Exploring of PST-TBPM in Monitoring Bridge Dynamic Deflection in Vibration

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Abstract. This study adopts digital photography to monitor bridge dynamic deflection in vibration. Digital photography used in this study is based on PST-TBPM (photographing scale transformation-time baseline parallax method). Firstly, a digital camera is used to monitor the bridge in static as a zero image. Then, the digital camera is used to monitor the bridge in vibration every three seconds as the successive images. Based on the reference system, PST-TBPM is used to calculate the images to obtain the bridge dynamic deflection in vibration. Results show that the average measurement accuracies are 0.615 pixels and 0.79 pixels in X and Z direction. The maximal deflection of the bridge is 7.14 pixels. PST-TBPM is valid in solving the problem-the photographing direction not perpendicular to the bridge. Digital photography used in this study can assess the bridge health through monitoring the bridge dynamic deflection in vibration. The deformation trend curves depicted over time also can warn the possible dangers.

1. Introduction

Deformation monitoring is an important content to assess bridge health, especially the deflection [1]. The increase of the bridge flexibility makes it more important. Although the fatigue and injury is a long-term process, the bridge safety accident happens in one moment. It therefore is more important to monitor the dynamic deflection of a bridge [2]. The traditional surveying methods [3] cannot monitor the dynamic deflection of a bridge. Physical sensors cannot monitor bridge global deflection [4]. GPS (Global Positioning System) monitors the dynamic deflection of a bridge with low accuracy [5, 6]. The three-dimensional laser scanning [7] is limited to monitor the dynamic deflection of a bridge due to its relative-long scanning cycle.

However, digital photography [8-10] can monitor the dynamic deflection of a bridge as it monitors a bridge by a digital camera, which can capture the instantaneous deformation in 1‰ second and can monitor a bridge seven times in one second. Although digital photography has not been as popular in bridge structures as in other fields, many pioneering applications in this field have illustrated the potential for growth [11]. Researchers in the City University of London adopted digital photography to monitor a military steel bridge [12]. Forno et al. [13] adopted digital photography to monitor a decommissioned masonry arch bridge and a full-scale laboratory model of the bridge. These examples suggest that digital photography has a unique advantage in monitoring the bridge deflection.

The aims of this study are to explore PST-TBPM in monitoring the dynamic deflection of a bridge in vibration and to assess the bridge health based on these dynamic deflection data and its trend curves.

2. Digital photography

2.1. Distortion correcting of a digital camera

This study adopts a grid method [14] to eliminate the distortion of a digital camera to improve measurement accuracy. Figure 1 illustrates the distortion resulting in one same point from Position A to Position A'. Δ X and Δ Y are the corresponding horizontal and vertical deformation, respectively.

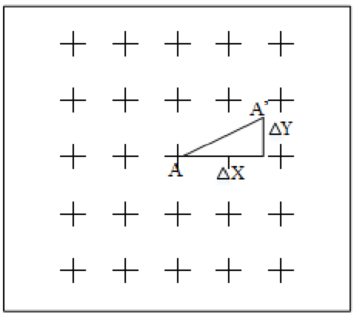


Figure 1. Influence of distortion error

For verifying the measurement accuracy of the digital camera, we used the direct linear transformation method [15] to calculate spatial coordinates of deformation point U0 and U1. Table 1 shows their actual coordinates, calculated coordinates and the differences between the actual coordinates of a deformation point and the corresponding calculates coordinates.

Table 1. Accuracy verification for deformation points U0 and U1

Name	Actual coordinates/m	Calculated coordinates/m	Differences/mm
U0-X	108.825	108.826	1
U0-Y	95.887	95.888	1
U0-Z	99.441	99.440	1
U1-X	109.067	109.065	2
U1-Y	96.935	96.934	1
U1-Z	99.394	99.394	0

Table1 shows that the maximum and minimum error is 2mm and 0mm, respectively. The average error is 1mm. This suggests that the camera used in this study can meet the accuracy requirements of deformation observation.

2.2. Photographing scale transformation-time baseline parallax method

The time baseline parallax method is commonly used to solve digital camera data [15]. But it consists of the parallax caused by the camera vibrating [16]. For improving the measurement accuracy, the PST-TBPM (Figure 2) was used to correct errors caused by the change of intrinsic and extrinsic parameters of digital cameras. And the photographing direction is perpendicular to the reference plane. The reference plane does not coincide with the object plane.

