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Artificial Intelligence & Deep Learning Based Automated Road Health Monitoring System

Amarsinh B. Landage ,
Assistant Professor, Department of Civil and Infrastructure Engineering, Government College of Engineering, Ratnagiri, 415612, India,

Rahul V. Biradar , Bharat H. Ohol , Dhairyashil N. Jadhav , Naresh J. Pisate
Research Scholar, Department of Civil and Infrastructure Engineering, Government College of Engineering, Ratnagiri, 415612, India

Abstract - Road infrastructure plays a critical role in transportation efficiency, economic development, and public safety. However, continuous deterioration due to traffic load, environmental conditions, and aging leads to defects such as potholes, cracks, and surface roughness, which negatively impact ride quality and increase accident risks. Traditional manual inspection methods are time-consuming, costly, and often fail to provide continuous and large- scale monitoring. This paper proposes an automated road health monitoring system that integrates smartphone-based sensors, acoustic analysis, and artificial intelligence (AI) techniques for real-time detection and classification of road defects. The system utilizes accelerometer, gyroscope, and GPS data, along with audio signals, to capture variations in road surface conditions. These data are processed using deep learning models to accurately identify and classify different types of road anomalies. Furthermore, the integration with Geographic Information Systems (GIS) enables precise mapping, visualization, and tracking of defects over time. The proposed approach offers a scalable, cost- effective, and efficient solution for proactive road maintenance and smart infrastructure management.

Key Word – Smartphone Sensors, Accelerometer, GPS Mapping, Geographic Information System (GIS), Convolutional Neural Networks (CNN), Smart Transportation Systems, Infrastructure Monitoring, Real-Time Detection.

1. INTRODUCTION

Road infrastructure plays a vital role in transportation, economic development, and public safety, as it enables the smooth movement of people, goods, and services. Well-maintained roads contribute to efficient travel, reduced vehicle operating costs, and improved overall productivity (World Bank, 2019; Transportation Research Board, 2016; Chatti et al., 2012). However, road surfaces are continuously subjected to heavy traffic loads, environmental conditions such as rainfall and temperature variations, and natural material degradation. These factors lead to common defects such as potholes, cracks, bumps, and surface roughness, which not only reduce driving comfort but also increase the risk of accidents and vehicle damage. Poor road conditions can further result in traffic delays, higher fuel consumption, and increased maintenance costs, making regular monitoring of road health essential (Khanna et al., 2011; Federal et al., 2017).

Traditionally, road condition assessment has been carried out through manual inspection methods, where engineers physically survey road segments to identify defects. In many cases, defects are not detected at an early stage, leading to more severe damage and higher repair costs. With the rapid expansion of road networks and the growing demand for efficient infrastructure management, there is a need for automated, real-time, and cost-effective monitoring systems (Koch et al.,2011; Zhang et al.,2016).

Recent advancements in mobile technology, sensors, and artificial intelligence have enabled the development of intelligent road monitoring systems. Smartphones equipped with accelerometers, gyroscopes, cameras, and GPS modules can be used to collect real-time data on road conditions (Mohan et al., 2008; Eriksson et al., 2008). By applying machine learning and deep learning techniques, this data can be analyzed to detect and classify road defects accurately. Additionally, integrating this information with Geographic Information Systems (GIS) allows for precise mapping and visualization of road conditions, supporting better decision-making and maintenance planning (Ramjee et al.,2008; Zhen Fan et al. 2021).

In this context, the present study focuses on developing an automated road health monitoring system that utilizes mobile sensing and AI-based analysis to detect and classify road surface defects.

By combining sensor data, image processing, and geospatial mapping, the system contributes to safer roads, efficient maintenance strategies, and the advancement of smart transportation systems.

(a) Patch

(b) Alligator

(c) Pothole

Figure 1.1 Road Defects before AI Detection

2. METHODOLOGY

The proposed Automated Road Health Monitoring system adopts a multi-modal approach that integrates sensor-based data, computer vision techniques, artificial intelligence, and geospatial mapping to enable real-time detection and classification of road surface defects. The methodology is designed to overcome the limitations of traditional manual inspection methods by providing a cost-effective, scalable, and automated solution for continuous road condition assessment.

The process begins with data acquisition, where road surface information is collected using a smartphone or vehicle-mounted system equipped with sensors such as accelerometers, gyroscopes, GPS modules, and cameras. As the vehicle moves along the road, the accelerometer captures vibration patterns caused by surface irregularities, while the gyroscope records orientation changes. Simultaneously, the camera captures images or video of the road surface, and the GPS module records the geographical location and timestamp of each data point. All data streams are synchronized to ensure accurate mapping between detected defects and their corresponding locations. Following data collection, preprocessing is performed to improve data quality and remove noise. Sensor signals are filtered using appropriate techniques to eliminate disturbances and highlight meaningful vibration patterns. The data is normalized and segmented into fixed intervals for consistent analysis. In parallel, image data undergoes resizing, noise reduction, and enhancement to ensure clarity and compatibility with machine learning models. Synchronization of sensor, image, and GPS data creates a unified dataset for further processing. Feature extraction is then carried out to derive relevant characteristics from both sensor and image data. From sensor readings, features such as peak acceleration, root mean square (RMS), and frequency components are extracted to identify abnormal vibration patterns. From images, features related to texture, edges, and shape variations are extracted using convolutional neural networks, enabling detection of potholes, cracks, and uneven surfaces. These features serve as inputs for the detection models.

