Multi-Modal Edge-AI System for Real-Time Road Health Diagnostics using Vision-Acoustic Sensor Fusion

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Abstract—

Road surface defects such as potholes are a major concern for road safety, vehicle performance, and infrastructure maintenance. Traditional inspection methods are often time-consuming, expensive, and unsuitable for continuous monitoring. This paper presents a Multi-Modal Edge AI System for Real-Time Road Health Diagnostics Using Vision-Acoustic Sensor Fusion. The proposed system combines OpenCV-based computer vision with vibration sensor data to improve the accuracy and reliability of pothole detection. A Raspberry Pi performs real-time edge processing, while GPS records the location of detected road defects for visualization on Google Maps. By integrating multiple sensing techniques, the system minimizes false detections and enables efficient road condition monitoring without relying on continuous cloud connectivity. The proposed approach provides a low-cost, scalable, and practical solution for intelligent transportation systems, smart city applications, and timely road maintenance.

Keywords— Edge AI, Road Health Monitoring, Pothole Detection, OpenCV, Sensor Fusion, Raspberry Pi, GPS, Computer Vision, Intelligent Transportation Systems (ITS), Smart Infrastructure.

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I. INTRODUCTION

Road transportation is an essential component of modern infrastructure that supports economic development, public safety, and daily commuting. A well-maintained road network ensures the smooth movement of people, goods, and emergency services. However, continuous exposure to heavy traffic, changing weather conditions, and increasing vehicle loads causes gradual deterioration of road surfaces, leading to potholes, cracks, and other structural defects. These road damages not only affect driving comfort but also increase the likelihood of accidents, vehicle wear, fuel consumption, and maintenance expenses. Therefore, regular monitoring of road conditions is necessary to improve road safety and ensure timely maintenance of transportation infrastructure.

Conventional road inspection methods mainly rely on manual surveys or specialized inspection vehicles. Although these approaches are capable of identifying road defects, they are often expensive, time-consuming, and labor-intensive. Since inspections are carried out only at scheduled intervals, newly developed potholes may remain unnoticed for extended periods. In addition, manual inspection is susceptible to human error, which can delay maintenance activities and reduce the overall efficiency of road management. As transportation networks continue to expand, there is an increasing need for automated systems that can detect road damage accurately and provide real-time monitoring.

Recent advancements in Artificial Intelligence (AI), Edge Computing, Computer Vision, and the Internet of Things (IoT) have enabled the development of intelligent road monitoring solutions. Unlike traditional cloud-based systems, Edge AI processes data directly on embedded devices, reducing communication delays, improving response time, and minimizing dependence on continuous internet connectivity. Affordable platforms such as the Raspberry Pi have made it possible to deploy computer vision algorithms in real-world environments, allowing road conditions to be analysed efficiently while keeping system costs low.

Vision-based road monitoring systems have shown promising results in detecting potholes, but their performance can be affected by poor lighting, shadows, rain, and other environmental conditions. To overcome these challenges, sensor fusion techniques combine information from multiple sensors to improve detection accuracy and reduce false alarms. Integrating visual data with vibration signals enables the system to verify road defects more reliably, resulting in a more robust and consistent road monitoring solution.

This paper proposes a Multi-Modal Edge AI System for Real-Time Road Health Diagnostics Using Vision-Acoustic Sensor Fusion. The proposed system uses a Raspberry Pi to perform real-time processing of images captured by a camera using OpenCV, while a vibration sensor records the impact caused by damaged road surfaces. The information from both sensors is fused to improve pothole detection accuracy. Once a pothole is identified, its location is obtained through a GPS module and displayed on Google Maps to support road maintenance planning and provide timely alerts to road users. The proposed approach offers a cost-effective, scalable, and efficient solution for intelligent road monitoring, making it well suited for smart city infrastructure and modern intelligent transportation systems.

