International Journal of Engineering Research and Science & Technology

ISSN 2319-5991 www.ijerst.com
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Peer Reviewed, Referred & Indexed Journal

Research Paper

EDGE-READY ROAD DAMAGE DETECTION USING AN ENHANCED YOLO WITH HYPERPARAMETER TUNING

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ABSTRACT— Maintaining road quality is a crucial aspect of smart city development and public safety, as damaged roads can lead to traffic congestion, accidents, and increased vehicle maintenance costs. Traditional road inspection methods rely heavily on manual surveys, which are not only time-consuming but also costly and prone to human error. With the rapid growth of urban infrastructure, the need for automated, accurate, and scalable road damage detection systems has become more urgent. Recent advances in deep learning and computer vision provide an opportunity to address these challenges by enabling real-time damage detection using high-performance object detection models.

In this study, we present a road damage detection framework built on the YOLOv10n model, optimized specifically for real-time deployment on edge devices. The proposed system incorporates advanced hyperparameter tuning to achieve a balance between accuracy and computational efficiency. Unlike heavier detection models, YOLOv10n is lightweight yet powerful, making it suitable for resource-constrained environments. The framework demonstrates robust detection capabilities with a precision of 0.986, recall of 0.973, mean average precision (mAP@0.5) of 0.988, and an F1-score of 0.978, confirming its reliability in identifying different types of road damages such as cracks, potholes, and surface wear.

The performance of the proposed framework was validated through deployment on two widely used edge devices: the NVIDIA Jetson Nano and the NVIDIA AGX Orin. On the Jetson Nano, the model achieved an inference speed of 0.13 seconds per frame (7.5 FPS), while on the AGX Orin, it reached 0.014 seconds per frame (67 FPS). These results demonstrate not only the scalability of the approach but also its efficiency in real-world applications. By enabling faster and more accurate road condition assessments, the system supports proactive maintenance strategies, reduces inspection costs, and ultimately contributes to safer and smarter transportation infrastructures.

Index Terms – Road Damage Detection, Enhanced YOLO, Edge Computing, Hyperparameter Tuning, Deep Learning, Object Detection, Computer Vision, Pavement Inspection, Smart Infrastructure, Real-Time Monitoring.

I. INTRODUCTION

Road infrastructure plays a vital role in ensuring the safety, efficiency, and sustainability of modern transportation systems. Well-maintained roads not only reduce the likelihood of accidents but also enhance driving comfort and decrease vehicle operating costs. However, road damage such as cracks, potholes, and surface wear is inevitable due to weather conditions, heavy traffic, and natural aging of materials. If not identified and repaired in time, such damages can lead to further deterioration, higher maintenance costs, and potential hazards for road users. Therefore, timely and accurate road damage detection is an essential component in the development of smart cities and intelligent transportation systems.

Traditional road inspection methods rely heavily on manual surveys conducted by experts or local authorities. While effective on a small scale, these methods are labor-intensive, costly, and prone to subjectivity, making them unsuitable for large-scale urban environments. Recent advancements in computer vision and artificial intelligence have enabled the development of automated road monitoring systems. Several deep learning-based approaches have been proposed for damage detection; however, most of them require high computational resources, making them impractical for real-time deployment on resource-constrained edge devices. This gap highlights the need for a lightweight yet accurate framework that can balance detection performance with real-time efficiency.

To address these challenges, this study proposes a YOLOv10n-based road damage detection framework optimized for real-time applications on edge devices such as NVIDIA Jetson Nano and AGX Orin. The system leverages hyperparameter tuning and model optimization techniques to achieve high accuracy while maintaining low computational complexity. Extensive evaluation shows that the proposed model achieves a precision of 0.986, recall of 0.973, mAP@0.5 of 0.988, and an F1-score of 0.978. Furthermore, the deployment results demonstrate promising inference speeds of 7.5 FPS on Jetson Nano and 67 FPS on AGX Orin, proving the scalability and robustness of the approach. This work contributes toward the advancement of smart road maintenance systems, enabling faster decision-making and improved road safety.