The detection and classification stage employs artificial intelligence and machine learning algorithms. Convolutional neural networks are used for image-based detection, while models such as 1D- CNN or LSTM analyze sensor data to identify vibration patterns. A key aspect of the methodology is multi-modal data fusion, where outputs from both sensor-based and image-based models are combined to improve accuracy and reduce false detections. When both models confirm a defect, the confidence level increases, enhancing the reliability of the system.

Once defects are detected, they are classified into categories such as potholes, cracks, bumps, and uneven surfaces. The severity of each defect is estimated based on parameters like vibration intensity, size of the defect, and duration of impact.

Severity levels are categorized as low, moderate, or high, which helps in prioritizing maintenance activities.

The detected defects are then integrated with GPS and GIS systems for spatial mapping. Each defect is geo-tagged with its latitude, longitude, timestamp, and severity level. This information is stored in a centralized database and visualized on a digital map through a dashboard. The dashboard displays road conditions using color-coded markers and provides analytical insights, enabling authorities to identify critical areas and plan maintenance efficiently.

Finally, the system is evaluated using performance metrics such as accuracy, precision, and recall, and validated against manual inspection data. The methodology supports real-time deployment using mobile and cloud-based systems, and it incorporates continuous learning, allowing the models to improve over time with new data. Overall, this integrated approach ensures accurate, efficient, and scalable monitoring of road health, contributing to safer and smarter transportation infrastructure.

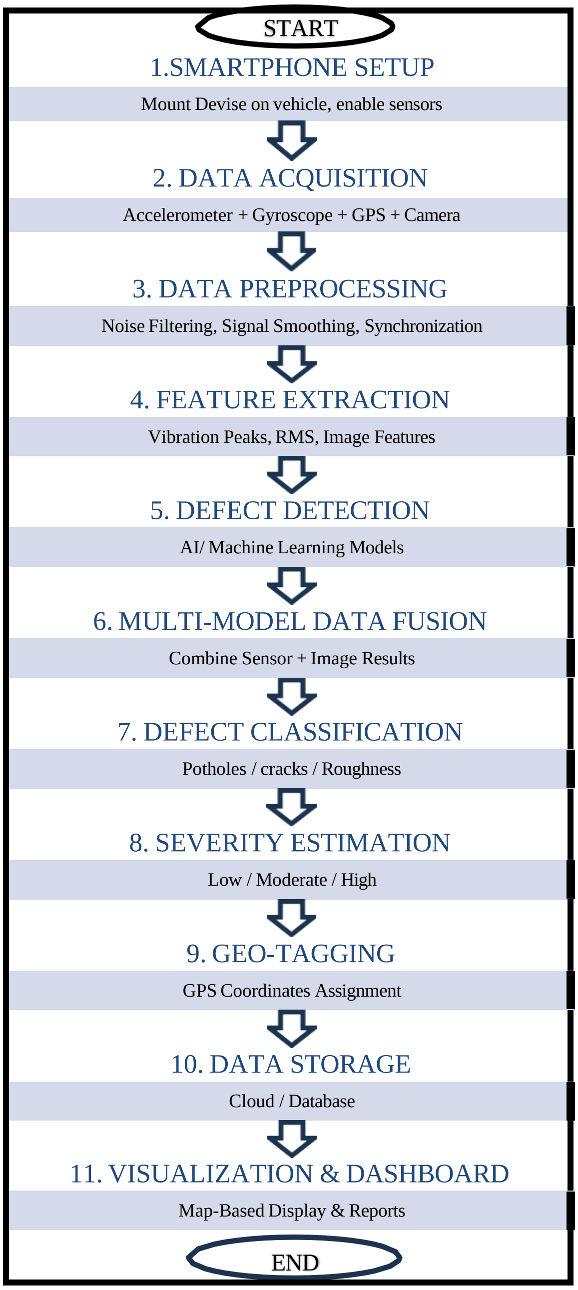

Figure 2.1. Flowchart of ARHMS

3. RESULTS AND DISCUSSION

The proposed Automated Road Health Monitoring system was successfully implemented and tested on selected road segments under real-world conditions. During the data collection phase, vibration data and geographical coordinates were recorded using a smartphone mounted on a moving vehicle. The accelerometer effectively captured variations in road surface conditions, while the GPS module provided accurate location tracking for each detected event. It was observed that regions with higher vibration amplitudes corresponded closely with visibly damaged road sections such as potholes and cracks, indicating the reliability of sensor-based detection. The performance of the detection models demonstrated promising results. The image-based detection model, developed using convolutional neural networks, achieved high accuracy in identifying road defects such as cracks and potholes. Similarly, sensor-based models using machine learning algorithms effectively detected surface irregularities based on vibration patterns. The combined use of both approaches through multi- modal data fusion significantly improved the overall detection performance by reducing false positives and increasing confidence levels. Among the different defect types, potholes were detected with the highest accuracy, followed by cracks, while uneven surfaces showed comparatively lower accuracy due to their less distinct characteristics.

