A Novel Image-based Measurement of Crack Characteristics with Tree Structure

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Abstract—This study proposes a novel image-based measurement of crack properties in concrete construction. The method first retrieves the crack skeleton and profile from the crack map generated by pre-processing the original image. Then, the crack skeleton is abstracted into a tree structure, and small edges from the crack trunk are removed to calculate the length of the crack. Finally, Euclidian distance transform is applied on the crack profile to calculate the width of the crack. The proposed method can identify crack properties automatically and enhance stability, durability, and safety evaluation of the concrete construction. Validity and accuracy are tested by experiments on crack images of real concrete construction.

Keywords—Image-based measurement, Crack property, Concrete construction, Safety evaluation, Non-destructive measurement

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1. Introduction

Concrete is a complex man-made composite that is widely used in civil engineering. The behavior of concrete construction is influenced by environmental affection, reinforcement, concrete matrix, and the bond among these features. Surface cracks are the external visible indications of the behavior of a loaded concrete construction. The appearance of surface cracks and crack propagation may reflect the current health condition and potential degradation of the concrete structure. Therefore, this condition could deteriorate steel reinforcement rods or pre-signal a forthcoming collapse [1].

Various approaches are available for measuring crack properties. Although the surface cracks of concrete buildings are measured, some limitations have been found in their traditional evaluation process. First, the evaluation is time consuming and difficult to operate. Completing the crack measurement processes of an entire building may take weeks for crack data. Moreover, subjective inspection as well as man-made factors may lead to erroneous judgments [2]. Different staff may obtain varied measurement results with manual methods. To measure crack properties, we need to first detect the crack automatically. Previous studies have stressed the use of boundary detection [3]. Yamaguchi et al. [6] presented a percolation model, which is adaptive and could be used in various crack detections. Their large test database and sufficient results can verify the precision of the percolation model, which is used in this study to detect the crack from the original images. Aside from detecting the localization of cracks, the measurement of crack properties is another difficult issue. Cheng et al. [7] presented a crack detection method based on a threshold operation that uses the mean and standard deviation of a gray-level concrete building image. The method can quickly extract the crack from the background, but the threshold may not be well controlled. Seung et al. [8] proposed a method that uses an improved Dijkstra algorithm that can enhance the velocity of calculating the crack length from concrete tunneling. However, this method is semi-automated and may need to manually assign a start seed. Yamaguchi et al. [9] used a calibration line and the brightness of a crack to identify the width of the crack. Zhu et al. [10] proposed an improved method that combines the percolation model and crack direction information to identify concrete crack properties after an earthquake. Although the method can efficiently obtain the average and maximum widths of the crack, the results may not reflect the width changes at every point of the crack. Fang et al. [11] used rotation angel information to derive the crack length and the width. The method can obtain the width of every point, but the rotation angel information is difficult to retrieve. Despite their defects, these methods can promote the development of image-based crack measurement and verify the feasibility of image-based methods.

Another constraint is the precision of a manual survey, which is limited by the measurement instrument. Although this instrument is inexpensive, an expensive instrument is often required to obtain more accurate results [12-13]. Mechanical and electrical sensors are generally required at this time. However, the drawback of such instruments is that the sensor is only able to measure in one prefixed direction, and this limitation makes these instruments lack flexibility. In complex environments, such as construction under deep water or in the air, concrete cracks cannot be directly measured easily. Therefore, manual measurement needs to be improved.

Section 2 summarizes and compares the related works. Section 3 first discusses the pre-processing of the original crack image and then presents a special crack tree to extract the length and width from the crack. Section 4 describes an application case of an outdoor concrete wall using the proposed method. Section 5 further validates the practicability and accuracy of the method by comparing with existing studies. Finally, Section 6 presents the concluding remarks and future works.

2. Description of the problem

Photogrammetry has been largely applied in the deformation measurement of concrete buildings since the beginning of the digital era. As an indirect and non-destructive method, image-based crack measurement has many advantages. The low cost makes the image-based crack measurement an economically feasible utility for recording concrete construction surface damages. In addition, image measurement results can be more stable, as data are not affected by man-made factors. Furthermore, the limited efficiency of manual evaluation can be overcome with a fully automatic image-based measurement.

A novel image-based measurement of crack properties is proposed in concrete construction. The method first retrieves the crack skeleton and profile from the crack map generated by pre-processing the original image. The crack skeleton is then abstracted into a tree structure, and small edges are removed from the crack trunk to calculate the length of the crack. Finally, the Euclidian distance transform (EDT) is applied. The proposed method can identify crack properties automatically.