II. RELATED WORK

A. Automatic Defect Detection of Pavement Diseases

Pavement disease detection is an important task for ensuring road safety. Manual visual detection requires a significant amount of time and effort. Therefore, an automated road disease identification technique is required to guarantee that city tasks are performed. However, due to the irregular shape and large-scale differences in road diseases, as well as the imbalance between the foreground and background, the task is challenging. Because of this, we created the deep convolution neural network—DASNet, which can be used to identify road diseases automatically. The network employs deformable convolution instead of regular convolution as the feature pyramid's input, adds the same supervision signal to the multi-scale features before feature fusion, decreases the semantic difference, extracts context information by residual feature enhancement, and reduces the information loss of the pyramid's top-level feature map. Considering the unique shape of road diseases, imbalance problems between the foreground and background are common, therefore, we introduce the sample weighted loss function. In order to prove the superiority and effectiveness of this method, it is compared to the latest method. A large number of experiments show that this method is superior in accuracy to other methods, specifically, under the COCO evaluation metric, compared with the Faster RCNN baseline, the proposed.

B. Real-Time Road Defect Monitoring from UAV Visual Data Sources

The use of UAVs and artificial intelligence has emerged as a promising approach for

monitoring road defects. This paper highlights the importance of these technologies in improving road inspection, maintenance, and safety. Traditional methods for inspecting roads are often time-consuming, expensive, and can put human inspectors in dangerous situations. However, drones equipped with high-resolution cameras and sensors can capture pavement image data quickly and safely. Deep learning algorithms can then analyze this data to identify and localize areas in need of repair. By leveraging these technologies, engineers and road construction experts can more efficiently monitor and maintain roads, reducing the costs associated with repairs and maintenance, while in parallel improving safety. To this end, this work emphasizes the potential of UAVs in conjunction with deep learning techniques to provide a more comprehensive view of road conditions, allowing for targeted repairs and more effective maintenance strategies, such as prefabrication and robotic interventions. Experimental results using objective evaluation criteria, such as precision, recall, F1-score, and IoU are promising, which entails that this study advocates for the adoption of these technologies to enhance the monitoring and maintenance of road infrastructures.

C. Road Damage Detection and Classification with Deep Learning Using Smartphone Sensor Data

Research on damage detection of road surfaces using image processing techniques has been actively conducted. This study makes three contributions to address road damage detection issues. First, to the best of our knowledge, for the first time, a large-scale road damage data set is prepared, comprising 9,053 road damage images captured using a smartphone installed on a car, with 15,435 instances of road surface damage included in these road images. Next, we used state-of-the-art object detection methods using convolutional neural networks to train the damage detection model with our data set, and compared the accuracy and runtime speed on both, using a GPU server and a smartphone. Finally, we demonstrate that the type of damage can be classified into eight types with high accuracy by applying the proposed object detection method. The road damage data set, our experimental results, and the developed smartphone application used in this study are publicly.

D. Digital Twin: Challenge Road Damage Detection on Edge Device

High efficiency and safety are critical factors in ensuring the optimal performance and

reliability of systems and equipment across various industries. Fault monitoring (FM) techniques play a pivotal role in this regard by continuously monitoring system performance and identifying the presence of faults or abnormalities. However, traditional FM methods face limitations in fully capturing the complex interactions within a system and providing real-time monitoring capabilities. To overcome these challenges, Digital Twin (DT) technology has emerged as a promising solution to enhance existing FM practices. By creating a virtual replica or digital copy of a physical equipment or system, DT offers the potential to revolutionize fault monitoring approaches. This paper aims to explore and discuss the diverse range of predictive methods utilized in DT and their implementations in FM across industries. Furthermore, it will showcase successful implementations of DT in FM across a wide array of industries, including manufacturing, energy, transportation, and healthcare. The utilization of DT in FM enables a comprehensive understanding of system behavior and performance by leveraging real-time data, advanced analytics, and machine learning algorithms. By integrating physical and virtual components, DT facilitates the monitoring and prediction of faults, providing valuable insights into the system's health and enabling proactive maintenance and decision making.

