Crack detection in historic structures using mixed Prewitt filter: Case study of the Historic Si-o-se-pol Bridge in Iran

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ABSTRACT

In contrast to new and modern structures, historical structures have cultural significance, and it is essential to make an effort to preserve them. For this purpose, fast and accurate damage detection of historical structures plays a crucial role. Thus, the current study introduces a novel and effective tool for detecting cracks in historic structures. A new and modified version of the Prewitt filter is proposed to detect cracks in the Si-o-se-pol Bridge, a historic bridge in Iran. Results of crack detection using vertical and horizontal Prewitt filters are compared to those obtained from the proposed mixed filter. The findings show that the mixed Prewitt filter has significantly better performance compared to the vertical and horizontal Prewitt filters.

1. Introduction

Historical and old structures have a cultural value, whereas modern and new buildings do not include such a value. Therefore, the preservation of historical structures is an effort to preserve valuable and unrepeatable cultural concepts. On the other hand, timely and accurate damage detection of historic structures can play a key role in their preservation and restoration.

Numerous studies have investigated the detection of damage and monitoring of the condition of historic structures through various methods. Avdelidis and Moropoulou (2004) utilized thermal images of historical buildings' surfaces to monitor their conditions, suggesting that infrared thermography can efficiently evaluate historic structures' materials to protect cultural heritage. Binda and Saisi (2001) introduced the state of the art of studies about historical buildings in Italy, highlighting the damage caused by severe earthquakes during the Second World War and emphasizing the need for careful diagnosis of the state of damage to successfully rehabilitate historical monuments. In another study, Binda and Saisi (2009) investigated the applications of non-destructive tests to monitor the damaged state of historic structures, focusing on crack detection, moisture distribution, and internal voids. Gentile and Saisi (2013) utilized operational modal analysis to investigate the dynamic behavior of two historic structures, while Mesquita, Arêde, Pinto, Antunes, and Varum (2018) created a wireless sensor network for long-term monitoring of the historic Foz Côa church in Portugal. Wang, Zhao, Zhao, and Zhao (2018) applied convolutional neural networks to separate healthy bricks from damaged ones, and Germanese, Leone, Moroni, Pascali, and Tampucci (2018) monitored cracks in historic structures via UAVs and planar markers. Among these methods, image processing-based damage detection has become increasingly important due to the continuous improvement of digital image quality produced by advanced cameras. Saadatmorad, Talookolaei, Milani, Khatir, and Le (2023) proposed an image processing-based crack detection method in historical structures using a derivative of RGB components of images obtained from historical structures, and their method's efficiency was verified on two historical sites in Iran, Khaju Bridge and Molla-Haji Mosque.

Surprisingly, there has been no research conducted on the utilization of the Prewitt filter in the context of crack detection in historical structures. However, Abdel-Qader, Abudayyeh, and Kelly (2003) have used four different edge detection methods, namely Fast Fourier Transform, Fast Haar Transform, Sobel, and Canny, for detecting edges in concrete bridges. Among these methods, the Fast Haar Transform yielded the best results. This outcome was attributed to the absence of a combination of vertical and horizontal filters. Yang, Wu, Zhao, Li, and Zhai (2011) proposed an improved Prewitt algorithm for detecting edges in general sample images. They implied that the reason for suggesting such an improved Prewitt algorithm was that the traditional Prewitt edge detection algorithm was sensitive to noise. Ahmed (2018) conducted a comparative study on Sobel, Prewitt, and Canny edge detection operators for image processing. According to the results, the Canny edge detection algorithm showed higher accuracy than Prewitt and Sobel edge detection techniques. The edges of that study were not cracks in historic structures. In this paper, we present an enhanced version of the Prewitt filter that incorporates both vertical and horizontal filters to detect cracks in historic structures. To assess the effectiveness of our proposed method, we apply it to the case study of the Historic Si-o-se-pol Bridge in Iran.

2. Methodology

Consider an image $I_{m\times n}$ as follows:

$$I_{m\times n} = \begin{bmatrix} f_{1\,1} & f_{1\,2} & f_{1\,3} & & f_{1n-2} & f_{1\,n-1} & f_{1\,n} \\ f_{2\,1} & f_{2\,2} & f_{2\,3} & \cdots & f_{2\,n-2} & f_{2\,n-1} & f_{2\,n} \\ f_{3\,1} & f_{3\,2} & f_{3\,3} & & f_{3\,n-2} & f_{3\,n-1} & f_{3\,n} \\ & \vdots & & \ddots & & \vdots & \\ f_{m-2\,1} & f_{m-2\,2} & f_{m-2\,3} & & f_{m-2\,n-2} & f_{m-2\,n-1} & f_{m-2\,n} \\ f_{m-1\,1} & f_{m-1\,2} & f_{m-1\,3} & \cdots & f_{m-1\,n-2} & f_{m-1\,n-1} & f_{m-1\,n} \\ f_{m\,1} & f_{m\,2} & f_{m\,3} & & f_{m\,n-2} & f_{m\,n-1} & f_{mn} \end{bmatrix} \quad (1)$$

Where n and m are the numbers of pixels in the direction of x and y, respectively.

