Image-based Deflection Measurement and Error Analysis

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Abstract. This paper gives an image-based and computerized solution to the deflection measurement of bridges with its corresponding design scheme of measuring devices. A laser transmitter is fixed on one end of the bridge. A dark cartridge with an optical screen and a camera is installed in the middle of the bridge. Light beam projects onto the optical screen, while the camera captures the image on the screen. Bridge deflection is measured by applying image-processing algorithms and then performing the related computation. The systematic error caused by tilting film and geometric distortion is analysed and eliminated. One of the advantages is that, this low-cost measuring scheme obtains direct deflection data and requires simple operations comparing with existing methods. Other advantages and disadvantages are also highlighted.

1. Introduction

The deflection of a bridge is the key parameter of its status evaluation. The traditional methods of bridge deflection consist of dial gauges and linear variable differential transducers (LVDTs)[1]. Their advantage is that, direct data of deflection characteristics of bridges can be acquired. However, difficult operations are also required to perform related measurement operations.

There are some other methods which include the fibre optic Bragg-grating (FBG) sensor[2,3], inclinometer[4,5], etc. The FBG is sensitive to noise, and it must be embedded into structure, which limits its compatibility with different conditions. The inclinometer is required to have a good transient response.

The GPS is conveniently employed to measure the deflection, but with low accuracy[6]. Another method is to measure deflection by capturing the image of the laser spot fixed on the bridge[7]. Since the image is captured through a telescope, the lens and their spin angles may induce errors. Overall, a convenient and direct method is expected for deflection measurement.

2. Image-based Deflection Measurement

To solve the problems above, an image-based deflection measurement scheme is presented in Figure 1. A laser transmitter is installed on a 3-axis platform, and the platform is fixed on a stationary surface of the bridge approach to keep the laser beam stable.

Image capturing devices are placed on the bridge beam. The laser beam casts onto the optical screen in the front of the device and projects a light spot. A camera installed in this device is deployed to capture images of the light spot. When a truck moves on the bridge beam, the optical screen of the image capturing device moves up and down following the bridge beam. Since the laser beam is stationary, the light spot moves consequently on the film. The shift amount of the light spot is the same as the deflection amount of the bridge beam at the corresponding position.
To detect the position of the light spot, a 2-D image sensor is provided. One of the solutions is installing a big-size charge-coupled device (CCD) or complementary metal oxide semiconductor (CMOS) image sensor as the spot projecting target. Its advantage is diminishing geometric distortion. However, the disadvantage is a higher cost. As is shown in Figure 1, an image capturing device is presented. It uses a frosted film to make a real image. And this image is captured by a digital camera in the dark box shown in Figure 1. This design has two advantages. One is easy to adjust the resolution by changing the lens. The other is lower cost. However, its disadvantage is a geometric distortion caused by the lens.

Figure 2. Correction of lens geometric distortion. Because the main distortion of the lens is radial, a calibration picture shown in Figure 2(a) is designated to reduce it. Supposed that Figure 2(b) is the image projected on the CMOS sensor from the calibration picture on the film behind lens, number 0 denotes the centre of the picture, and numbers 1 to 6 indicate rings with radius from 1 unit to 6 units (1 unit expands to 5mm as an instance), respectively. Marking that \((x_0',y_0')\) is the coordinate of the image centre, and \(r_1'\) to \(r_6'\) represent radiuses on the image related to ring 1 to 6 on the picture. \((x',y')\) is the coordinate of the point \(p'\). Coordinate \((x,y)\) of the point \(p\) on the picture can be calculated by the equations 1 to 3. In case \(r = 0\), \(p\) is the centre, where \(x = y = 0\). In equation 2, \(U\) indicates the steps from 1mm to 5mm.

\[
\begin{align*}
    r' &= \sqrt{(x' - x_0')^2 + (y' - y_0')^2} \\
    r &= 3U + \frac{r' - r_4'}{r_4' - r_3'} U \\
    x &= \frac{x' - x_0'}{r' - r_4'} r, y = \frac{y' - y_0'}{r' - r_4'} r (r' \neq 0)
\end{align*}
\]

The final step is to calculate the coordinate of the spot center. Supposed that \(N\) is the count of all the spot pixels, \((x_i,y_i)\) is the coordinate of each spot pixel. \((x_c,y_c)\) is the coordinate of the spot center, which can be calculated by equation 4.
\[ x_c = \frac{\sum_{i=1}^{N} x_i}{N}, \quad y_c = \frac{\sum_{i=1}^{N} y_i}{N} \] (4)

For the necessity of accuracy, it is also significant to segment the spots from the background. A threshold is set to distinguish the spots from background because the laser spot is stronger than the diffused reflection of sunlight. Pixels of which grey values are greater than threshold belong to the spot, the others lie in the background.