III. PROPOSED METHODOLOGY

The proposed system introduces a YOLOv10n-based framework for real-time road damage detection, specifically optimized for deployment on edge devices. YOLOv10n is a lightweight yet powerful object detection model that offers improved efficiency compared to earlier versions like YOLOv7, while maintaining high detection accuracy. By incorporating hyperparameter tuning and optimization techniques, the system achieves a balance between computational efficiency and detection precision, making it well-suited for continuous road monitoring in smart city applications. In this framework, YOLOv10n processes road images or live video feeds to identify and localize damages such as potholes, cracks, and surface wear. The model's lightweight architecture allows faster inference with reduced hardware requirements, enabling smooth deployment on devices like NVIDIA Jetson Nano and NVIDIA AGX Orin. The system achieves remarkable results with a precision of 0.986, recall of 0.973, mean average precision

(mAP@0.5) of 0.988, and F1-score of 0.978, demonstrating both reliability and scalability.

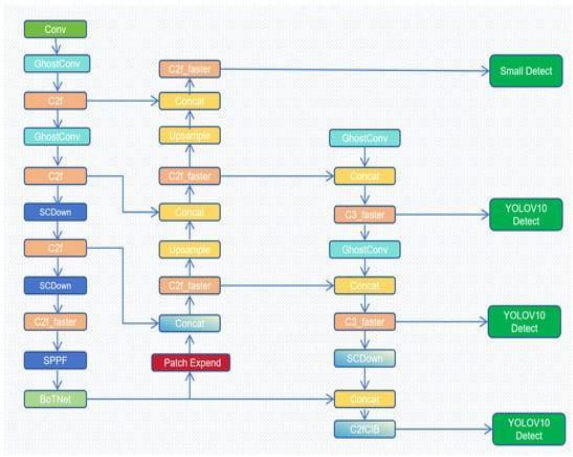


Fig. 1: System Overview

3.1 Data Collection and Preprocessing

In this module, images of roads are collected from various sources such as open datasets, roadside cameras, or drone footage. The collected data is cleaned, annotated, and augmented to improve diversity. Preprocessing steps such as resizing, normalization, and noise reduction are performed to ensure that the images are suitable for training the YOLOv10n model.

3.2 Model Selection (YOLOv10n Framework):

This module focuses on selecting **YOLOv10n** as the detection model. YOLOv10n is chosen because of its lightweight architecture and ability to deliver high accuracy while maintaining real-time performance. Model hyperparameters are tuned to achieve an optimal balance between precision, recall, and inference speed.

3.3 Training and Validation:

In this module, the YOLOv10n model is trained using the prepared dataset. Training involves feeding annotated images to the model, adjusting weights, and optimizing loss functions. A portion of the dataset is reserved for validation to monitor the model's performance and prevent overfitting.

3.4 Deployment on Edge Devices:

Once trained, the model is deployed on edge devices such as **NVIDIA Jetson Nano** and **NVIDIA AGX Orin**. This module ensures that the model runs efficiently in real-world conditions with limited hardware resources. Inference time and frame rate are measured to evaluate real-time performance.

3.5 Road Damage Detection and Output Generation:

This module represents the final stage of the system. The deployed model processes live video streams or road images to detect and classify damages like cracks and potholes. The results are visualized with bounding boxes and labels, and can be further integrated into smart city maintenance dashboards for decision-making.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

The proposed edge-ready road damage detection system based on an enhanced YOLO model with hyperparameter tuning was evaluated using accuracy, precision, recall, F1-score, and mean Average Precision (mAP). Experimental results demonstrated improved detection performance for various types of road damages, including cracks, potholes, and surface deformations, while maintaining low inference time on edge devices. Hyperparameter optimization enhanced the model's detection accuracy and reduced false detections under different environmental conditions such as shadows, lighting variations, and complex road textures.