For edged detection of an image $I_{m\times n}$, first-order derivative filters are mainly used. The first-order derivative of the one-dimensional function $f(x)$ can be approximated by one-dimensional gradients. Forward approximation of the first-order derivative of the function $f(x)$ is expressed as follows:

$$f'_{(x)} \approx \frac{f(x+h) - f(x)}{h} \quad (2)$$

Where h denotes the Backward approximation of the first-order derivative of the function f(x) is expressed as follows:

$$f'_{(x)} \approx \frac{f(x) - f(x+h)}{h} \quad (3)$$

Central approximation of the first-order derivative of the function $f(x)$ is expressed as follows:

$$f'_{(x)} \approx \frac{f(x+h) - f(x-h)}{2h} \quad (4)$$

To perform the edge detection, the central approximation is a suitable way to have the derivative filter both in the x and y directions as follows:

$$f(x,y) = \frac{f(x+h,y) - f(x-h,y)}{2h} \rightarrow \text{Derivative in } x - \text{direction:} \quad [-1 \quad 0 \quad 1] \quad (5)$$

$$f(x,y)=\frac{f(x,y+h)-f(x,y-h)}{2h}\rightarrow \text{Derivative in y}-\text{direction:}\quad \begin{bmatrix}-1\\0\\1\end{bmatrix} \tag{6}$$

It is assumed that the x-coordinate and y-coordinate increase in the right and down directions, respectively. Different edge detection filters are developed by weighting the derivatives along x and y directions to implement them numerically.

By introducing the one-dimensional standard averaging filters in x and y directions as follows:

$$\text{Standard averaging filter in x}-\text{direction:}\quad [1\quad 1\quad 1] \tag{7}$$

$$\text{Standard averaging filter in y}-\text{direction:}\quad \begin{bmatrix}1\\1\\1\end{bmatrix} \tag{8}$$

Convolution operations between the central approximations and the standard averaging filters result in the following Prewitt filters:

$$\text{Prewitt filter in x}-\text{direction:}\quad \begin{bmatrix}1\\1\\1\end{bmatrix} * [-1\quad 0\quad 1]=\begin{bmatrix}-1&0&1\\-1&0&1\\-1&0&1\end{bmatrix} \tag{9}$$

$$\text{Prewitt filter in y}-\text{direction:}\quad \begin{bmatrix}-1\\0\\1\end{bmatrix} * [1\quad 1\quad 1]=\begin{bmatrix}-1&-1&-1\\0&0&0\\1&1&1\end{bmatrix} \tag{10}$$

The Prewitt filtering is performed using the Prewitt operator. The Prewitt operator can detect edges in an image using convolution with two filters. One of the filters is applied to the horizontal direction, and the other is applied to the vertical direction. These masks have the size 3×3 as follows:

$$G_x=\begin{bmatrix}-1&0&1\\-1&0&1\\-1&0&1\end{bmatrix} \tag{11}$$

$$G_y=\begin{bmatrix}1&1&1\\0&0&0\\-1&-1&-1\end{bmatrix} \tag{12}$$

According to Dong and Shisheng (2008), for filtering by the Prewitt operator, the convolution operation is used as follows:

$$P_H=\begin{bmatrix}-1&0&1\\-1&0&1\\-1&0&1\end{bmatrix} * \begin{bmatrix} f_{1\,1} & f_{1\,2} & f_{1\,3} & & f_{1n-2} & f_{1\,n-1} & f_{1\,n}\\ f_{2\,1} & f_{2\,2} & f_{2\,3} & \cdots & f_{2\,n-2} & f_{2\,n-1} & f_{2\,n}\\ f_{3\,1} & f_{3\,2} & f_{3\,3} & & f_{3\,n-2} & f_{3\,n-1} & f_{3\,n}\\ & \vdots & & \ddots & & \vdots & \\ f_{m-2\,1} & f_{m-2\,2} & f_{m-2\,3} & & f_{m-2\,n-2} & f_{m-2\,n-1} & f_{m-2\,n}\\ f_{m-1\,1} & f_{m-1\,2} & f_{m-1\,3} & \cdots & f_{m-1\,n-2} & f_{m-1\,n-1} & f_{m-1\,n}\\ f_{m\,1} & f_{m\,2} & f_{m\,3} & & f_{m\,n-2} & f_{m\,n-1} & f_{mn} \end{bmatrix} \tag{13}$$