Compared with manual measurement approaches, the main advantages of the image-measurement approach are that non-contact technique is used, which can be accessed and monitored remotely, and guaranteed precision is completed, which comes from a suitable optical device that may be more adaptive to the situation. Therefore, the automatic image measurement for cracks of infrastructures mainly focuses on the crack properties on the surface of concrete construction. To improve these methods, this study measured the crack length and the width together. The method is different from the above methods, which only detect the crack length or the width alone. Moreover, some of the discussed visual methods only focus on crack detection and disregard the retrieval of crack properties that could reflect the health condition of the concrete construction. The proposed method can capture the property data of surface cracks to provide more information about the concrete structure. Abstracting the crack skeleton into a tree structure can reduce the storage of crack images and make the proposed method more efficient. As an automatic method, the proposed system excludes the interference of artificial factors and promotes the stability of results compared with semi-automatic methods.

3. Methodology

3.1 The crack profile using Canny edge detection

Crack images of concrete surface captured by optical cameras can be obtained, and the crack profile using Canny edge detection is retrieved as shown in Fig. **1**.

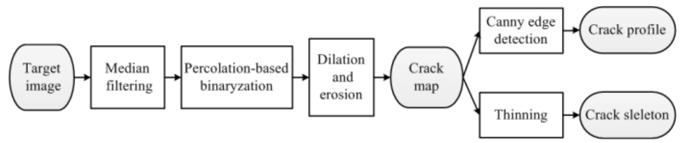


Fig. 1 the crack profile using Canny edge detection.

3.2 Retrieval of crack length

This study shows how to use the crack tree to retrieve the acrylic properties of concrete surface cracks. The crack tree includes crack trunk and edges and a branch point corresponds to a tree branch. A tree structure can reduce storage data and retrieve the process more efficiently as shown in Figure 2.

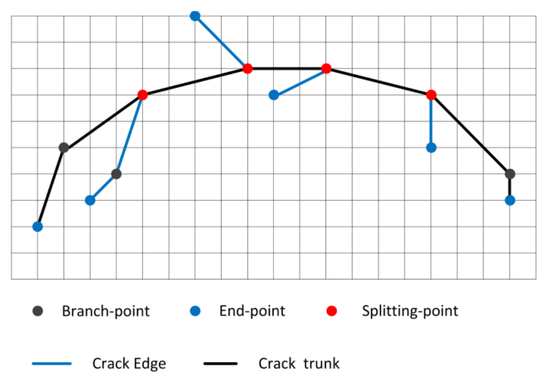


Fig. 2 An example of the tree structure of a crack skeleton.

In civil engineering, the length of the crack trunk often represents the length of a crack and the crack edges to prevent disturbance are removed. The crack length retrieval method presented in this study preserves the crack trunk and prunes the edges automatically.

3.3 Retrieval of crack width

Crack width can provide critical information about the degeneration of a concrete structure. Therefore, crack width identification is considerably practical. However, the definitions of crack width are not unified and usually depend on experiments [14]. In this study, crack width is defined according to engineering experience. As shown in Fig. 3, both A and B are terminals of the crack. The dotted line represents the crack trunk, and the continuous line indicates the profile of the crack. The crack profile can be divided into two open boundaries P_1 and P_2 alongside the trunk. The width w of point C, which lies on P_2, is defined as the shortest Euclidean distance from C to a point D, which lies on the other side of the crack profile.

This study proposes a crack width measurement method based on the EDT, which is easy to achieve. EDT is widely used in computer graphics, geographic information system spatial analysis, and pattern recognition [15]. EDT identifies the space position of the target point and processes the binary image into a gray image instead of its Euclidean distance to the nearest target point. Choosing two points $A(x_1, y_1)$ and $B(x_1, y_1)$ in the 2-D plane, the Euclidean distance of two points is defined as

$$D = \sqrt{(x_1 - x_2)^2 - (y_1 - y_2)^2} \tag{1}$$

A binary image can be represented by the array A_{mn}, where $A_{ij} = 1$ corresponds to the target points and $A_{ij} = 0$ corresponds to the background points. Assume that $B = \{(x, y) | A_{ij} = 1\}$ is the set of target points, and the EDT requires calculating the D_{ij} of all pixels in array A_{mn}.

$$D_{ij} = min\{\text{Distance}[(i, j), (x, y)], (x, y) \in B\} \tag{2}$$

where $\text{Distance}[(i, j), (x, y)] == \sqrt{(i - x)^2 - (j - y)^2}$. Then, we can obtain the distance map of the binary image after the EDT accordingly.