As equation 4 shows, each pixel has the same weight. If there is a dark point of the image sensor in the spot range, it will lose the weight and induce errors. Generally, the diameter of a laser light spot is 3 to 5 mm. For the accuracy of 0.01 mm / pixel, a spot should contain 70k to 200k pixels, where the weight of a dark point only 1 ppm and therefore can be neglected. However, one or more bright spots far away from the light spot shown in Figure 3 may induce errors that are not negligible.

There are two ways to be employed to remove these bright spots. One is increasing the threshold, the other is performing regional shrinkage. If the bright spots are comet like, the first one is prioritized; and the second one is employed to remove standalone bright points.

3. Implementation of Devices

This device consists of the laser transmitter with the remotely controlled 3-axis platform and an image capturing device. They are both controlled by a main computer. Figure 3 illustrates the connections. An application program runs on the computer to perform image capturing, image processing, geometric correction, calibration, and to present results finally.

![Figure 3. Connections of devices.](image)

3.1. Laser Transmitter

The first part is focused on the laser transmitter installed on a 3-axis platform. It controls the laser transmitting and the direction of the laser beam. There are 2 rotors controlling horizontal and vertical directions. To meet the requirement of fine adjusting on vertical direction, there is an elevator added blow the vertical rotator. Figure 4 shows the detail.

![Figure 4. Laser transmitter with 3-axis platform.](image)
The three movable components are driven individually by step motors with a battery supplying the power. As a result, operators can remotely control the position of the laser spot on the main computer.

3.2. Image-capturing Device
Follow the method introduced above, instead of the CMOS image sensor, a device combined with a piece of film with a digital camera is designed. They are enclosed by a dark box as illustrated in Figure 5. This film is forested and partly transparent. While laser beams project onto the film, a light spot appears. Because the film is partly transparent, it can be identified in the dark box.

![Figure 5. Structure of the image capturing device.](image)

A digital camera with a set of lenses is employed to capture the image. The resolution of the camera in this design is 2048 in width and 1536 in height. Generally, the deflection is in vertical direction. The camera with a cartridge is installed on the wall of the dark box rotated by 90 degrees, and this will make 2048 pixels in a vertical direction and 1536 pixels in a horizontal direction. The cartridge can be moved on a pair of tracks. Different resolutions and measurement scopes can be reached by adjusting its position and the lens.

3.3. Image Capturing
The mode of auto-capturing is adopted for the requirement of static and dynamic deflections. In this mode, it will take the same intervals to capture a series of images. A block of memories is allocated as a buffer for the 16 frames of images. The buffer works in mode FIFO (First In, First Out) as is shown in Figure 6. Synchronous sampling and asynchronous reading can be realized. Consequently, the sampling operation is dynamic. Moreover, the sampling time is the exposure time. Since the maximal frame rate is 30 frames per second, the maximal sampling rate is also 30 samples per second.

For the measurement of static load, seven frames of images are captured sequentially after launching sampling. A process is designed to perform the following calculations.

\[
\bar{x} = \frac{\sum_{i=1}^{7} x_i}{7} \quad \bar{y} = \frac{\sum_{i=1}^{7} y_i}{7}
\]

\[
\Delta r_i = \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2}
\]

Then this function removes the two points related to the first two maximal values of \(\Delta r_i\), and calculates the average of \(x\) and \(y\) of the other points as the coordinate of the current position.
3.4. Calibration

The calibration consists of the amplitude of the image and correction of geometric distortion. A pattern of circles is designed to realize the process. Using equations 1 to 3, all the pixels on the captured image can be mapped to the coordinates on the film. There is a solid relationship between the pixels and the points on the film. A look-up table, which has the same size as the captured image, is set to quickly get the related coordinates on the film. A two-dimensional array is allocated to store the table. Its content can be assigned by equation 7.

\[
\text{LUT}_x[x'][y'] = x = f_x(x', y'), \text{LUT}_y[x'][y'] = y = f_y(x', y')
\] (7)

In which, \(x'\) and \(y'\) are the coordinate of pixels on the captured image. The values of \(x\) and \(y\) can be calculated by equations 1 to 3. Because of the non-linear distortion of the lens, the image mapped from the captured image may have some holes on the spot. An operation of region expansion is adopted to remove them. Ultimately the corrected spot is ready for calculating the coordinate of the spot center.

3.5. Image Processing

It is the key to get a good spot for accurate measurement. Figure 7 illustrates the flowchart of image processing.
The first step is to get a high-quality raw image by setting a suitable gain and exposure time. The second step is to make a smoothing spot by setting the threshold. The third step is removing the comet like bright spots by the algorithm of region shrinkage shown in Figure 8(a).