II. LITERATURE REVIEW

Y. Wu, K. Chen, and T. Liang (2026), in "Edge-Cloud Collaborative Pothole Detection via Federated Temporal Segmentation," proposed an intelligent pothole detection framework that combines edge computing with cloud collaboration using federated learning. In this approach, road data is processed directly on edge devices, which helps reduce latency and bandwidth usage. Federated learning enables multiple devices to train a common deep learning model without sharing raw data, thereby improving privacy and scalability. The proposed temporal segmentation technique accurately detects potholes and road anomalies in real time. The experimental results demonstrated improved performance for intelligent transportation
applications and highlighted the importance of

combining edge computing with federated learning for modern road monitoring systems.[1]

I. Romero, H. Mantz, T. Walter, and M. Schneider (2025), in "Multi-Sensor Pothole Detection and Monitoring System," presented a road monitoring framework that integrates multiple sensing technologies to improve pothole detection. The system combines vision sensors, vibration sensors, and monitoring modules to analyse road conditions more effectively. By applying sensor fusion techniques, information from different sensors is merged to reduce false detections and improve overall detection accuracy. The embedded processing unit enables real-time monitoring, making the system reliable even under different environmental conditions. The study concluded that multi-sensor integration significantly enhances the robustness and performance of pothole detection systems.[2]

A. G. Nair, J. Baskar, V. Kumar, and A. Krishnan (2025), in "DeepRoadGuard: Enhanced Pothole Detection Using Bayesian Fusion and Night-Vision Data," focused on improving pothole detection during nighttime and other low-light conditions. The proposed framework combines night-vision camera data with Bayesian sensor fusion techniques to achieve reliable road anomaly detection. Deep learning models analyse the captured images along with additional sensor information to improve prediction accuracy. This approach minimizes false detections caused by poor lighting, shadows, and reflections. Experimental results showed that the system performs better than conventional vision-based methods, making it suitable for intelligent transportation systems and autonomous driving applications.[3]

Muhammad Haroon Asad, Saran Khaliq, Muhammad Haroon Yousaf, Muhammad Obaid Ullah, Afaq Ahmad, and Qian Chen (2025), in "Pothole Detection Using Deep Learning: A Real-Time and AI-on-the-Edge Perspective," proposed an Edge AI-based pothole detection system capable of performing real-time road damage detection using lightweight deep learning models deployed on Raspberry Pi and OAK-D hardware. The authors evaluated different object detection models, including YOLO variants and SSD-MobileNet, by comparing their detection accuracy and execution speed. Since all processing is performed directly on edge devices, the framework eliminates continuous cloud communication and reduces system latency. Experimental results confirmed that lightweight deep learning models can accurately detect potholes under different lighting and environmental conditions. The study demonstrated that Edge AI provides an efficient, cost-effective, and practical solution for intelligent road monitoring.[4]

Junkui Zhong, Deyi Kong, Yuliang Wei, Bin Pan, et al. (2025), in "YOLOv8 and Point Cloud Fusion for Enhanced Road Pothole Detection and Quantification," introduced an advanced pothole detection framework that combines the YOLOv8 object detection model with point cloud information collected from depth cameras. By integrating visual images with three-dimensional depth data, the system improves pothole localization, size estimation, and depth measurement. Sensor fusion techniques further reduce false detections and provide more accurate road damage assessment compared to conventional image-based methods. Experimental evaluation demonstrated better detection accuracy under complex road conditions, making the framework suitable for autonomous vehicles, intelligent transportation systems, and smart road infrastructure monitoring.[5]

Iren Damayanti and Zico Pratama Putra (2025), in "Deploying Edge AI for Road Surface Damage Detection Using TensorFlow Lite and Teachable Machine," presented an Edge AI framework for detecting road surface damage using TensorFlow Lite models deployed on embedded and mobile devices. The proposed system employs lightweight convolutional neural networks that are optimized for real-time execution without relying on continuous cloud connectivity. This approach enables efficient road damage classification while maintaining low power consumption on affordable hardware platforms. Experimental
results demonstrated that Edge AI can provide

accurate and responsive road monitoring, making it a practical solution for smart infrastructure applications. The study also highlighted the benefits of deploying lightweight AI models for intelligent transportation systems.[6]

S. Sharma, P. Verma, R. Gupta, and A. Kumar (2024), in "Edge Intelligence-Based Road Damage Detection Using Lightweight Deep Learning Models," proposed an intelligent road monitoring system that uses lightweight deep learning models deployed on edge computing devices. The system captures road images through a vehicle-mounted camera and processes them locally using optimized convolutional neural networks. Performing computations directly on the edge device reduces response time, minimizes network dependency, and enables faster decision-making. The proposed model is designed to operate efficiently on resource-constrained embedded platforms while maintaining high detection accuracy. Experimental evaluation showed that the system successfully detects potholes, cracks, and other road surface defects under different environmental conditions. The authors concluded that edge-based processing improves system reliability, lowers communication costs, and enhances data privacy, making the solution suitable for intelligent transportation systems and smart road infrastructure. [7]

