Automatic Assessment of Road Pavement Condition Using a Generative Adversarial Network Model with Gradient Penalty and U-Net-Based Segmentation

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ABSTRACT

Today, road Pavement Management Systems (PMS) require a transition from traditional methods to automated approaches to ensure safety and reduce maintenance costs. With the advancement of technology, including Autonomous Vehicles (AVs) and Intelligent Transportation Systems (ITS), the need for automatic detection and segmentation of asphalt pavement distress has become critical. However, developing deep learning-based models in this domain faces the critical challenge of the scarcity and imbalance of training data. This study presents a novel approach for the automated detection and segmentation of asphalt distress, aiming to assess pavement condition based on the hypothesis that generating realistic synthetic data can overcome data limitations. In the proposed method, a Wasserstein Generative Adversarial Network with Gradient Penalty (WGAN-GP) was first developed to generate high-quality and diverse crack images using the Crack500 dataset, ensuring training stability and preventing mode collapse. Subsequently, a U-Net model was trained for pixel-wise segmentation on the combined dataset (real and synthetic). The primary innovation of this research lies in integrating the improved GAN architecture with a segmentation model to address overfitting and enhance model generalization across various environmental conditions. Results demonstrated that adding synthetic images significantly enhanced segmentation performance, achieving a Dice coefficient of 0.961 and an Intersection over Union (IoU) of 0.925. Furthermore, qualitative assessment indicated the model's superior capability in detecting fine and complex cracks in other public datasets. Finally, by integrating the model outputs into a Surface Condition Index (SCI), the proposed framework provides an intelligent, accurate, and cost-effective capability for assessing pavement conditions.

KEYWORDS

Pavement Management System, Wasserstein Generative Adversarial Network with Gradient Penalty (WGAN-GP), Pavement Crack Segmentation, U-Net Model, Surface Condition Index (SCI).

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1. **Introduction**

Pavement Management Systems (PMS) are essential planning tools that assist road authorities in decision-making processes to maintain road networks in a timely and cost-effective manner while ensuring user comfort and safety [1, 2]. Traditional planning approaches for pavement maintenance often consider rehabilitation only after significant structural failure has occurred. This reactive approach leads to more severe and expensive rehabilitation measures and may create unsafe conditions for road users before decisions are made. Consequently, the reproducibility, accuracy, and objectivity of distress detection are crucial advancements in this process.

Pavement cracks are a primary type of road distress and a key concern in highway inspection. If not repaired in time, they can lead to structural pavement failure. Automatic detection of pavement distress relies on images captured by various tools, utilizing two main methods: Image Processing (IP) based models and Deep Learning (DL) based models. While IP approaches use thresholding and edge detection, they often fail under complex conditions such as shadows or uneven lighting. Conversely, DL advancements have significantly improved crack identification. However, acquiring high-quality data for training DL algorithms remains a serious challenge. The number of crack images in public and on-site datasets is limited, which is often insufficient for developing robust prediction models [3, 4]. Furthermore, data imbalance can severely affect model performance.

To address these limitations, Generative Adversarial Networks (GANs) have been proposed as a powerful method for generating crack image datasets [5]. However, training GANs can suffer from issues such as gradient vanishing and mode collapse. To overcome these challenges, the Wasserstein GAN with Gradient Penalty (WGAN-GP) utilizes the Wasserstein distance to improve training balance [6]. This study aims to develop an intelligent framework for pavement condition assessment by employing WGAN-GP to generate synthetic data, thereby enriching the training set for a U-Net segmentation model using the CRACK500 dataset [7]. This approach aims to enhance accuracy and automatically calculate the Surface Condition Index (SCI).

2. **Methodology**

The research methodology is organized into a four-stage framework: Data Preparation, Synthetic Data Generation, Modeling/Training, and Evaluation.

2.1. Data Preparation

The public CRACK500 dataset [7] was selected as the primary source for training and evaluation. To ensure computational efficiency and model compatibility, the images were pre-processed. This included resizing all images to dimensions of 128×128 pixels and normalizing pixel values to a standard range to facilitate faster convergence during the training of the neural networks.