$$P_V = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ -1 & -1 & -1 \end{bmatrix} * \begin{bmatrix} f_{1\,1} & f_{1\,2} & f_{1\,3} & \cdots & f_{1\,n-2} & f_{1\,n-1} & f_{1\,n} \\ f_{2\,1} & f_{2\,2} & f_{2\,3} & \cdots & f_{2\,n-2} & f_{2\,n-1} & f_{2\,n} \\ f_{3\,1} & f_{3\,2} & f_{3\,3} & & f_{3\,n-2} & f_{3\,n-1} & f_{3\,n} \\ & \vdots & & \ddots & & \vdots & \\ f_{m-2\,1} & f_{m-2\,2} & f_{m-2\,3} & & f_{m-2\,n-2} & f_{m-2\,n-1} & f_{m-2\,n} \\ f_{m-1\,1} & f_{m-1\,2} & f_{m-1\,3} & \cdots & f_{m-1\,n-2} & f_{m-1\,n-1} & f_{m-1\,n} \\ f_{m\,1} & f_{m\,2} & f_{m\,3} & & f_{m\,n-2} & f_{m\,n-1} & f_{mn} \end{bmatrix} \quad (14)$$

Where P_H and P_V are the horizontal and vertical Prewitt-filtered images.

By adding the P_H and second image, a new image called the characteristic image is crated.

The mixed Prewitt-filtered image is expressed as follows:

$$P_C = P_H + P_V = \begin{bmatrix} P_{1\,1} & P_{1\,2} & P_{1\,3} & \cdots & P_{1\,n-2} & P_{1\,n-1} & P_{1\,n} \\ P_{2\,1} & P_{2\,2} & P_{2\,3} & \cdots & P_{2\,n-2} & P_{2\,n-1} & P_{2\,n} \\ P_{3\,1} & P_{3\,2} & P_{3\,3} & & P_{3\,n-2} & P_{3\,n-1} & P_{3\,n} \\ & \vdots & & \ddots & & \vdots & \\ P_{m-2\,1} & P_{m-2\,2} & P_{m-2\,3} & & P_{m-2\,n-2} & P_{m-2\,n-1} & P_{m-2\,n} \\ P_{m-1\,1} & P_{m-1\,2} & P_{m-1\,3} & \cdots & P_{m-1\,n-2} & P_{m-1\,n-1} & P_{m-1\,n} \\ P_{m\,1} & P_{m\,2} & P_{m\,3} & & P_{m\,n-2} & P_{m\,n-1} & P_{mn} \end{bmatrix} \quad (15)$$

3. Case study

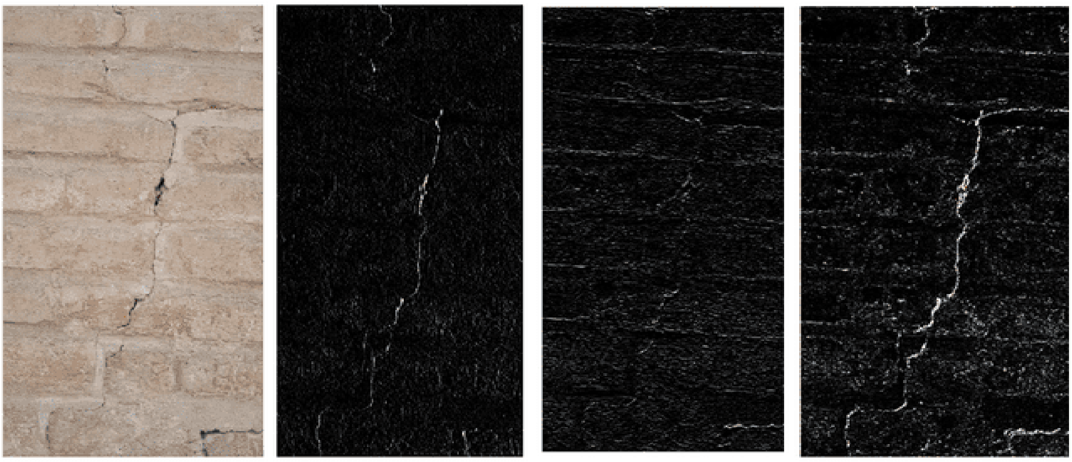
Si-o-se-pol Bridge (also known as Allahverdi Khan Bridge) is a historic bridge located on the Zayanderud River in Isfahan Province, Iran. The bridge was constructed in the 17th century during the rule of Shah Abbas Safavi to use as both a dam and a bridge (Figure 1). The bridge is 295m in length, and the bridge's width is 14m. Also, it has 33 spans.

