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Structural Crack Image Enhancement: A Review of Techniques for Varied Environmental Conditions

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Abstract

Structural health monitoring is crucial for ensuring the safe operation of civil engineering infrastructure. With the deep integration of computer vision technology and traditional inspection methods, along with the rapid advancement of smart maintenance concepts, image enhancement and quality improvement techniques for crack images captured in complex environments-such as above water, underwater, and in tunnels-have become increasingly important. These images often suffer from issues like blurriness, low contrast, and significant noise interference. By systematically reviewing spatial domain enhancement, frequency domain enhancement, and emerging deep learning-based methods, the core enhancement mechanisms and applicable scenarios of these approaches can be clarified, thereby providing a solid theoretical and technical foundation for intelligent crack identification and automated detection in complex environments in the future.

Keywords

Image Enhancement, Spatial Filtering, Frequency Domain Transform, Deep Learning.

1. Introduction

Image detection methods typically rely on clear and standardized visual environments. However, in complex engineering settings such as underwater, tunnel, and humid or corrosive conditions, captured crack images often exhibit inherent limitations like low contrast, blurred details, and severe noise interference. For instance, in underwater inspections, light scattering and absorption result in hazy images; in tunnels, insufficient lighting and background clutter hinder crack identification; during long-term outdoor monitoring, rain stains and dirt can significantly degrade image quality. In these challenging scenarios, traditional image enhancement techniques often fall short of meeting the stringent requirements for accuracy, robustness, and real-time performance in detection tasks. To address these issues, researchers worldwide have deeply integrated computer vision, advanced image processing, and deep learning techniques into this field, developing a series of enhancement and improvement methods tailored for crack images in complex environments.

Crack image enhancement technology is a digital processing procedure that applies targeted transformations to either spatial domain pixel values or frequency domain coefficients of an image, aiming to highlight crack features and suppress background noise. It is a technical system designed to improve the visual separability between cracks and their background by leveraging both algorithmic priors and data-driven models to recover and strengthen detailed information. This technology not only effectively enhances the visual discernibility of cracks but also provides a high-quality data foundation for subsequent automated identification, precise segmentation, and quantitative analysis. Thereby, it fundamentally improves the automation level and reliability of structural health monitoring. Consequently, systematic research on crack image enhancement technologies under various environmental conditions is of significant importance.

2. Research on Above-Water Image Enhancement

Scholars domestically and internationally have conducted in-depth exploration and validation on key issues such as brightness enhancement, noise suppression, detail improvement, and practical detection efficacy of pavement crack images in low-illumination environments, by designing innovative image enhancement algorithms and integrated software systems.

He Shijie et al.[1]addressed issues such as uneven brightness, noise amplification, and color distortion in low-light image enhancement by developing two distinct enhancement methods and integrating them into a comprehensive software system. The first algorithm employs a genetic algorithm for block-based tone mapping, which effectively avoids over-exposure or under-exposure problems through regional segmentation and multi-scale fusion. The second algorithm combines dual-tree complex wavelet transform with singular value decomposition to perform targeted processing in the frequency domain, thereby suppressing noise and improving enhancement speed. Experimental results demonstrated that both proposed algorithms outperformed comparative methods such as MSR, CRM, and LIME in terms of both subjective visual assessment and objective metrics (e.g., AG, EN, and PSNR), effectively enhancing image brightness, contrast, and detail preservation. This research provides a complete solution ranging from algorithmic innovation to system integration for visual tasks in low-light environments.

Luo Rui et al.[2]addressed the limitations of traditional image enhancement algorithms in road crack images-such as insufficient visibility and the tendency of classical Retinex algorithms to produce "halo artifacts" and disrupt grayscale pixel domains-by proposing an image enhancement method that combines an improved Retinex algorithm with a fuzzy logic algorithm. The method processes pixels in different frequency bands through sub-band decomposition and introduces fuzzy logic rules and membership functions for adaptive pixel adjustment. Results demonstrate that the improved algorithm outperforms traditional Retinex algorithms in objective metrics such as mean brightness, contrast, and information entropy, while also requiring less processing time. Experiments on various types of pavement crack images show that the algorithm effectively enhances overall visual quality, improves crack clarity and hierarchical detail, and reduces halo artifacts. By integrating algorithmic strategies, this study successfully mitigates the inherent drawbacks of Retinex, offering an efficient image enhancement solution for the preprocessing stage of automated road crack detection systems.

In summary, the experimental results of both authors demonstrate strong consistency. Whether by combining genetic algorithms with tone mapping, integrating frequency-domain decomposition with spatial processing, or improving Retinex in combination with fuzzy logic, all approaches significantly enhance the visual quality and usability of pavement crack images under both low-light and normal lighting conditions. Consistent positive progress has been achieved in suppressing halo artifacts, preserving details, improving objective metrics, and supporting subsequent detection tasks.