2.2. Synthetic Data Generation

To address the data imbalance and scarcity, a WGAN-GP model was developed. Unlike traditional GANs, WGAN-GP employs the Wasserstein distance metric and a gradient penalty term, which enforces the Lipschitz constraint. This architecture significantly improves training stability and prevents the generator from producing a limited variety of samples (mode collapse). The model was trained on the pre-processed real images to learn the statistical distribution of crack features. Once trained, the generator was used to create a large set of realistic synthetic pavement crack images, encompassing various crack topologies (longitudinal, transverse, alligator).

2.3. Segmentation Model

A U-Net architecture was utilized for the pixel-wise segmentation of pavement distresses. The U-Net is an encoder-decoder network known for its effectiveness in biomedical image segmentation and linear feature extraction. In this study, the U-Net was trained using a hybrid dataset consisting of the original real images and the newly generated synthetic images. The integration of synthetic data serves as a sophisticated data augmentation strategy, exposing the model to a wider variety of crack patterns and background textures.

2.4. Surface Condition Index Calculation

Following segmentation, the binary masks output by the U-Net (where 1 represents a crack and 0 represents background) were processed to calculate the SCI. The SCI is a quantitative metric derived from the density and severity of the detected cracks, allowing for the translation of visual data into actionable numerical ratings for Pavement Management Systems.

3. **Results and Discussion**

The proposed framework was evaluated based on its ability to generate realistic images and the subsequent improvement in segmentation accuracy.

3.1. Impact of Synthetic Data

The evaluation revealed that the WGAN-GP model successfully generated high-fidelity images that closely mimicked the texture and geometric properties of real asphalt cracks. When these synthetic images were added to the training set, the U-Net model's ability to generalize improved significantly. The model achieved a Dice Coefficient of 0.961 and an Intersection over Union (IoU) of 0.925. These metrics indicate a high overlap between the predicted crack masks and the ground truth, surpassing models trained solely on limited real data.

3.2. Automated Assessment and SCI

The system demonstrated high robustness in detecting fine and complex cracks under varying conditions. A key output of this research is the automated calculation of the SCI. Figure 1 presents example of longitudinal crack. For each sample, the figure displays the model's segmentation prediction, skeleton image, and the final calculated SCI value. The close resemblance between the prediction and the skeleton image confirms the model's precision, while the SCI value provides a direct metric for maintenance decision-making.

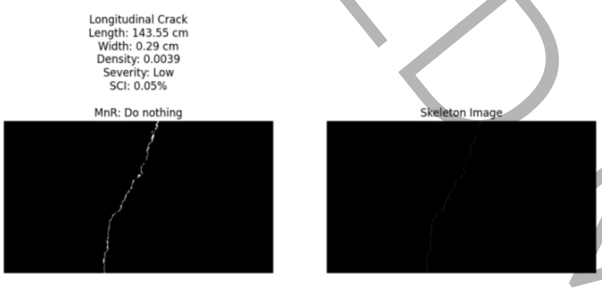

Figure 1. Example of longitudinal crack alongside the results of SCI calculation

The results indicate that the proposed method not only identifies the location of the distress but also quantifies its severity accurately. The SCI values derived from the automated segmentation were consistent with visual inspections, validating the potential of this framework to replace manual, labor-intensive surveys.

4. **Conclusion**

This study established an automated, intelligent framework for road pavement condition assessment, specifically addressing the challenge of data scarcity in deep learning applications. By integrating WGAN-GP for synthetic data generation with a U-Net segmentation model, the research successfully demonstrated a reliable method for detecting asphalt distresses.

Key findings and contributions include:

- The WGAN-GP model proved effective in generating high-quality, diverse synthetic crack images, successfully mitigating the issues of data imbalance and scarcity;
- Training the U-Net model with a hybrid dataset (real + synthetic) resulted in superior performance, achieving a Dice coefficient of 0.961 and an IoU of 0.925;
- The model showed high capability in identifying fine and complex cracks across different environmental conditions, demonstrating better generalizability than models trained only on real data;
- The integration of the segmentation output into an automated SCI provides a critical, low-cost, and accurate tool for PMS, facilitating timely maintenance decisions.

5. **References**

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