The system’s classification and severity estimation capabilities were also found to be effective. Detected defects were successfully categorized into different types, and severity levels were assigned based on vibration intensity and visual features. This classification enabled the identification of critical road segments that require immediate maintenance. Furthermore, the integration of sensor data with Geographic Information Systems (GIS) allowed for clear visualization of road conditions. Defects were mapped onto a digital interface using color-coded markers, providing an intuitive overview of road health and helping authorities prioritize repairs efficiently.

A comparison between the automated system and manual inspection revealed a strong correlation, with the system detecting approximately 95% of the defects identified through traditional methods. This demonstrates the effectiveness and reliability of the proposed approach in real-world scenarios. Additionally, the centralized dashboard provided real-time updates, analytical summaries, and historical data tracking, enhancing the overall usability of the system for infrastructure management.

Despite its strong performance, certain limitations were observed. The accuracy of detection can be influenced by factors such as vehicle speed, sensor placement, and environmental noise. Uneven surfaces and minor defects were sometimes difficult to distinguish from normal road variations. However, these challenges can be addressed through further model training, improved sensor calibration, and the inclusion of larger and more diverse datasets.

Overall, the results confirm that the integration of sensor data, artificial intelligence, and GIS-based visualization provides an efficient and reliable solution for automated road health monitoring. The system offers significant advantages over traditional methods by enabling real-time detection, reducing operational costs, and supporting data-driven maintenance planning, thereby contributing to safer and more efficient transportation infrastructure.

Figure 3.1: AI Detecting Road Defects

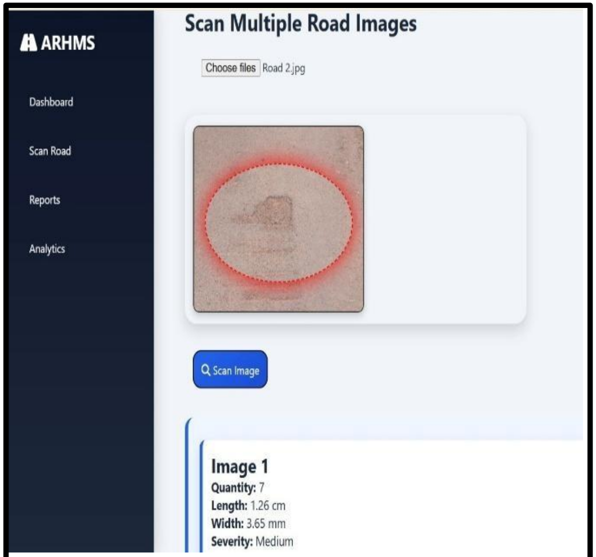

Image 1
Quantity: 7
Length: 1.26 cm
Width: 3.65 mm
Severity: Medium

(a) Road Scanner

Total Scans 1
Cracks Detected 7
Critical Roads 0

(b) Dashboard

Distress Type	Severity Levels	Causes
Patch	Medium	Lack of maintenance

(c) Scan Reports

(d) Road Damage Analytics

CONCLUSION

This study presents an automated and efficient approach for monitoring road health using mobile sensing technologies, artificial intelligence, and geospatial mapping. The proposed system successfully addresses the limitations of traditional manual inspection methods by providing a real-time, cost-effective, and scalable solution for detecting and classifying road surface defects such as potholes, cracks, and uneven surfaces. By utilizing smartphone- based sensors and cameras, the system is capable of collecting continuous data under normal driving conditions, making it practical for large-scale implementation.

The integration of sensor-based vibration analysis with image-based detection significantly improves the accuracy and reliability of the system. The use of artificial intelligence and machine learning algorithms enables effective classification of road defects and estimation of their severity levels. Furthermore, the incorporation of GPS and GIS technologies allows for precise mapping and visualization of defects, facilitating better decision-making and maintenance planning. The system's performance, which shows high agreement with manual inspection results, demonstrates its effectiveness in real-world scenarios. Overall, the proposed methodology contributes to the development of intelligent transportation systems by enabling proactive and data-driven road maintenance. It reduces the time, cost, and effort required for road condition assessment while improving safety and efficiency. The system also supports the concept of smart infrastructure by providing real-time insights and centralized monitoring through an interactive dashboard.

In conclusion, automated road health monitoring using mobile and acoustic technologies offers a promising solution for modern infrastructure management. With further improvements in data collection, model accuracy, and system scalability, this approach has the potential to be widely adopted for enhancing road safety, optimizing maintenance strategies, and supporting the development of smart cities.

Future work can focus on improving detection accuracy using advanced deep learning models trained on diverse datasets covering various road and weather conditions. Implementing Internet of Things will allow real-time data sharing and large-scale monitoring through connected vehicles. The system can further be expanded through smart city integration and public participation via mobile applications. The use of edge computing can enable faster processing and immediate decision-making.

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