Figure 1. A picture of the considered Si-o-se-pol Bridge as a case study

The Si-o-se-pol Bridge was constructed by Iranian poet and architect Hossein Bana Isfahani, supervised by Georgian statesman Allahverdi Khan Undiladze, in light of King Shah Abbas I's decision to turn the city of Isfahan into the capital of art, sport, and trade. Similar to most Persian architectural works, repetition and symmetry are observed in this bridge. Brick, Saruj, plaster, and stone are the main construction materials of the bridge. In this paper, cracks in different sections of the bridge are considered to evaluate the performance of the proposed damage detection technique.

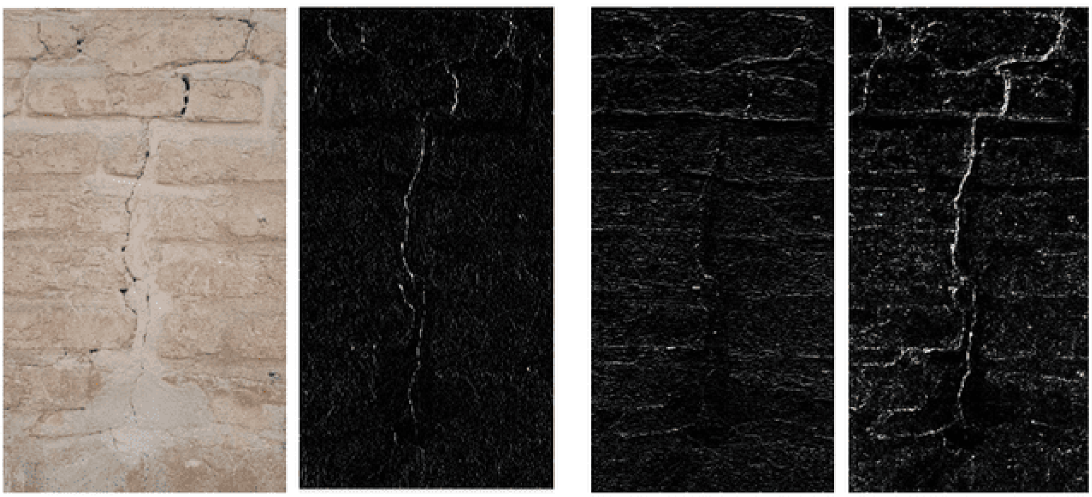
4. Results

This section considers four crack scenarios in our historical building to evaluate its performance. As seen in Figures 2 to 5, the results of the four crack scenarios include the vertical Prewitt filter, horizontal Prewitt filter, and the proposed mixed Prewitt filter. By comparing these figures with their corresponding original images, it is demonstrated that in all four crack scenarios, the proposed mixed Prewitt filter can detect cracks in the historic structure's walls better than the two other methods (i.e., the vertical Prewitt filter and the horizontal Prewitt filter). As can be seen from the results, using the mixed Prewitt filter to identify cracks in structures includes both horizontal and vertical edges of the image. This filter proves to be an effective tool in identifying cracks in historic masonry structures. In this way, researchers and activists in the restoration of historical buildings can use such a mixed filter for a more careful evaluation of masonry historical structures to apply the necessary actions to preserve the structures. Furthermore, the Prewitt filter can assist other crack detection methods in historical structures, including machine learning-based methods and other image-based techniques.



Original image | Vertical Prewitt filter | Horizontal Prewitt filter | Proposed improved Prewitt filter

Figure 2. Results of case 01 crack detection



Original image | Vertical Prewitt filter | Horizontal Prewitt filter | Proposed improved Prewitt filter

