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An inexpensive method for monitoring deflections in bridges by machine vision

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ABSTRACT

The objective of this study is to develop an inexpensive, low maintenance and accurate method to measure and monitor deflections in bridges using machine vision. In the experimental study presented in this paper, a 1:10 scale steel bridge model was constructed and loaded to obtain images of a deformed structure. Images of the deflected steel bridge model under various levels of loading were taken by a digital camera with a 50mm prime lens at a distance of 1m from the bridge. Vertical deflections of the bridge model were computed through the location change of markers on the bridge under loading. Analysis results were compared with deflection data measured by dial gauges. Results showed that the developed digital image analysis method was able to determine deflections of the bridge model in less than 5% error for images taken at a distance of 1m away from the bridge. In comparison to traditional techniques, this machine vision based method has advantages in low maintenance, high reliability, and accuracy in deflection measurement. It has the ability for easy integration with existing image analysis and artificial intelligence for nonstop monitoring and reporting of structure conditions. The same technique may be applied to measure deflections of other structures.

Keywords: structural health monitoring; deflection; digital image processing; bridge

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1. Introduction

Overloading has long been a main cause for bridge deteriorations and failures. As bridges are overloaded, excessive deformations in bridges can be expected. Consequently, information about bridge deformations over a period of time can provide indications of the extent of overloading and bridge deteriorations. As the bridge deformations are continuously collected and monitored, bridge owners will be able to make critical decisions on when to conduct repair or maintenance based on implications from the collected data, making the bridge management more efficient.

Traditional techniques used for measuring bridge deformations include strain gauge, linear variable differential transformer (LVDT), global positioning system (GPS), and electro-optical instruments. While many techniques are available for monitoring structural deformations, this study focuses on utilizing machine vision for monitoring bridge deflections. Using machine vision for deflection monitoring offers the following benefits: (1) it provides a nondestructive measuring technique; (2) it provides a means to measure deflections at locations in which installations of instrument are challenging; and (3) it provides a simple, robust, and economical measuring system.

Digital image processing techniques have been widely used in the past for measuring localized strains of various specimens (Savic and Hector Jr., 2009; Grytten et al., 2009; Jerabek et al., 2010). Recently, a new application of digital image processing techniques has been investigated, i.e. structural health monitoring. Kim and Kim (2011) presented a digital image processing method to monitor displacements of multiple points in a structure. Henke et al. (2015) developed a measuring system using digital image processing techniques for monitoring deformations of a roof structure in a building. For monitoring deformations of the roof structure, they installed light-emitting diodes (LEDs) at various locations of roof beams as measuring points. The results of their study were used to develop a continuous monitoring system and establish five operating stages for a gymnasium. Santini Bell et al. (2015) applied digital image correlation (DIC) to measure displacements in a girder bridge. The results of their study indicated that challenges existed in determining true deflections for small deflections with low resolution. It was suggested that more research should be conducted to investigate relationships between resolution and a minimum detectable deflection.

This study is the first phase of a multi-phase research program. The objective of this study is to develop a reliable and affordable displacement measuring system using machine vision. This paper proposes a simple procedure to process digital images for displacement measurements. The following sections present the development of the proposed machine vision measuring method and an experimental study for method validation.

2. Development of a displacement measurement system based on machine vision

2.1 Imaging system calibration

The goal of calibration was to detect the displacement of markers, calibrate the image pixel size and determine the precision of the imaging system. In the pilot study, a

blue square target (76.2 mm × 76.2 mm) was first placed on a white board and then moved downward four times with an increment of 100 mm each time. During the study, the camera remained stationary as the target moved verically at a distance of 1m from the marker. A schematic of the pilot study is presented in Fig. 1. Given the actual displacement data, the photo pixel size in millimiter were calculated. The precision and the largest possible displacement of markers were estimated.