K. Ghafoor, M. A. M. Sadeeq, and S. R. M. Zeebaree (2023), in "IoT and Cloud Based Automated Pothole Detection Model Using Extreme Gradient Boosting," introduced an IoT-enabled pothole detection framework that combines cloud computing with the Extreme Gradient Boosting (XGBoost) machine learning algorithm. Road condition data collected through sensors is transmitted to cloud servers for analysis and monitoring. The machine learning model classifies potholes and other road anomalies with improved accuracy, while IoT communication enables remote monitoring and predictive maintenance. Experimental results demonstrated efficient pothole classification and real-time monitoring capabilities. However, the authors noted that the system depends heavily on reliable internet connectivity and cloud infrastructure, which may affect its performance in areas with limited network access. [8]

Mounir Ghogho et al. (2023), in "Sustainable Road Pothole Detection: A Crowdsourcing Based Multi-Sensors Fusion Approach," proposed a crowdsourcing-based framework for continuous road condition monitoring. The system combines data collected from smartphone accelerometers, GPS sensors, and vehicle-mounted cameras to detect potholes more effectively. By applying multi-sensor fusion techniques, the framework improves detection reliability and significantly reduces false positives. The crowdsourcing approach allows road information to be collected from multiple users, eliminating the need for dedicated inspection vehicles. Experimental results demonstrated that the proposed system provides a scalable, cost-effective, and reliable solution for smart city road maintenance. [9]

Yu Ting Huang, Mohammad R. Jahanshahi, Fangjia Shen, and Tarutal Ghosh Mondal (2023), in "Deep Learning-Based Autonomous Road Condition Assessment Leveraging Inexpensive RGB and Depth Sensors and Heterogeneous Data Fusion: Pothole Detection and Quantification," presented an autonomous road inspection system that combines RGB cameras with depth sensors for accurate pothole detection and measurement. The proposed framework uses heterogeneous data fusion to integrate colour images with depth information, enabling precise estimation of pothole dimensions and overall road surface conditions. Lightweight deep learning models deployed on an edge computing platform provide real-time performance while maintaining low computational overhead. Experimental results showed improved localization accuracy compared to conventional vision-based approaches, demonstrating that combining multiple sensing technologies significantly enhances road condition assessment. [10]

R. G. Gowda and G. P. Revathi (2023), in "Real Time Pothole Detection Using Machine Learning and Edge Computing," proposed a real-time pothole detection system that combines machine learning with edge computing technologies. In this framework, AI models are deployed directly on edge devices to minimize processing delays and reduce dependency on cloud-based systems. Road images captured by cameras are analysed locally using computer vision techniques, allowing the system to respond quickly to road defects. Experimental results demonstrated efficient pothole detection with low latency, making the framework suitable for intelligent transportation systems and smart road monitoring applications. [11]

R. Fan, H. Wang, and M. Liu (2022), in "Road Surface 3D Reconstruction and Pothole Detection," introduced a pothole detection approach based on stereo vision and three-dimensional road surface reconstruction. The proposed framework uses disparity mapping and depth estimation techniques to analyse road conditions more accurately. By measuring pothole depth, size, and shape using 3D information, the system achieves higher detection precision than conventional two-dimensional image-based methods. Computer vision algorithms are employed for road segmentation and anomaly detection. Experimental evaluation showed high accuracy in pothole depth estimation; however, the authors pointed out that the method requires significant computational resources for real-time processing. [12]

M. Prakash B. and K. C. Sriharipriya (2022), in "Enhanced Pothole Detection System Using YOLOX Algorithm," presented a real-time pothole detection framework based on the YOLOX deep learning algorithm. The system analyses road images captured by cameras and detects potholes with improved speed and accuracy compared to earlier YOLO models. Deep learning techniques are used to extract important road features and identify potholes under different environmental conditions. Experimental results confirmed that the proposed framework provides reliable detection performance while reducing processing time, making it suitable for embedded AI systems, autonomous vehicles, and intelligent transportation applications. [13]

