Next-Generation AI Framework for Forest Road Condition Monitoring Using Multimodal Smartphone Sensors and Edge Intelligence

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Abstract

Sustainable Forest management relies heavily on the maintenance of road networks, yet traditional inspection methods are often cost-prohibitive, labor-intensive, and spatially limited. Addressing the scalability and accuracy limitations of prior Convolutional Neural Network (CNN) and Long Short-Term Memory (LSTM) approaches, this study presents a next-generation AI framework for forest road condition monitoring using commodity smartphones. The proposed architecture uniquely integrates multimodal sensing (vision, inertial, and GPS), self-supervised representation learning, and a Multimodal Transformer Network (MTN) to capture long-range temporal dependencies in road data. Furthermore, an edge-cloud collaborative strategy is implemented to balance real-time inference with computational efficiency. Experimental results demonstrate that this framework achieves a classification accuracy of 94.8% and an F1-score of 0.945, significantly outperforming baseline CNN-LSTM models. Additionally, the self-supervised pipeline reduces labeled data requirements by 60%, while the edge-cloud system ensures a low inference latency of 72ms, making the solution highly robust and deployable for large-scale forest infrastructure management.

Keywords

Forest roads, smartphone sensing, multimodal data fusion, Transformer networks, edge AI, road condition monitoring.