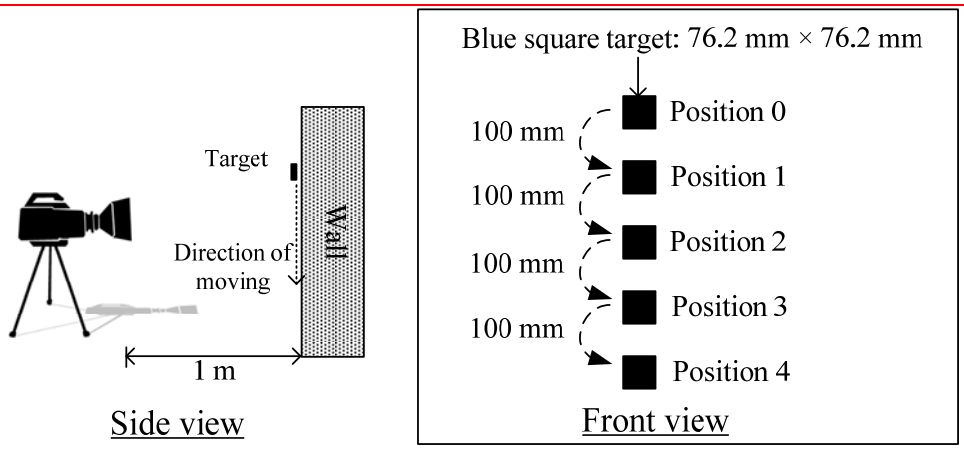


Fig. 1 Schematic of the pilot study

The following procedure were to estimate the pixel size associated with the aforementioned designated displacements of the target.

Step 1 -- Exact the blue channel and convert it to a binary image using Otsu's method.
Step 2 – Segment the marker and calculate the centroid.
Step 3 – Compute the pixel size in millimeter and estimate the precision of the calibration.

Fig. 2 shows a schematic of the digital image processing procesure for one target position. The same procedure was applied to locate the centroid of the target for each position shown in Fig. 1 – Position 0 to Position 4. After the centroids of the target were determined, the numbers of pixels between Position 0 and other positions (Position 1 to Position 4) were calculated by subtracting the row coordinate for Position (i) from the row coordinate for Position (i+1). Since the distance between each target position was carefully controlled and fixed at 100 mm, an estimate of the pixel size was feasible through dividing the traveled distance by the number of pixels in it. Table 1 lists counted numbers of pixels between various target positions and the estimated pixel size.

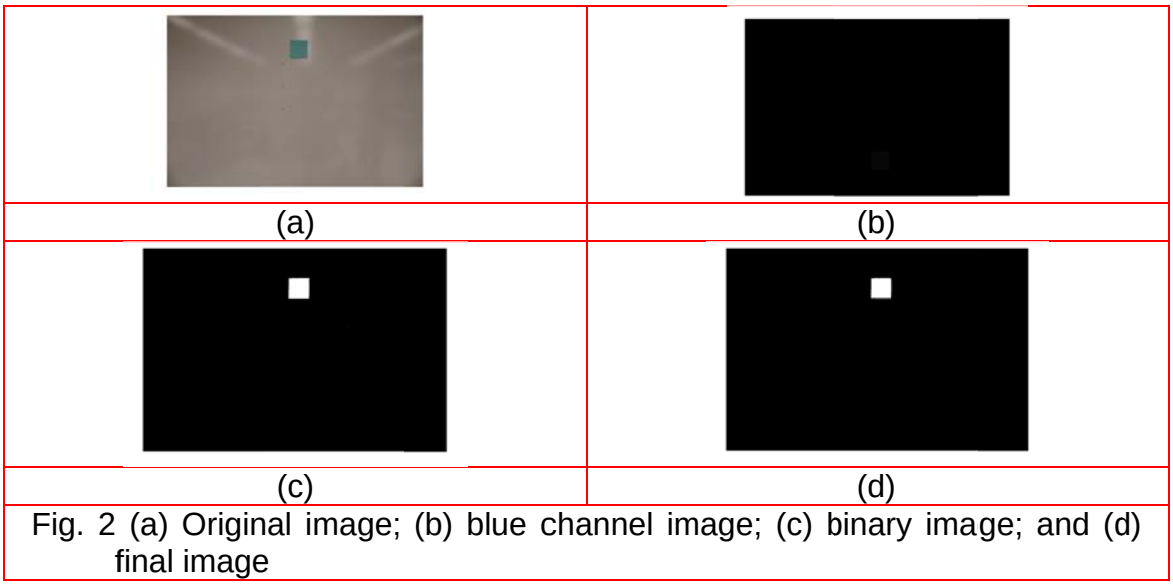


Fig. 2 (a) Original image; (b) blue channel image; (c) binary image; and (d) final image

Table 1 Estimated pixel size from the pilot study

	Traveled distance (mm)	Counted number of pixels	Estimated size of one pixel (mm)
Position 0 – Position 1	100	459	0.218
Position 0 – Position 2	200	928	0.216
Position 0 – Position 3	300	1380	0.217
Position 0 – Position 4	400	1842	0.217

The average size of a pixel in the vertical direction in which the target traveled was 0.217 mm. This average pixel size was used in the experimental program (described in next section) to calculate bridge deflections under various levels of gravity loads. The pilot study demonstrated that the technique has high accuracy in displacement measurement and has a wide deformation detection range.