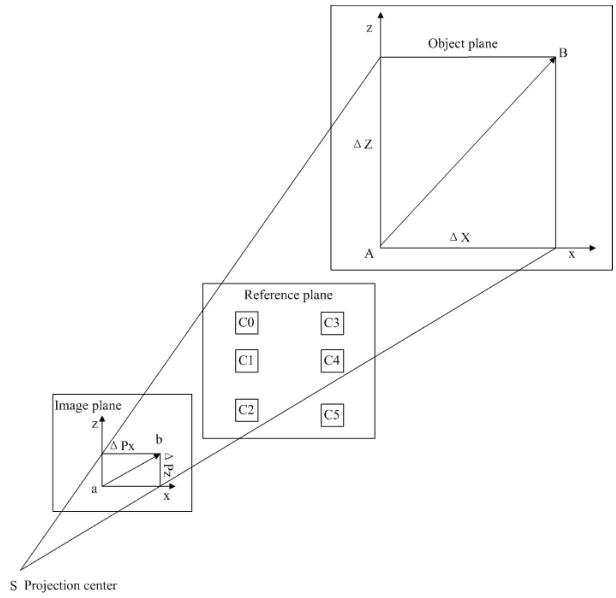


Figure 2. Photographing scale transformation- time baseline parallax method

Reference plane in Figure 2 consists of six reference points labeled as C0-C5. It is used to match images and eliminate the parallax.

Thus, we obtained the deformations based on the photographing scale M:

$$\left.\begin{aligned}\Delta X_R' = \frac{SA}{S\mathrm{a}}\Delta P'_x = M\Delta P'_x \\ \Delta Z_R' = \frac{SA}{Sa}\Delta P'_z = M\Delta P'_z\end{aligned}\right\} \quad (1)$$

Where M is the photographing scale on the reference plane, SA and Sa are the photographic distance and the focus respectively, $(\Delta P'_x, \Delta P'_z)$ are the corrected displacements of the deformation point on the image plane. $\Delta X_R'$ and $\Delta Z_R'$ are the corrected horizontal and vertical deformation of deformation point on the reference plane

Then, the actual deformations are obtained by the coefficient of the photographic scale transformation:

$$\left.\begin{aligned}\Delta X' = \Delta is \cdot \Delta X_R' \\ \Delta Z' = \Delta is \cdot \Delta Z_R'\end{aligned}\right\} \quad (2)$$

Where Δis is the coefficient of the photographing scale transformation, $(\Delta X', \Delta Z')$ are the corrected actual deformations of the deformation point on the object plane.

3. Bridge test

Figure 3 shows Caiyuan road bridge which is a footbridge. It is 102.52 meters in length, 17.8 meters in width. Its span is 92.04 meters.

Before the test, the digital camera was set on the north of Xiaoqing river and the deformation points labeled as U0-U7 was lay on its deck uniformly to study the dynamic deflection trend of the bridge in vibration. In addition, the reference system formed by the reference points labeled as C0 to C7 was set near the camera, which was used to calculate the baseline data and to match the successive images with the zero image, respectively. The photographing direction is perpendicular to the reference system.

Figure 3. Test field of the bridge

The test process is as follows:

(1) The digital camera was used to monitor the bridge in static as a zero image.

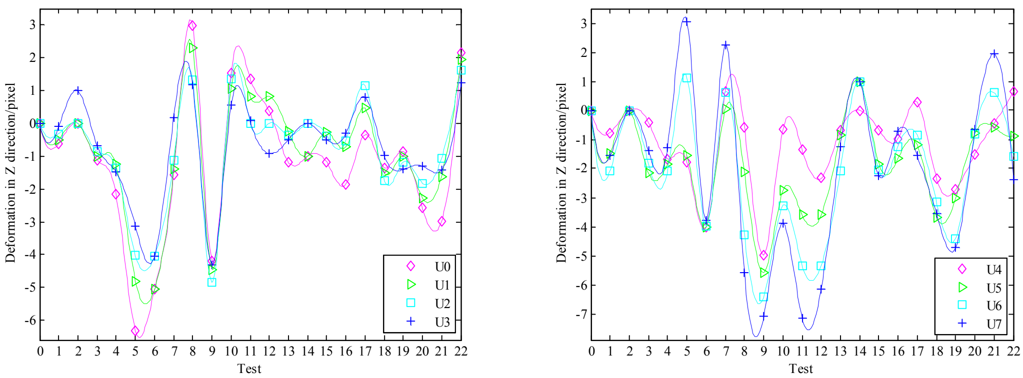
(2) The digital camera was used to monitor the bridge every three seconds as the successive images when the crane was operating resulting in the vibration of the bridge.

4. Data analysis

Due to the calculation, the average measurement accuracies are 0.615 pixels and 0.79 pixels in X and Z direction. In order to assess the bridge health, the deflection trend curves (Figure 4) are depicted based on these dynamic deflection data.