3. Research on Underwater Image Enhancement

Domestic and international scholars have conducted in-depth research and optimization on key aspects such as underwater image quality improvement, crack identification accuracy, and quantitative analysis of structural defects by developing diverse image enhancement models and integrated detection-quantification frameworks.

Zhuo Qiye et al.[3]proposed an integrated framework for underwater image enhancement and structural defect recognition based on deep learning. The method established an underwater image quality assessment system comprising 16 evaluation metrics to comprehensively evaluate the performance of 21 enhancement algorithms. An improved YOLOv8 model-incorporating an additional small-object detection layer, a global attention mechanism, along with replacement of lightweight modules and loss functions-was utilized for defect detection. Results demonstrated that the evaluation system exhibited strong consistency between qualitative and quantitative metrics, with enhanced image quality positively correlated with detection performance. The improved model achieved increased mAP50 (from 96.8% to 97.3%), mAP50-95 (from 81.9% to 84.4%), and score (from 0.8474 to 0.8673) on the original dataset. Crack dimension quantification was realized through a DeepLabV3+ segmentation model and an expanded circle algorithm, yielding post-enhancement width calculation errors below 10%. This study systematically evaluated the impact of enhancement algorithms on detection and segmentation performance, providing a complete technical pathway for automated underwater defect identification and quantification.

Luo Yaowei et al.[4]developed a bridge underwater structure crack detection method based on the fusion of image enhancement and an improved U-Net. The approach first employs a UDNet to enhance low-quality underwater images. Subsequently, an improved U-Net incorporates the Convolutional Block Attention Module (CBAM) to boost feature extraction capability and utilizes a combined loss function of Focal Loss and Dice Loss to address the class imbalance between positive and negative samples. Results demonstrated that on a self-constructed underwater crack dataset, the fused method achieved a precision of 85.36%, recall of 75.45%, F1-score of 80.10%, and Intersection over Union (IoU) of 66.81%, showing significant improvement compared to the original U-Net. Image enhancement effectively improved input quality, while the attention mechanism and optimized loss function collectively increased the model's segmentation accuracy and generalization capability. This study, through an end-to-end enhancement-segmentation fusion strategy, significantly enhanced both the visual effect and segmentation accuracy for underwater crack detection.

Ma Jinxiang et al.[5]proposed an underwater optical image enhancement algorithm based on degradation characteristic indicators. The method first identifies the degradation type of the original image according to four types of degradation characteristics-non-uniform illumination, low signal-to-noise ratio, narrow dynamic range, and color distortion-then performs targeted image restoration, and finally applies bounded generalized log-ratio operations for image enhancement. Results show that the method effectively restores degradation parameters to reasonable ranges in both artificially lit and natural light scenarios. For instance, the contrast of crack images improved from 6.15 to 107.35, and the dynamic range ratio increased from 60.00% to 76.08%. Compared with nine other algorithms, the proposed method demonstrates significant superiority in both image restoration and enhancement. This study provides a systematic solution for improving underwater image quality and supporting subsequent processing tasks.

Lin Chuan et al.[6]addressed the issues of underwater image quality degradation and crack quantification by proposing a method based on deep and transfer learning for underwater image enhancement and crack quantification. The approach utilizes a conditional diffusion model to learn the implicit mapping between marine images and clear images, achieving enhancement of dam area underwater crack images through cross-domain transfer. Combined with the YOLOv12 network for crack detection and segmentation, morphological operations are employed to extract parameters such as crack area, length, and width. Results indicate that the proposed enhancement method significantly improved no-reference metrics: Information Entropy (IE), UCIQE, and UIQM increased by 12.41%, 9.91%, and 218.45%, respectively, compared to the original images. The crack detection mAP reached 78.1%, representing a 51.7%

improvement over the original images, with a quantification error controlled at approximately 5%. This study establishes a closed-loop "enhancement-detection-quantification" framework, providing an effective technical solution for underwater intelligent inspection.

In summary, the experimental results of various authors demonstrate strong consistency. By defining degradation characteristic indicators, combining physical models with mathematical operations, or utilizing diffusion models and transfer learning for cross-domain enhancement, these approaches effectively improve the visual quality, contrast, and detail information of underwater images. Consistent progress has been achieved in enhancing detection accuracy and enabling quantitative crack parameter analysis.

4. Research on Tunnel Image Enhancement

Scholars worldwide have conducted in-depth research and optimization by integrating image enhancement techniques with deep learning models, significantly improving the brightness, contrast, anti-interference capability, and applicability of crack detection systems.

