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Intelligent Concrete Crack Detection for Structural Health Monitoring

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Abstract

This study investigates the efficient structural health monitoring, concrete fractures must be accurately and promptly detected since they are a significant signal of structural degradation. In this thesis, methods for automatic crack identification and classification in concrete structures using deep learning and image processing are presented. To improve edge identification and crack segmentation in noisy environments, a hybrid approach that combines the GrabCut algorithm with an enhanced Sobel filter is suggested. A graphical user interface for real-time crack assessment is created using MATLAB. For precise crack identification and classification, a modified Dual-Attention Faster R-CNN linked with ResNet-101 is also suggested. The efficacy and resilience of the suggested strategies are demonstrated by experimental assessment on both public and self-prepared datasets.

Keywords: Concrete, Compressive strength, Strength, RCA

1. Introduction

Concrete is the most widely used construction material in civil infrastructure due to its high strength, durability, and cost-effectiveness. However, concrete structures are susceptible to deterioration over time as a result of environmental exposure, excessive loading, aging, material fatigue, and seismic activities. One of the earliest and most critical indicators of structural deterioration is the formation of cracks. If these cracks are not detected and addressed at an early stage, they can propagate, compromising the structural integrity, safety, and service life of buildings, bridges, tunnels, pavements, and other infrastructure. Therefore, accurate and timely crack detection is a fundamental aspect of structural health monitoring (SHM) and preventive maintenance[1-3].

Conventional crack inspection methods primarily rely on manual visual assessment, which is labor-intensive, time-consuming, subjective, and prone to human error. These limitations have motivated the development of automated inspection techniques using computer vision, image processing, and artificial

intelligence. Recent advances in deep learning, particularly convolutional neural networks (CNNs), have significantly improved the accuracy and efficiency of crack detection and classification by enabling robust feature extraction and automated decision-making. Nevertheless, challenges such as complex backgrounds, varying crack patterns, uneven illumination, and image noise continue to affect the performance of existing methods[4-5].

This study investigates efficient structural health monitoring through the automatic detection and classification of concrete cracks using advanced image processing and deep learning techniques. A hybrid image processing approach combining the GrabCut algorithm with an enhanced Sobel filter is proposed to improve crack segmentation and edge detection, particularly in noisy environments. To facilitate practical implementation, a MATLAB-based graphical user interface (GUI) is developed for real-time crack assessment and visualization. Furthermore, a modified Dual-Attention Faster Region-Based Convolutional Neural Network (Faster R-CNN) integrated with a ResNet-101 backbone is proposed for accurate crack detection and classification. The dual-attention mechanism enhances feature representation by emphasizing significant spatial and channel information, thereby improving detection accuracy under challenging conditions[6-8].

The proposed methodologies are evaluated using both publicly available and self-prepared datasets to assess their effectiveness, robustness, and generalization capability. Experimental results demonstrate that the proposed hybrid image processing framework and deep learning model achieve high detection accuracy and reliable classification performance, making them suitable for practical structural health monitoring applications. This research contributes to the development of intelligent, automated, and efficient crack inspection systems that can support timely maintenance decisions, reduce inspection costs, and improve the safety and longevity of concrete infrastructure.

2. Literature Review

2.1 The Hybrid GrabCut–Improved Sobel Filter (GCA-ISF):
A novel hybrid approach combining the GrabCut algorithm with an Improved Sobel Filter (GCA-ISF) is proposed for precise crack detection in concrete structures. The integration of region-based segmentation and enhanced edge detection improves crack localization, particularly in noisy and complex backgrounds.

2.2 Improved Sobel Filter for Edge Detection:
An enhanced Sobel filter is developed to improve crack edge detection. Unlike the conventional Sobel operator that uses fixed filter masks, the proposed method updates the filter mask dynamically based on the image variance, resulting in improved edge preservation and more accurate crack segmentation under varying image conditions.

2.3 Modified Faster Region-Based Convolutional Neural Network (MFRCNN):
A Modified Faster Region-Based Convolutional Neural Network (MFRCNN) is proposed for the unified detection and classification of concrete cracks. The proposed architecture enhances feature extraction and object localization, leading to improved detection accuracy and robustness.

2.4 CBAM-Based Multi-Scale Feature Learning:
To further enhance the performance of the proposed MFRCNN, a Convolutional Block Attention Module (CBAM)-based multi-scale feature learning strategy is incorporated. The attention mechanism enables the network to focus on informative spatial and channel features, thereby improving the detection of fine and irregular crack patterns.

2.5 MATLAB-Based Graphical User Interface (GUI):
A MATLAB-based graphical user interface (GUI) is developed to implement the proposed GCA-ISF method for real-time crack assessment. The GUI provides an interactive platform for image acquisition, crack segmentation, visualization, and structural health evaluation of concrete structures.

2.6 Django-Based Web Application for Real-Time Assessment:
A Django-based web application programming interface (API) is designed and implemented for the proposed MFRCNN framework. The web application enables real-time crack detection and classification, facilitating remote monitoring and evaluation of the structural integrity of concrete infrastructures.

2.7 Comprehensive Performance Evaluation:
A detailed qualitative and quantitative performance analysis is carried out to validate the effectiveness of the proposed methods. The proposed image processing and deep learning frameworks are evaluated using both publicly available and self-prepared datasets, and their performance is compared with existing state-of-the-art techniques using standard evaluation metrics such as accuracy, precision, recall, F1-score, mean Average Precision (mAP), and computational efficiency.