The measurement method of the crack width based on the proposed EDT is summarized as follows:

Find the terminals of the crack trunk after length measurement. Divide the crack profile into two open boundaries, P_1 and P_2 alongside the trunk. Afterwards, mark every point in P_1 as the target point. Reset other points (include points in P_2) as the background points.

Apply the EDT to the reset image.

The value of every point in P_2 in the distance map shows the varying widths along the crack trunk. The mean width can also be obtained from this map.

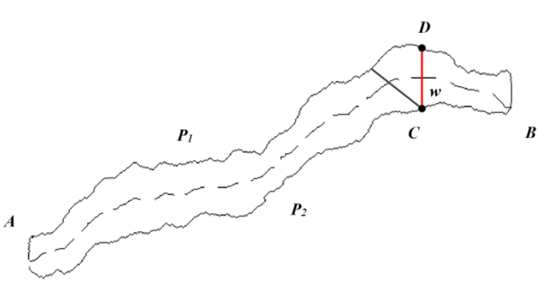


Fig. 3 Definition of crack width according to engineering experience.

4. Experiments

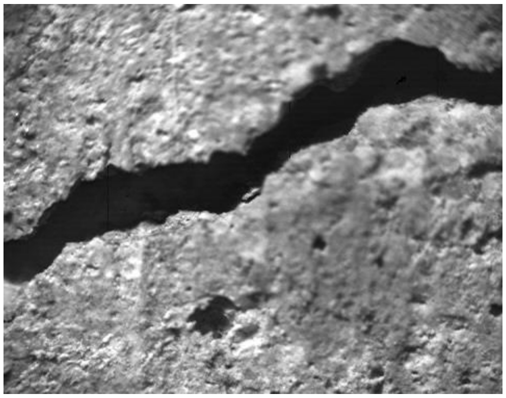
4.1 Crack monitoring experiment setup

The complete process of the crack quantification is demonstrated on a concrete construction surface using the proposed framework and checking the real accuracy. Specifically, we monitored an outdoor concrete architecture using a designed crack image acquisition system. Fig. 4 shows the setup of the crack image acquisition system. The system comprises an optical camera, two tripods, and illuminators. A Nikon camera and an illuminator were used for capturing crack images from the wall. An 16 GB memory card in the camera was used to store crack images for subsequent analysis processing. The camera was calibrated by a Ti-TIMES CC-050-O-3 checkerboard plate before the monitor. The accuracy of the calibration plate is ± 0.0015 mm in both x and y axes. Calibration is necessary in advance to ease the transfer of the pixel length or width to the real scale. The condition could be complicated without a stable device.

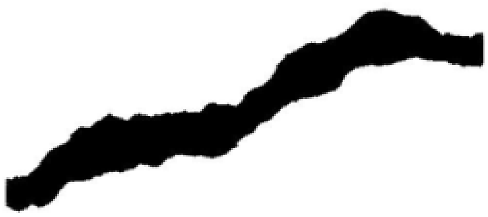
Fig. 4. Experiment setup for an outdoor concrete architecture.

4.2 Image-based retrieval of crack properties

One of original crack images captured from the concrete architecture surface can be obtained from Fig. 5. The background was removed successfully in the percolation-based model.



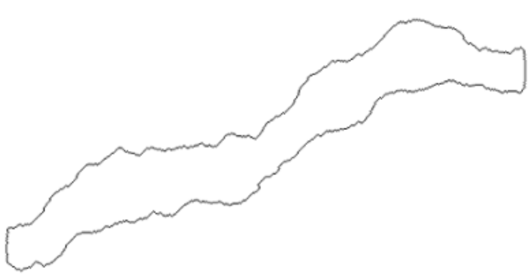
(a) the original image of concrete surface crack



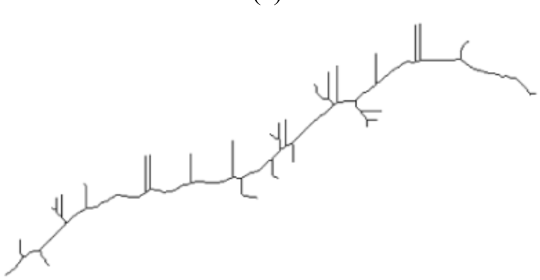
(b) the generated crack map after pre-processing

Fig. 5 The captured crack image

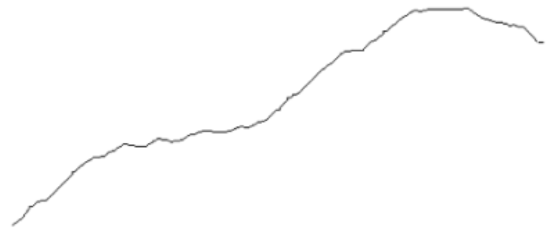
The profile and skeleton of the given crack can be obtained from Fig. 6(a) and (b), respectively. Fig. 6(c) exhibits the crack trunk generated by the proposed edge removal method. The distance map of the captured crack image with EDT an be obtained from Fig. 6(d). The crack profile of length versus width of the given crack is plotted in Fig. 7. These figures provide useful data on the growth of the crack.