3. Experimental program

The experimental program of this study included conducting load testing on a 1:10 scale steel bridge and obtaining images of the deformed steel bridge. Results from this experimental study were used to develop an inexpensive and accurate method to measure deflections in bridges through machine vision. Details and results of the experimental program are presented in the following sections.

3.1 1:10 scale steel bridge model

In order to simulate bridge deformations under a controlled environment, a 1:10

scale steel bridge model with a span of 20 feet was designed and built in an indoor facility. A schematic of the designed 1:10 scale steel bridge is shown in Fig. 3. The superstructure of the bridge comprised top chord members, bottom chord members, square tubes bracing top chord members, truss beams bracing bottom chord members, and hangers connecting top and bottom chords. Also part of the bottom chords, diagonal tubular members were added to form secondary trusses. The secondary trusses were designed to support gravity loads. Then the loads were transferred to the top chords through hangers.

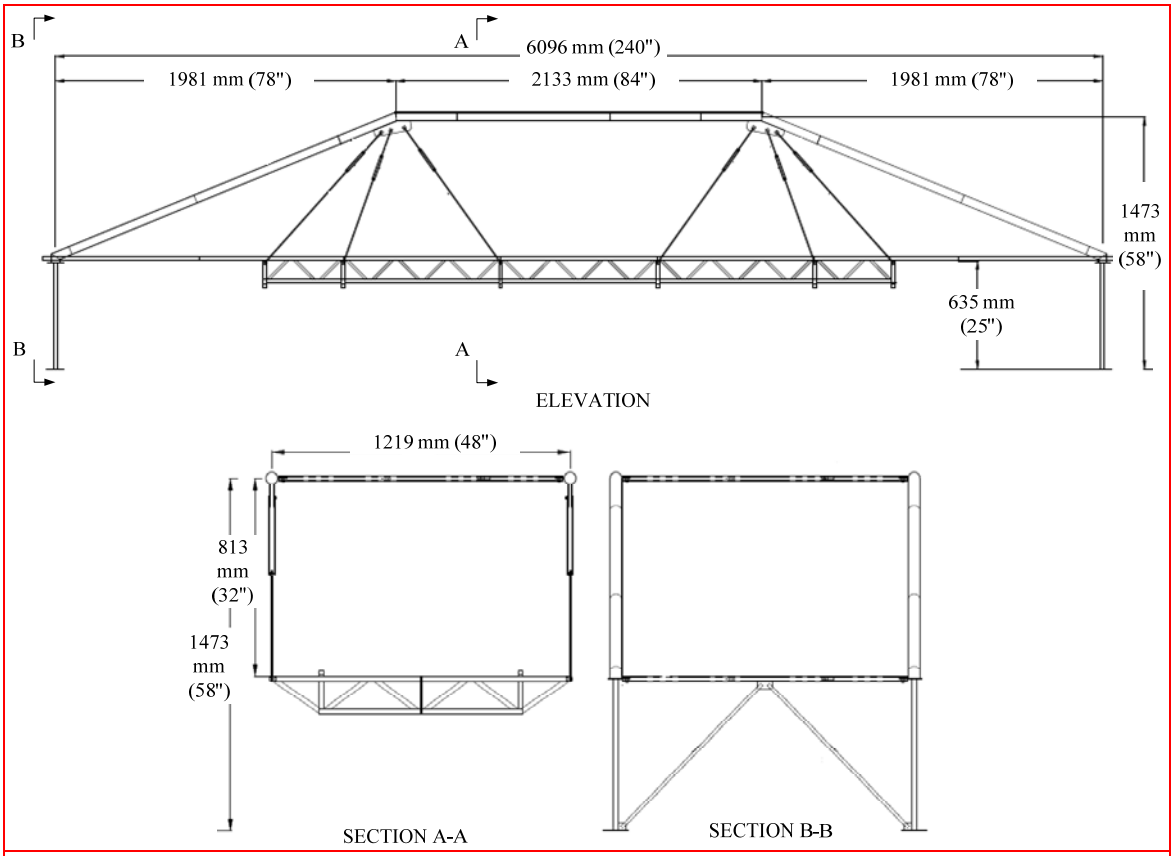


Fig. 3 Schematic of the built 1:10 scale steel bridge

3.2 Test instrumentation and test results

An experimental study was carried out to determine the accuracy of the proposed displacement measurement system in monitoring deflections of a loaded structure. The main goal of the experimental study was to apply the developed displacement measurement system to monitor the mid-span deflection of the built bridge model. A 76.2 mm × 76.2 mm square yellow target was placed in the middle of the lower truss member for monitoring the mid-span deflections of the bridge model. Two freestanding 76.2 mm × 76.2 mm square blue targets, remaining stationary throughout the testing, were put besides the monitored target as the reference points. To identify the accuracy of the mid-span deflections measured by the machine vision, a dial gauge was installed at the truss member underneath the target to measure vertical deflections of the target.