Overall, the proposed methodologies provide an intelligent, accurate, and efficient framework for automated crack detection and classification, contributing significantly to structural health monitoring systems for concrete infrastructure.

3. Materials and Method

An experiment was conducted using digital images of self-prepared concrete specimens to evaluate the performance of the proposed crack detection method. The concrete specimens were fabricated and tested under controlled laboratory conditions to ensure consistent crack generation. Since the primary objective of this research is the analysis of cracks from digital images, only a concise overview of the experimental procedure is presented. Concrete specimens measuring 100 mm × 100 mm × 500 mm were cast using cement, fine aggregate, coarse aggregate, and water in accordance with IS 456:2000 specifications. After adequate curing, the specimens were subjected to controlled compressive loading in a Universal Testing Machine (UTM) to induce cracks.

The applied load was continuously monitored and recorded until visible cracks were formed. High-resolution images of the cracked specimens were then captured using a Nikon D5100 digital camera under natural daylight conditions. Multiple specimens were tested to obtain cracks of varying lengths, widths, and orientations by adjusting the applied loading conditions. The cracked regions were identified as the regions of interest (ROI) for further analysis.

The collected images were used to create a custom dataset for training and evaluation. As the dataset contained limited samples with varying crack characteristics, data preprocessing techniques, including data augmentation, dataset partitioning, and image annotation, were employed to improve dataset diversity, reduce overfitting, and enhance the accuracy and robustness of the proposed crack detection and classification framework.

4. Result

In order to detect structural deterioration and guarantee the longevity and safety of concrete infrastructure, crack detection is essential to structural health monitoring (SHM). Significant signs of structural deterioration include cracks in highways, bridges, buildings, columns, pavements, reservoirs, and other concrete structures. Excessive loading, mechanical stress, bending, corrosion, alkali reactions, subpar building materials, poor structural design, incorrect reinforcement detailing, or natural calamities like earthquakes, floods, and landslides can all cause these fissures. Non-destructive testing (NDT), optical approaches, and conventional visual inspection are examples of current crack detection procedures. Among these, manual visual inspection is still frequently employed, especially in developing nations.



Fig.1 Original Crack

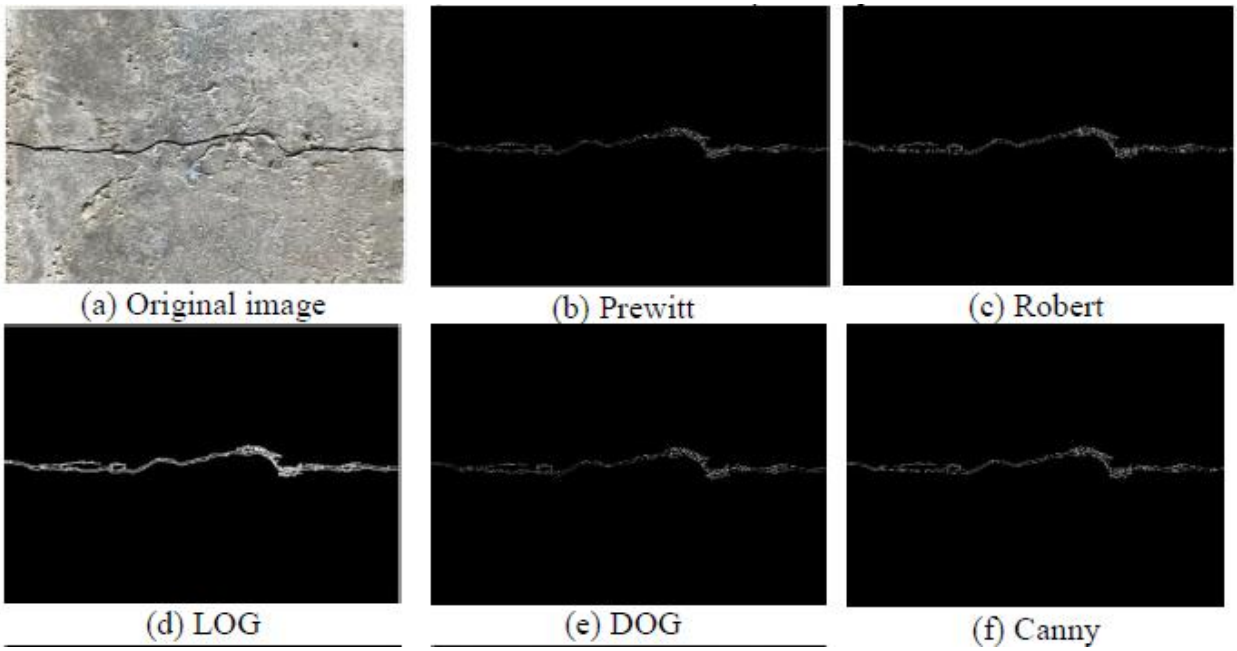


Fig. 2 Crack Detection assessment by ML

5. Conclusion

The manual inspection is prone to human error and uneven findings because it is labor-intensive, time-consuming, subjective, and heavily dependent on the inspector's competence. Repetitive examinations also lower overall inspection efficiency and raise maintenance expenses. Automated crack detection methods that provide better accuracy, consistency, and quicker analysis have been made possible by recent developments in deep learning and image processing. However, a web-based platform for real-time structural health monitoring and a unified framework that can identify and classify cracks in a single system are still required. By addressing these issues, public safety may be increased, infrastructure maintenance can be greatly improved, and inspection costs can be decreased.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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