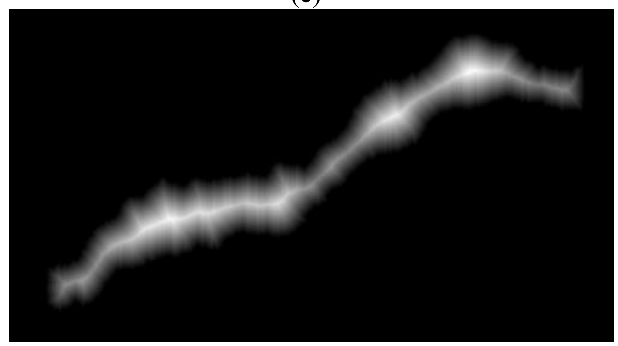
(a)



(b)



(c)



(d)

Fig. 6 Visual retrieval of crack length and width: (a) the crack profile; (b) the crack skeleton; (c) the crack trunk; (d) the crack distance map.

To make the analysis more accurate, we divide the crack trunk into five segments, as shown in Fig. 8, and determine the properties of each segment. The length and width are calculated at their respective marked points. Table 1 presents the results.

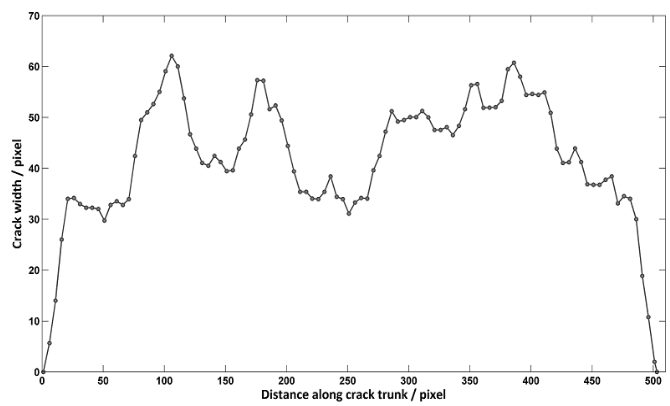


Fig. 7 Variation of crack width along length.

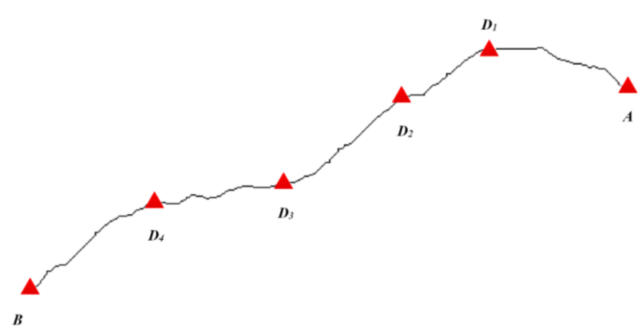


Fig. 8 Crack trunk divided into five segments.

Table 1 Crack properties measurement results using the proposed method of the divided crack.

Crack segment	Length in mm	Width in mm	AVG(width) in mm
A	0	0	0
D_1	1.11	0.61	0.45
D_2	1.86	0.52	0.55
D_3	2.96	0.44	0.39
D_4	3.83	0.55	0.51
B	5.13	0	0.37

4.3 Comparison and discussion

To evaluate the performance further, we collect a set of 30 crack images captured from different concrete architecture surfaces to validate the effectiveness and accuracy of the proposed method. These crack images are obtained with the same calibrated equipment previously described. We compare the performance of our method with the results of manual measurements that use mechanical instruments, such as a graduated card, a Vernier caliper, a comparator, and a micrometer. The approach is also compared with the image-based measurement method proposed by Seung et al. Their method uses the Dijkstra algorithm to calculate the crack length after completing the crack extraction. The width of the points is calculated by composing each area.