A schematic of the test instrumentation is shown in Fig. 4.

In order to create various deformation in the bridge, the testing consisted of four loading steps with incremental loads. During the testing, bags of portland cement were placed approximately in the middle of the lower truss members of the bridge. The weight of each portland cement bag was carefully measured before placed on the bridge. Multiple pictures were taken by a digital single-lens reflect camera (Cannon Rebel T2i) at a distance of 1 m directly in front of the target before and after each loading step. The distance between the camera and target was controlled to be identical to the distance used in the pilot study. Therefore, the pre-determined pixel size could be utilized to estimate bridge deflections monitored by machine vision. Results of load vs. dial gage measured displacement are shown in Fig. 5.

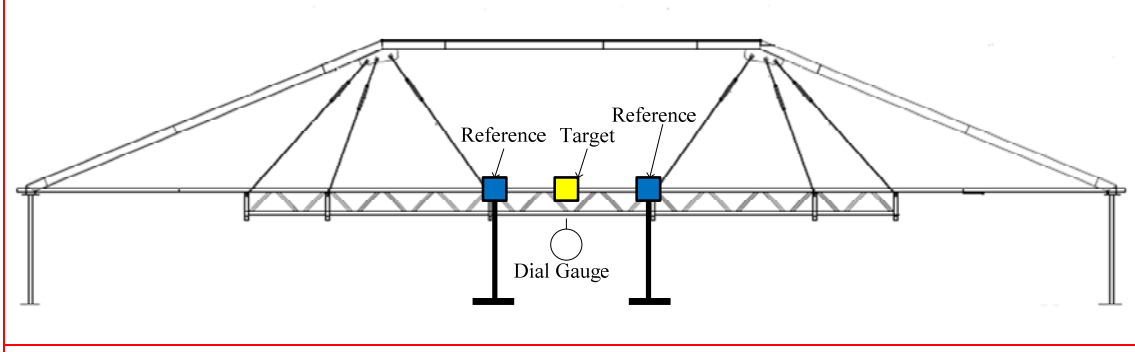


Fig. 4 Schematic of the test instrumentation

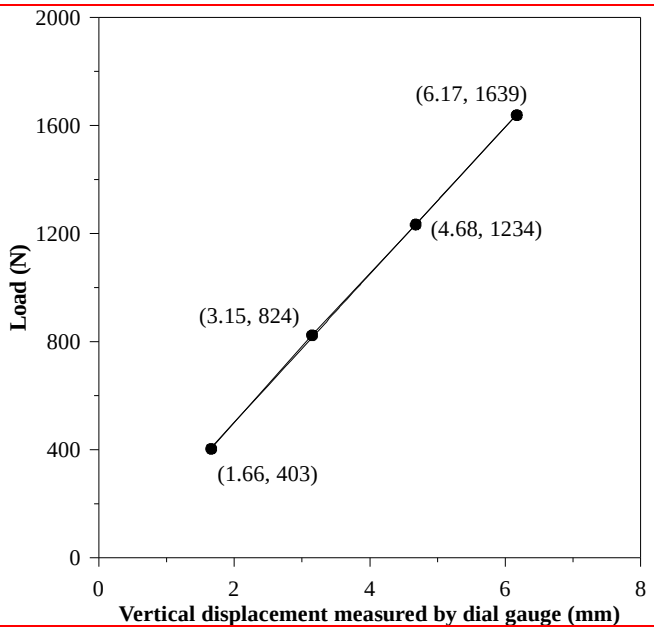
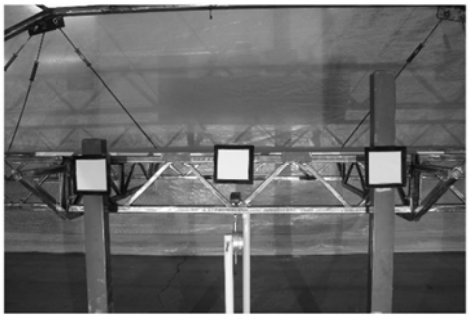


Fig. 5 Load vs. vertical displacement measured by the dial gauge

3.3 Application of the developed displacement measurement technique

The displacement measurement technique proposed in this study could be summarized in three main stages: preprocessing, analysis, and post processing.