Figure 3. Results of case 02 crack detection

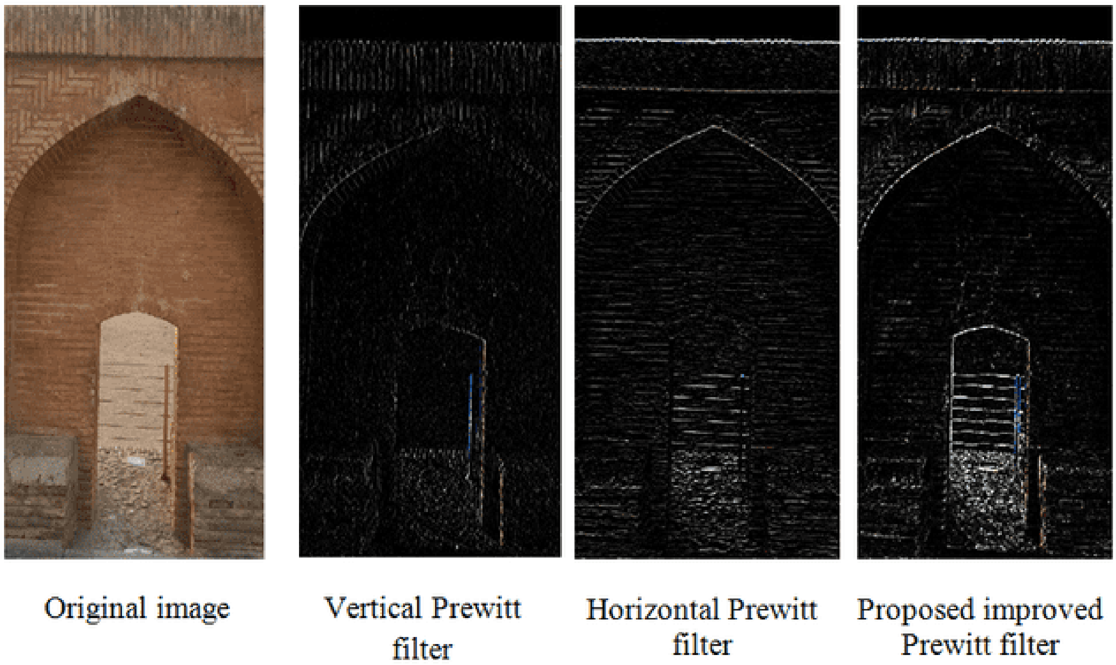


Figure 4. Results of case 03 crack detection

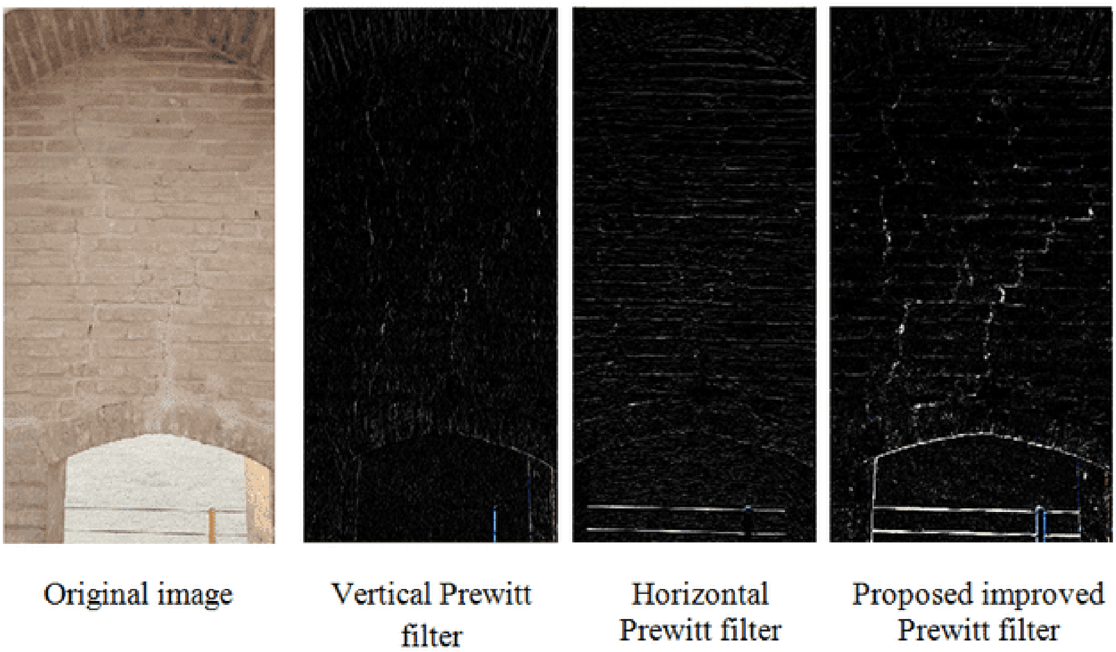


Figure 5. Results of case 04 crack detection

5. Conclusions

As the resolution of digital photos increases, image processing techniques are gaining popularity. One area where image processing techniques can be used is in the monitoring of the condition of historic structures. In the current study, a mixed version of Prewitt's image processing algorithm is introduced to identify cracks in the walls of a historical bridge in Iran called the Si-o-se-pol Bridge. The results show that the proposed method can detect cracks in historic structures.

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