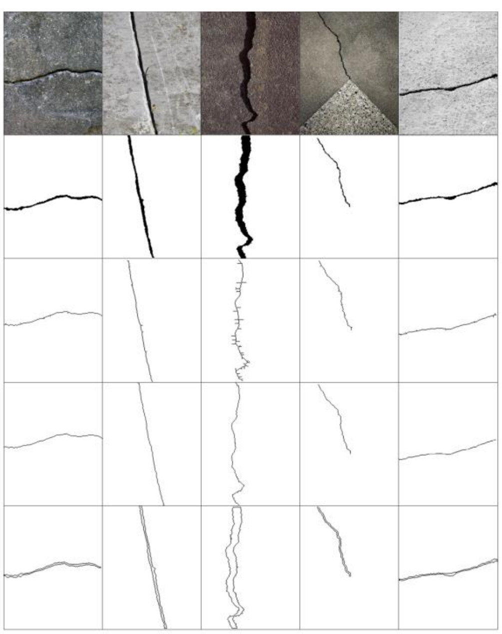
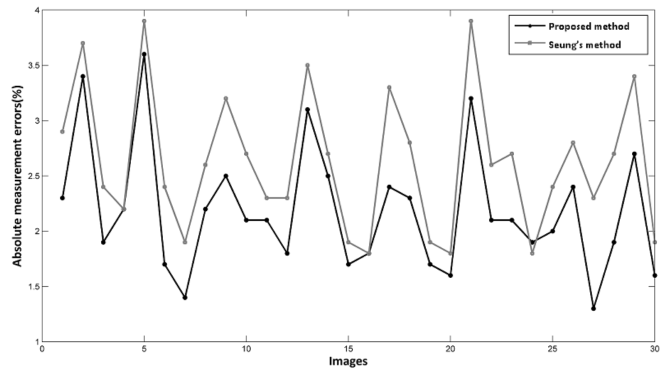


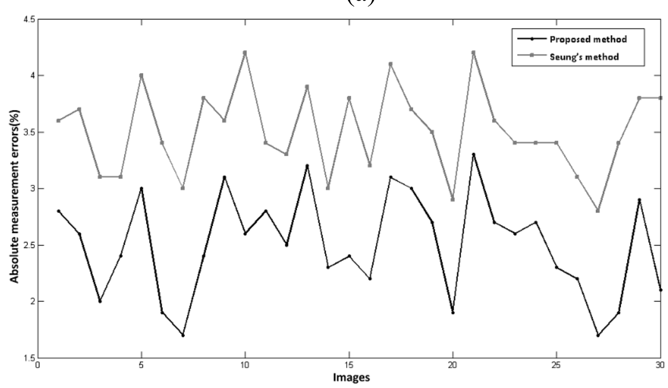
Fig. 9 Crack retrieval on five images.

The first row presents original images. The second row presents crack maps generated by pre-processing. The third row presents crack skeletons detected through thinning. The fourth row presents the crack trunks captured by the edges removal method. The last row presents the crack profiles detected from the crack map by Canny in Figure 9. The method achieves good performance in detecting the crack from the preliminary images and in obtaining the crack trunk and crack profile.

Crack properties including length and width can be calculated using image processing by applying a defined rule. To evaluate the crack measurement results, the crack properties retrieved by the proposed and Seung's methods are compared. In Fig. 10(a) and (b), the absolute measurement errors are calculated by applying the above methods on 30 crack images. Table 2 presents the statistical results of the crack properties using the two methods.



(a)



(b)

Fig. 10 Absolute measurement errors of crack properties measured by Seung's method in 30 crack images both compared with manual survey: (a) the crack length; (b) the crack width.

The average errors are 2.18% for crack length and 2.51% for crack width using the proposed method. In any case, the measuring error is less than 3.6% in length and 3.3% in width. The crack tree model, which can reduce storage capacity, indicates that the computational efficiency of the proposed algorithm is better than that of Seung. This result is sufficient for most civil applications of crack measuring, such as geological applications and construction works.

Table 2 Measurement errors for 30 crack images.

Method	Width	Length

	Total	Average	Std	Total	Average	Std
Proposed method	*75.40 %*	*2.51%*	*0.43%*	*65.50%*	*2.18%*	*0.57%*
Seung's method	*104%*	*3.48%*	*0.39%*	*78.70%*	*2.62%*	*0.60%*

5. Conclusion

This study can measure crack properties and the proposed method can be applied in many civil applications. The method starts with crack skeleton and profile detection with pre-processing. Then, the crack skeleton of a tree structure is constructed, and the length is calculated. Afterwards, identifying the crack width is conducted by applying the EDT to the crack profile. The validity and the accuracy of the proposed method are ensured through comparisons with manual surveys and existing image-based methods.

However, the method requires the calibration and this step may not be practical enough. The future improvements should modify the crack model and apply binocular vision in crack image measurement.

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