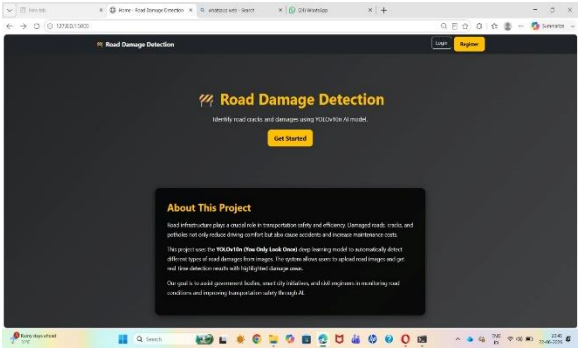


Fig. 2: Home Page

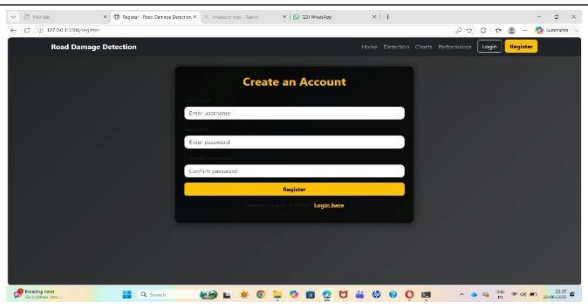


Fig. 3: Registration

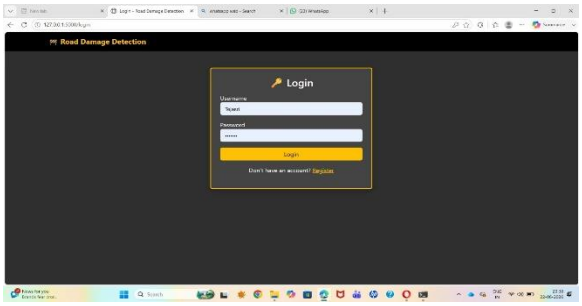


Fig. 4: Login

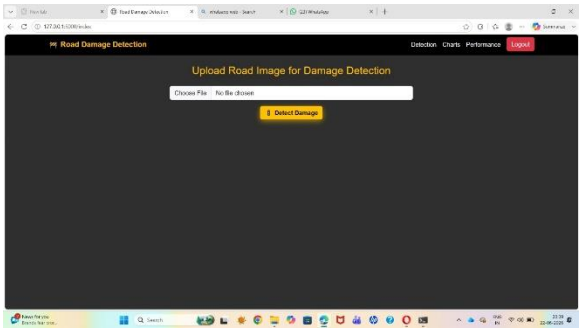


Fig. 5: Upload Image

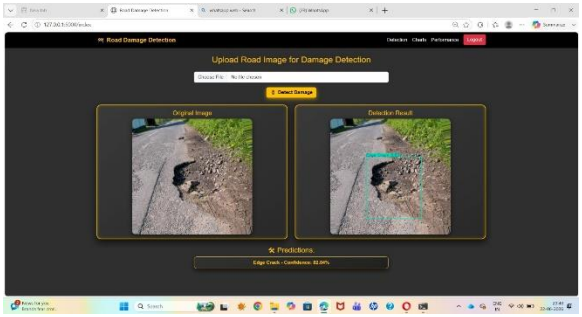


Fig. 6: Damage Detection

V. CONCLUSION

Road infrastructure maintenance is a critical requirement for ensuring transportation safety and supporting the growth of smart cities. Traditional road inspection methods, though reliable on a small scale, are highly labor-intensive, time-consuming, and prone to human errors, making them unsuitable for large-scale monitoring. This project addressed these challenges by developing an automated road damage detection system using the YOLOv10n algorithm, which is lightweight, efficient, and optimized for real-time deployment on edge devices. The proposed system demonstrates that YOLOv10n can achieve high accuracy while maintaining low computational requirements, making it far more practical than earlier models such as YOLOv7. With a precision of 0.986, recall of 0.973, mean average precision (mAP@0.5) of 0.988, and an F1-score of 0.978, the framework reliably identifies road damages such as potholes, cracks, and surface wear. The system's deployment on NVIDIA Jetson Nano and NVIDIA AGX Orin further validates its adaptability, achieving real-time inference speeds of 7.5 FPS and 67 FPS, respectively. These results highlight the model's scalability and practical use in real-world smart city infrastructures.

Beyond the performance metrics, the project contributes significantly to the vision of intelligent transportation systems by enabling proactive maintenance planning and reducing the dependency on manual inspections. By providing timely insights into road conditions, this system can help reduce accidents, lower vehicle maintenance costs, and improve the overall safety and reliability of transportation networks.

While the current implementation focuses on visual damage detection using edge devices, there remains potential for further enhancement. Future work could integrate predictive analytics, IoT-enabled sensors, or satellite-based monitoring systems to provide deeper insights into road health. Additionally, expanding the system to classify the severity of damages and prioritize repair schedules would make it even more useful for municipal authorities. In conclusion, the proposed YOLOv10n-based framework proves to be an effective, scalable, and efficient solution for real-time road damage detection. By combining high accuracy with resource efficiency, the system lays the foundation for smarter, safer, and more sustainable urban transportation infrastructures.

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