![Figure 8. Region scaling of 3x3 neighborhood.](image)

The fourth step is to map the distorted image on the film. The fifth step to remove the black point from the spot by performing region expansion shown in Figure 8(b). And the last step is to calculate the coordinate of the spot center. For the measurement of static deflection, repeat steps 1 to 6 for seven times and calculate the result according to the equation 5 and 6.

4. Error Analysing

4.1. The Error from the Deflection Angle

As is shown in Figure 1, the laser transmitter is installed at one end of the bridge, and image capturing devices are placed in the middle of the bridge. Therefore, a tilted bridge surface caused by deflection could lead to error in deflection measurement. The bridge surface shown in Figure 9 presents the surface that image capturing devices are placed on, where \( \alpha \) denotes the tilting angle.

![Figure 9. Error from the tilting film.](image)

Since the film surface is perpendicular to the horizontal plane (the bridge surface), and face to laser beam, there is a tilt when a load acts on the bridge as is shown in Figure 9. The tilting angle \( \alpha = \tan^{-1} \left( \frac{d}{s} \right) \), and the distance from spot to the centre is \( d_c = \frac{d}{\cos \alpha} \). In most cases, the maximal value of \( d \) is 50 mm while \( s \) equals to 10 m. As a result, \( \alpha \) is less than 0.29°. The difference between \( d_c \) and \( d \) is less than \( 6.25 \times 10^{-7} \) m. Therefore, the error caused by the tilting film is negligible.

4.2. Thresholds

This section will take an image with resolution of 768 by 1024 as an example. As is shown in Figure 10, a target bright spot on the top right corner with noise spots is captured. To enhance the bright spot and weaken the noise, the first step is binarizing the map. However, while binarizing the original image, an optimized threshold of gray level must be specified to remove noise and comets within the image. Figure 11(b) will demonstrate the result of noise removal with the process of binarization. Different threshold during binarization process will lead to a different effect on noise removal. Thresholds set greater than optimized value will weaken the light spot, whereas, thresholds set less than optimized value would even enhance the original noise. Therefore, proper threshold selection is critical during binarization.

4.3. Bright Spots on the Background

The binarization process could leave residual standalone bright pixels of noise spots. These pixels can be eliminated by the region-shrinkage method.
Figure 10. A raw image with one bright spot and multiple noise points.

Figure 10 presents a raw image, and Figure 11 presents partial results of image processing with respect to Figure 10. Figure 11(b) presents a binarized image with standalone bright pixels removed with the source image of Figure 11(a).

4.4. Geometric Distortion

Since the lens is installed in front of photosensitive elements to obtain optimized focus, distortion of the image can be induced. The distortion caused by the lens can be eliminated through curve-fitting methods. In this section, an example of a curve-fitting mapping scheme is employed to correct the distortion.

Take parameters with $n = 2$ listed in equation 8, and the geometric distortion can be eliminated.

$$x' = x \sum_{t=0}^{n} k_t r^{2t}, y' = y \sum_{t=0}^{n} k_t r^{2t}$$  (8)
Figure 11(d) shows the distortion-corrected image with the equation 8. However, gaps with black lines can be induced by the distortion correction method. These gaps can be fixed by inserting pixels with the regional expansion method. The corrected result of region expansion is presented in Figure 11(e).

4.5. Static Deflection
In Figure 11(d), the coordinate of the light spot center is (649, 889) of (768, 1024), with the original point at the bottom left corner. Taking a film of 50 millimeters in height as an example, the center point maps to (42.26 mm, 43.41 mm), while the real point maps to (40.58 mm, 41.81 mm). In terms of error, the divergence of coordinate caused by distortion calculates to 2.32 mm.

5. Conclusion
This paper gives an image-based solution to deflection measurement, which obtains direct measurement results, requiring simple operations and low cost. To solve the problem stated above, image-processing algorithms are implemented, and systematic error is analysed and eliminated. First, with the scheme shown in Figure 1, an image-capturing procedure is designed. Next, a series of computerized image-processing illustrated in Figure 7 will be performed to enhance the detail and eliminate the error. Finally, the deflection of the bridge at a given point can be computed. In terms of systemic error, the error caused by tilting film is proved negligible comparing with existent optical deflection measurement solutions[8][9]. Moreover, the divergence of the coordinate of the light centre induced by geometric distortion can be corrected with the method introduced in section 4.4.

Acknowledgments
This research was supported by Inner Mongolia Traffic Science and Technology Project and Baotou Transportation Investment Group Co., Ltd. We are also grateful to Michelle Gichaba who moderated this paper, and improved the paper significantly.

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