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Comparative analysis of image binarization methods for crack identification in concrete structures

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ABSTRACT

Surface cracks in concrete structures are critical indicators of structural damage and durability. Manual visual inspection, the most commonly used method in practice, is inefficient from cost, time, accuracy, and safety perspectives. A promising alternative is computer vision-based methods that can automatically extract crack information from images. Image binarization, developed for text detection, is appropriate for crack identification, as texts and cracks are similar, consisting of distinguishable lines and curves. However, standardizing crack identification using image binarization is challenging, because binarization depends on the method and associated parameters. We investigate image binarization for crack identification, focusing on optimal parameter determination and comparative performance evaluation for five common binarization methods. Crack images are prepared to obtain optimal parameters by minimizing errors in estimated crack widths. Subsequently, comparative analysis is conducted using crack images with different conditions based on three performance evaluation criteria: crack width and length measurement accuracy and computation time.

1. Introduction

Civil infrastructure is subjected to a wide variety of loadings including self-weight, service loads, and environmental loads during the lifetime. These loadings can potentially induce structural damage and even failures, resulting in social and economic loss. Regular inspections of civil infrastructure systems are enforced by law in many industrialized countries to evaluate structural integrity and provide associated countermeasures. Particularly for concrete structures, surface cracks are one of the common items in the inspection process, because cracks often indicate structural damage and problems associated with concrete durability [1–3]. Manual visual inspection is the most widely used method in practice for crack monitoring in concrete structures to investigate whether crack growth over time would degrade structural integrity. However, manual visual inspection is labor intensive, costly, and inaccurate, as the results inevitably depend on the inspector's skill.

Various new technologies have been introduced, including digital image processing, dynamic property-based algorithms [4,5], nondestructive evaluation approaches [6–8], and new crack sensors [9], to overcome the challenges of manual visual inspection. Digital image processing, which can measure crack locations and widths from digital images, is considered to be a powerful alternative to manual visual inspection, particularly for identification of surface cracks. Digital image correlation (DIC) can be used for the crack identification purpose [10,11] by comparing concrete surface images before and after crack initiation. Applying DIC is often impractical particularly when the reference images without cracks are unavailable. For reference-free crack assessment, Dare et al. [12] developed a route-finder algorithm that identifies a crack connecting two given points to be provided by a user. This semi-automatic approach has been found to be inefficient, when a large number of crack images must be processed. More recent research efforts have been devoted to developing automatic methods with minimal human intervention. Edge-detection algorithms are also considered in crack detection, as boundaries between crack and background pixels can be found as edges [13,14]. Because edges are often undetected and disconnected, additional post-processing must be carefully performed for complete crack detection. Another approach is to use differences in pixels associated with cracks and backgrounds, which are typically dark and bright, respectively. Image binarization algorithms can transform the dark and bright pixels in a grayscale image into a binary image with only black and white information. Primarily developed for detecting text from digital images [15–19], image binarization has been used for crack detection purposes, as texts and

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cracks have essentially similar shape characteristics, consisting of distinguishable lines and curves [20,21]. Mathematical morphology, in combination with image binarization, is used to enhance crack detection performance by transforming noisy crack pixels to realistic crack shapes [22–24]. More information regarding crack detection methods based on image processing has been reported by Jahanshahi et al. [25].

Among the diverse crack identification methods, image binarization is seen to have a strong potential to extract crack information from digital images effectively. In the binarization process, pixels in a grayscale image with higher pixel values than a specified threshold are marked as one (white) in the converted binary image, while those with lower values become zero (black). Each binarization method has its own schemes for calculating the threshold, generally using statistical properties such as the mean and standard deviation of pixel values. Thus, crack identification performance inevitably depends on the selected binarization method and the associated binarization parameters.

Comparative studies of various binarization methods have been conducted extensively for text identification purposes [26–30]. An optical character reader is generally used to recognize characters in binary images; the number of correctly detected characters indicates the performance of the binarization method used in the evaluation, whereas thickness and length of identified characters are not of interest. In contrast, crack monitoring generally requires the size of crack openings as an essential factor. This fact has two important implications: (1) the performance evaluation studies in the literature are inappropriate for the crack detection problem and (2) not all recommended binarization parameters can be expected to provide accurate estimations of crack sizes. While the threshold value is quite sensitive to the binarization parameters, optimal values for the parameters have not been studied for crack detection. Indeed, these issues must be properly addressed for automated crack monitoring to replace the traditional practice of using manual visual inspection.

