%. CNNs are particularly known for their capability to identify visual patterns, like potholes, from images of road surfaces. Although CNN-only performed considerably well, it was still subject to misclassification, particularly where partial occlusion of the road existed or under non-uniform lighting conditions. The fusion of an accelerometer and a CNN model outperforms in terms of accuracy by achieving 92% detection accuracy of potholes. Taking advantage of the fusion of data from two sources, the fusion method greatly reduced false positives and improved the robustness of pothole recognition. These findings are aligned with state-of-the-art research that has demonstrated sensor fusion can enhance detection accuracy and system stability.[7] The higher performance of the fusion model in detection accuracy proves the complementary strength of accelerometer and visual data, demonstrating that fusing these two technologies could benefit both identification accuracy and well-known pothole detection sensitivity. The heatmaps from GPS data in Figure 4 provide an important visual description of the spatial distribution of potholes in the area focused on for this research study. These heatmaps will assist urban planners and the local government when they want a quick visual indication of traffic density and would like to prioritize areas for repairs based on pothole concentration. This geospatial perspective on road maintenance can ensure that resources are properly allocated and repair efforts go to the most urgent areas, reducing accidents, with the ultimate aim of increasing the safety of all roads. However, there are some limitations as well. A major drawback is the size of the dataset for both accelerometer and image analysis. A larger, more diverse dataset would further improve the generalizability of the models and give a better picture of their performance in different road types and conditions. Furthermore, due to extreme weather conditions, e.g., rain and fog, the road images captured were not clear, which affects the accelerometer data and image quality. In future research, weather conditions should be considered to collect more data from diverse road types, environmental conditions, or geographical locations. This decision may result in a stronger testing of the performance of the model under real-world use. Furthermore, an extension of the model could be considered if we incorporate environmental parameters like lighting and weather details into the model specifications. As a result, the model will improve its portability and precision under different conditions. In addition, future work may include the scalability aspect of this system across other regions and its viability test for deployment on a large scale, particularly in urban areas where potholes are unchecked.

Overall, the findings from this study support the viability of using AI-powered systems, combining smartphone sensors and image classification, to detect and map potholes in real-time. The use of the fusion method, in particular, promises advancement in road safety supervision and maintenance.

Conclusion

This research study draws attention to the usage of AI-based systems with built-in sensors of smartphones for the identification and mapping of potholes on roads. In developing countries where road facilities are still insufficient, the proposed solution is a low-cost, scalable solution that can greatly improve road safety. Utilizing available technology aids, including accelerometers and cameras, the system offers a useful way of detecting and handling potholes automatically and provides a solution to more efficient road repair operations. An improved accuracy with the integration of the accelerometer data and the AI-based image classification proves that the proposed system is a scalable tool for road safety monitoring. In addition, the system has adaptability in various environments and road conditions; hence, it can be widely used from an urban area to a rural area. For future work, researchers could enhance the diversity of the dataset by considering different kinds of roads and environmental types and testing the system under different weather conditions. Moreover, investigating the incorporation of higher-level AI models and sensors might improve the accuracy and scalability of this system. As it continues to be developed, this AI-based strategy will have the potential for widespread use as a sustainable solution to road safety issues around the globe.

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