Shen Jintao et al.[7]addressed the issues of low brightness, insufficient detail visibility, and the difficulty in acquiring paired data for images captured in dark tunnel environments by proposing two low-light image enhancement algorithms combined with Faster R-CNN for defect identification. The first method designs a U-Net-based enhancement algorithm in HSV color space, which reduces the correlation between brightness and color by converting the color space. It enhances the brightness component using an improved U-Net integrated with a channel attention mechanism, and incorporates guided filtering and Laplacian sharpening to improve contour and texture details. The second method develops a multi-branch cyclic generative adversarial network (CycleGAN) based on U-Net, where a multi-branch generator extracts both shallow and deep features, and global-local discriminators are employed to enhance the realism of generated images, effectively eliminating the reliance on paired data. Results demonstrate that both algorithms significantly outperform comparative methods such as Retinex-Net and MBLLEN in objective metrics (AG, EN, PSNR, SSIM). Ablation experiments validate the effectiveness of each module. The final defect detection system achieves high-precision identification of cracks, spalling, and potholes in low-light tunnel environments. This study provides a comprehensive solution for low-light tunnel image enhancement and target recognition.

Qian Dengsuo et al.[8]addressed the issue of segmentation accuracy degradation in road defect detection caused by uneven illumination and complex backgrounds by proposing a method that integrates image enhancement with U-Net-based segmentation. The approach first employs the Retinex decomposition algorithm and grayscale transformation for image preprocessing to improve brightness uniformity and contrast. A U-Net convolutional neural network was then constructed to achieve pixel-level defect segmentation, and the Pavement Condition Index (PCI) was introduced to quantitatively assess the severity of defects. Results demonstrated that on the Kaggle road crack dataset, the enhanced images exhibited clearer crack edges and significantly improved segmentation completeness. Comparing different loss functions, Dice Loss achieved the optimal Dice score (0.9804), and the method showed strong robustness in complex environments. This research effectively combines image enhancement with a deep learning model, enabling efficient and visualizable road defect detection and assessment.

Zhou Lijun et al.[9]addressed the issue of missed detection in tunnel crack images caused by low contrast and interference from contamination points by proposing a crack extraction algorithm based on image enhancement and watershed segmentation. The method first compensates for contamination points using background information to balance image contrast, then enhances the image through top-hat and bottom-hat transformations. Combined with the watershed algorithm, segmentation lines are obtained, and crack edges are accurately identified by comparing the positional differences between these lines and surrounding grayscale values. Results demonstrated that on a test set of 100 tunnel crack images, the algorithm achieved an average precision (r) of 92.16% and recall (s) of 91.58%, significantly outperforming traditional binarization-based minimum connected domain methods while maintaining robustness under noise interference. By effectively integrating morphological enhancement and watershed segmentation, this study provides a reliable solution for detecting cracks in low-contrast and contaminated tunnel images.

Liu Jian et al.[10]addressed the issues of low signal-to-noise ratio, poor contrast, and difficult edge recognition in tunnel lining crack images by proposing an image quality enhancement method based on histogram equalization theory and border augmentation. The approach integrates Histogram Equalization (HE) and Contrast Limited Adaptive Histogram Equalization (CLAHE) to enhance the saliency of crack regions and balance the background. Simultaneously, a border (black or white) is added to the image to alter the relative position of cracks, making them more concentrated toward the image center, thereby improving edge crack identification accuracy. Experimental results demonstrated that, in tests conducted on YOLOv5, Faster R-CNN, and YOLOv3-MobileNet, the equalization-based enhancement method increased the mAP by 13.5%, 5.6%, and 22.2%, respectively. The border augmentation method achieved the best performance when a black border with 1/9 of the image width was added, resulting in a further 3.4% improvement in mAP and accelerated model convergence. This study validates the universality of the proposed enhancement method across different detection models, providing an efficient data processing solution for the intelligent identification of tunnel cracks.

In summary, the experimental results of the four authors demonstrate strong consistency. The integration of image enhancement techniques with deep learning models effectively improves the brightness, contrast, and detail discernibility of tunnel and road crack images, while significantly enhancing detection accuracy, robustness, and model convergence speed under varying environmental conditions.

5. Conclusion

Through a review and synthesis of relevant domestic and international literature, it is evident that significant progress has been made in the field of structural crack image enhancement across multiple environments in recent years. However, two core challenges persist in practical applications. For mobile detection platforms such as drones and underwater robots, many high-performing deep learning models struggle to achieve efficient lightweight deployment and real-time processing on edge devices with constrained computational, storage, and power resources due to their substantial computational overhead. Furthermore, most existing enhancement algorithms are designed for specific image degradation patterns. When confronted with dynamic and complex scenarios where multiple degradation factors intertwine, their robustness, domain generalization capability, and cross-environment adaptability still require in-depth investigation and improvement.

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