Step 1 – Extract the blue channel of the acquired image, as shown in Fig. 6.



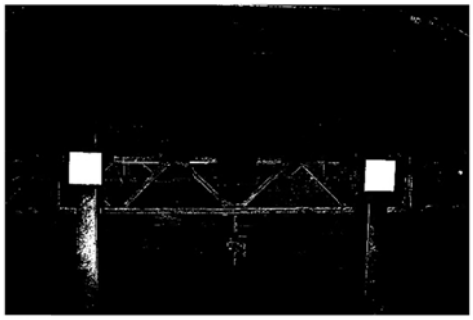
(a)

(b)

Fig. 6 (a) The grayscale image obtained from Step 1; (b) after removing the red and green channels from the image

Step 2 – Convert the blue channel into a binary image, as shown in Fig. 7.

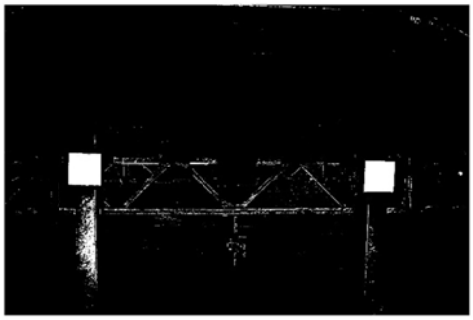
(a)



(b)

Fig. 7 Convert the only color channel that was kept in Step 2 to a binary image. (a) and (b) show the images before and after the conversion

Step 3 – Remove noises in the binary image. This step is to remove other white objects that were not the reference points from the image by converting them to black. Fig. 8 shows the images before and after noises were removed. After obtaining Fig. 8(b), analysis was performed to identify the centroids of the two reference points in the image, which were then used to determine the displacement of the target.



(a)

(b)

Fig. 8 (a) the image before noises were removed; (b) the image after noises were removed (in this case, only the square reference points were kept). The same procedure was performed separately to keep the target in the image

Steps 1 to 3 were repeated for obtaining binary images of the square target after each of the four loading stages. Subsequently, the centroid of the target for each loading stage was determined. The next step was to estimate the displacement for each target in each loading condition in pixels. This was done by calculating the difference in centroids locations for the moving targets and the reference targets.

3.4 Application results

Table 2 shows the comparison between the dial gauge and machine vision data. The differences between the dial gauge and machine vision data ranged from 0.36 mm for the loading step 1 to 0.09 mm for the loading step 4. As the vertical displacement increased, the error of the machine vision data decreased. At the first loading step, the displacement measured by machine vision showed a 21.7% error for a vertical displacement of 1.66 mm. Nevertheless, when the vertical displacements were greater than 3 mm, the errors were significantly reduced (all under 5%, ranged from 3.5% to 1.5%). The error was mainly attributed from the camera resolution. Determined in the pilot study, the pixel size at a working distance of 1 m was about 0.217 mm, which was in the same order of the recorded differences. As the machine vision measurement system proposed herein relied on the ability to accurately identify the centroids of the target and references and the position of the target relative to the references in terms of pixels, the size of the pixel dictated the accuracy of the measurement as the locations of the centroids could only be as accurate as the pixel size. The results of this study showed that the proposed measurement method could achieve an excellent accuracy when the actual deflection was insensitive to the pixel size.

Table 2 Estimated pixel size from the pilot study

Load (N)	Vertical displacement measured by the dial gauge (mm)	Vertical displacement calculated by the proposed technique (mm)	Difference (mm)	Error (%)
403	1.66	1.30	0.36	21.7
824	3.15	3.04	0.11	3.5
1,234	4.68	4.56	0.12	2.6
1,639	6.17	6.08	0.09	1.5

4. Conclusions

Based on the results of the current study, the following conclusions can be drawn:

1. The accuracy of the proposed machine vision deflection measurement system is sensitive to the size of pixels in pictures. It is suggested by the test data presented herein that the proposed method is adequate for measuring deflections that are insensitive to the pixel size with a good accuracy (less than 5% error).
2. As the locations of the centroids of the target and references are represented by pixels, the accuracy of the centroid determinations are sensitive to the size of pixels.
3. Given that the anticipated bridge deflections are insensitive to the pixel size, the proposed machine vision measurement system provides an inexpensive, accurate, and reliable alternative to traditional deformation measurement systems, such as LVDT or strain gauges.

Future studies are recommended to measure bridge deformation with pattern recognition on high visible and infrared reflective paintings. The bridge deformation can be monitored continuously with high spatial resolution along the bridge.

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