N. Ma, H. Wang, J. Zhao, and Q. Yang (2022), in "Computer Vision for Road Imaging and Pothole Detection: A State-of-the-Art Review of Systems and Algorithms," presented a comprehensive review of existing pothole detection techniques based on computer vision and artificial intelligence. The authors compared various machine learning, deep learning, and image processing methods by evaluating their detection accuracy, execution speed, and implementation complexity. The review also discussed several challenges faced by current systems, including poor lighting conditions, shadows, rainfall, and motion blur. The study concluded that lightweight AI models and multi-modal sensor fusion are promising approaches for improving the reliability and accuracy of future intelligent road monitoring systems. [14]

J. Fan, Y. Wang, M. Liu, and X. Shen (2021), in "Multi-Scale Feature Fusion for Road Pothole Detection," proposed a pothole detection framework based on multi-scale feature fusion. The method combines image features extracted at different scales to improve pothole localization and detection accuracy. Semantic segmentation techniques are used to identify damaged road regions of different sizes and shapes more effectively. Experimental results demonstrated that multi-scale feature fusion provides better segmentation performance than conventional convolutional neural network approaches. The authors also emphasized the importance of large, well-annotated datasets for training deep learning models capable of achieving reliable pothole detection. [15]

K. R. Ahmed, M. T. Hossain, and S. Rahman (2021), in "Smart Pothole Detection Using Deep Learning Based on Dilated Convolution," proposed a deep learning-based pothole detection system that utilizes dilated convolution to improve feature extraction without reducing image resolution. By expanding the receptive field of the neural network, the model captures more detailed road features and accurately identifies potholes of different shapes and sizes. Road images are processed using convolutional neural

networks to detect damaged surfaces efficiently.

Experimental results showed that the proposed method achieved higher detection accuracy than conventional CNN-based approaches. However, the system's performance was found to decline under noisy environments and poor lighting conditions. [16]

A. Dhiman and R. Klette (2020), in "Pothole Detection Using Computer Vision and Learning," presented a pothole detection framework based on computer vision and machine learning techniques. The proposed system analyses road images captured by cameras using image processing algorithms and deep learning models to identify road surface defects. Various feature extraction and classification methods were evaluated to improve pothole detection performance. Experimental results demonstrated reliable detection under normal road conditions, making the approach suitable for automated road inspection and intelligent transportation applications. However, the authors observed that lighting variations, shadows, and adverse weather conditions can affect the system's overall accuracy. [17]

E. N. Ukhwah, Y. K. Suprapto, and E. M. Yuniarno (2019), in "Asphalt Pavement Pothole Detection Using Deep Learning Based on YOLO Neural Network," proposed a real-time pothole detection framework using the YOLO deep learning algorithm. The system processes images of asphalt roads captured through cameras and accurately identifies potholes within the road surface. The YOLO model enables fast object detection while maintaining high localization accuracy. The network is trained using road damage datasets to improve detection performance under different conditions. Experimental evaluation confirmed that the proposed method provides efficient pothole classification and real-time operation, making it suitable for smart transportation and automated road inspection systems. [18]

R. Carlos, E. Meneguette, and L. Villas (2018), in "Evaluation of Detection Approaches for Road Anomalies Based on Accelerometer Readings," evaluated different techniques for detecting road anomalies using accelerometer sensor data. The study analysed vibration patterns generated when vehicles travelled over damaged road surfaces and compared several machine learning and signal processing methods for pothole identification. The accelerometer-based approach was found to be a simple and cost-effective solution for monitoring road conditions. Experimental results demonstrated effective pothole detection and road irregularity analysis. However, the authors noted that variations in vehicle suspension systems and driving behaviour could lead to false detections. [19]

U. Bhatt, S. Mani, E. Xi, and J. Z. Kolter (2017), in "Intelligent Pothole Detection and Road Condition Assessment," proposed an intelligent framework for road condition assessment using artificial intelligence techniques. The system analyses road images along with sensor information to detect potholes and evaluate overall road quality. Machine learning algorithms automatically classify different types of road damage and support continuous monitoring of transportation infrastructure. Experimental analysis showed improved road anomaly detection compared to traditional inspection methods. The study also emphasized the growing importance of AI-driven solutions for large-scale road monitoring and efficient maintenance planning. [20]

III. CONCLUSION

The proposed Multi-Modal Edge AI System provides a reliable and cost-effective solution for real-time pothole detection using Edge AI and sensor fusion. By combining computer vision, vibration sensing, and GPS, the system improves detection accuracy and supports timely road maintenance. This approach contributes to safer roads and more efficient intelligent transportation systems.

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