This study presents a comparative analysis for performance evaluation of the widely used image binarization methods and proposes associated optimal binarization parameters. After describing the image binarization methods and the parameters necessary in the threshold calculation, a parametric analysis is conducted to determine the optimal parameters for each method. Subsequently, a comparative analysis of the image binarization methods is performed for a variety of crack conditions, such as crack shape, length, width, concrete surface texture, illuminance, and working distance.

2. Materials and methods

2.1. Image binarization

Image binarization methods are used to convert a grayscale image into a binary image. In the case of color images, pixel values of the original image must be turned into grayscale values ranging from zero (black) to 255 (white) by calculating a weighted sum of their red, green, and blue components. In the binarization process, each pixel in the grayscale image is examined by comparing its pixel value with a threshold: a higher pixel value than the threshold leads to a pixel value of one (white) in the binary image, and a lower value results in a pixel value of zero (black), as can be seen in the example in Fig. 1. For example, when the average pixel value is used as a threshold, the pixel value is higher than the corresponding threshold in A, and thus the binarization result is one (white), whereas the result is zero (black) in B, because the pixel value is lower than the threshold. Binarization methods can be distinguished by the means they use to determine the threshold [15–19]. These involve the binarization parameters, including (1) the window in which the threshold calculation is conducted (see the blue and red boxes in Fig. 1) and (2) the sensitivity that controls the contributions of the statistical parameters of the pixel values to the threshold calculation. After image binarization, the resulting image is then binarized with the pixel values zero and one, as shown in Fig. 1.

2.2. Determination of threshold values

A number of image binarization methods have been developed to acquire binary images more effectively and accurately, particularly for text identification purposes. This study considers several representative methods, including Bernsen's, Niblack's, Sauvola's, and Wolf's methods, and the NICK method [15–19]. Bernsen [15] proposed Eq. (1) to calculate a threshold by considering maximum and minimum intensities of a selected window.

$$T_{Bernsen} = \frac{Z_{max} - Z_{min}}{2} \tag{1}$$

where Z_{max} and Z_{min} are the maximum and minimum values in the pixel histogram of each window. When $Z_{max} - Z_{min}$ evaluated in a window is less than a prescribed value, the full image is used for determining the threshold instead. This method is generally useful for distinguishing a specific object from the background in the case of high-contrast images.

Niblack [16] considered the local mean and standard deviation of pixel values in a window:

$$T_{Niblack} = m + k \times s \tag{2}$$

where k is the sensitivity, and m and s are the mean and standard deviation in a selected window, respectively. While Niblack's method is simple and straightforward to use, its performance can be significantly degraded when the image background is noisy owing to its high dependency on the standard deviation.

Sauvola and Pietikäinen [17] modified Niblack's method to mitigate its sensitivity to the standard deviation by normalizing the standard deviation by a factor R, the dynamic range, as in Eq. (3).

$$T_{Sauvola} = m \times \left\{1 - k \times \left(1 - \frac{s}{R}\right)\right\} \tag{3}$$

Sauvola's method is known to be effective for searching texts from noisy backgrounds as a result of considering the dynamic range, unless the pixel-value difference between text and non-text is small.

To address the deficiency of Sauvola's method, Wolf and Jolion [18] normalized the contrast and mean in the equation for computing a threshold, as follows:

$$T_{Wolf} = (1 - k) \times m + k \times M + k \times \frac{s}{R} \times (m - M) \tag{4}$$

where M is the minimum pixel value of the entire grayscale image. In Wolf's method, the dark colors can be separated effectively from the backgrounds, because this method considers the minimum pixel value of the entire image in deciding a threshold.

Khurshid et al. [19] developed the NICK method based on Niblack's method by adding the mean square to the variance as follows:

$$T_{NICK} = m + k\sqrt{B + m^2} \tag{5}$$

where B is the variance. This method shifts the threshold down by adding the mean square to the variance to delete background noises in the source image. As shown, each image binarization method has its own equation to determine the threshold based on statistical properties of grayscale pixels in each window. Thus, the image binarization results vary with the image binarization method used as well as the selected binarization parameters.

2.3. Issues in image binarization for concrete crack sensing

The primary goal of using image binarization methods in this study is to accurately determine crack information such as locations and widths. The window size and sensitivity of a binarization method must be selected properly to localize the exact crack pixels from the grayscale