Table 2. Measurement accuracy/pixel

C6		C7	
X	Z	X	Z
0.77	0.74	0.46	0.84



(a) (b)

Figure 4. Deformation trend curves of deformation points in vibration

Table 3. Relative deflection/pixel

Test	U0	U1	U2	U3	U4	U5	U6	U7
1	-0.61	-0.49	-0.31	-0.09	-0.77	-1.47	-2.07	-1.56
2	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
3	-1.12	-1.01	-0.86	-0.68	-0.41	-2.16	-1.82	-1.38
4	-2.17	-1.25	-1.36	-1.48	-1.67	-1.84	-2.07	-1.27
5	-6.32	-4.80	-4.03	-3.13	-1.78	-1.55	1.13	3.05
6	-5.06	-5.06	-4.06	-4.05	-4.03	-4.01	-3.98	-3.77
7	-1.57	-1.39	-1.13	0.18	0.64	0.05	0.62	2.25
8	2.99	2.31	1.32	1.17	-0.57	-2.12	-4.27	-5.58
9	-4.18	-4.45	-4.85	-4.30	-4.98	-5.58	-6.41	-7.08
10	1.54	1.07	1.37	0.56	-0.66	-2.76	-3.27	-3.88
11	1.37	0.82	0.01	0.08	-1.34	-3.60	-5.34	-7.14
12	0.38	0.82	0.01	-0.92	-2.33	-3.60	-5.34	-6.14
13	-1.18	-0.25	-0.36	-0.49	-0.67	-0.84	-2.07	-1.26
14	-1.00	-1.00	0.00	0.00	0.00	1.00	1.00	1.00
15	-1.18	-0.26	-0.37	-0.49	-0.67	-1.84	-2.06	-2.26
16	-1.85	-0.72	-0.53	-0.30	-0.97	-1.66	-1.24	-0.71
17	-0.34	0.46	1.16	0.81	0.28	-1.19	-0.84	-1.55
18	-1.35	-1.50	-1.73	-0.98	-2.36	-3.69	-3.16	-3.56
19	-0.86	-0.99	-1.18	-1.40	-2.72	-3.01	-4.40	-4.72
20	-2.58	-2.27	-1.82	-1.30	-1.51	-0.80	-0.81	-0.66
21	-2.99	-1.61	-1.06	-1.42	-0.45	-0.58	0.61	1.94
22	2.17	1.95	1.62	1.23	0.65	-0.87	-1.58	-2.37

Table 4 shows the relative deformation values of deformation points labeled as U0 to U7. The negative and positive in Table 4 represent the deformation point moving down and up. The maximal deflection of the bridge is 7.14 pixels.

Figure 4 shows that the deformation trend of one deformation point on bridge deck conforms to the others in Z direction. This suggests a good rigidity of the bridge. Caiyuan road bridge therefore is safety.

5. Conclusion

This study use digital photography based on PST-TBPM to monitor the dynamic deflection of the bridge in vibration. Deformation trend curves of the bridge are depicted over time based on these dynamic deflection data to assess the bridge health. Through analyzing test results, the following conclusions are obtained:

(1) The measurement accuracy of PST-TBPM reaches the sub-pixel. The average measurement accuracies are 0.615 pixels and 0.79 pixels in X and Z direction.

(2) The maximal deflection of the bridge is 7.14 pixels.

(3) The deflection trend of one deformation point on bridge deck conforms to the others, which suggests a good rigidity of the bridge.

(4) The deformation trend curves depicted over time can warn the possible dangers.

It is proved that digital photography based on PST-TBPM can solve the problem-the photographing direction not perpendicular to the bridge. But it requires the photographing direction perpendicular to the reference system. Digital photography can monitor the dynamic deflection of a bridge. Digital photography used in this study provides data support for the site decisions to the bridge structure safety. And it will be popular in monitoring bridge dynamic deflection in the future.

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References
[1] P. Qiang, G. Xun, and Z. M. Zheng, "A review of health monitoring and damage detection of bridge structures," *Earthquake Engineering & Engineering Vibration,* vol. 23, pp. 61-67, 2003.
[2] I. Lipták, A. Kopáčik, J. Erdélyi, and P. Kyrinovič, "Dynamic Deformation Monitoring of Bridge Structure," *Selected Scientific Papers - Journal of Civil Engineering,* vol. 8, pp. 13-20, 2013.
[3] P. A. Psimoulis and S. C. Stiros, "Measuring Deflections of a Short-Span Railway Bridge Using a Robotic Total Station," *Journal of Bridge Engineering,* vol. 18, pp. 182-185, 2013.
[4] O. Abudayyeh, H. Aktan, I. Abdelqader, and U. Attanayake, "Development and Validation of a Sensor-Based Health Monitoring Model for the Parkview Bridge Deck," *Durability,* 2012.
[5] B. Yehuda and M. Diego, "Physical applications of GPS geodesy: a review," *Reports on Progress in Physics,* vol. 79, p. 106801, 2016.
[6] T. H. Yi, H. N. Li, and M. Gu, "Experimental assessment of high-rate GPS receivers for deformation monitoring of bridge," *Measurement,* vol. 46, pp. 420-432, 2013.
[7] T. K. Sinha, B. M. Dawant, V. Duay, D. M. Cash, R. J. Weil, R. C. Thompson*, et al.*, "A method to track cortical surface deformations using a laser range scanner," *IEEE Transactions on Medical Imaging,* vol. 24, pp. 767-781, 2005.
[8] R. R. P. D. Samuel, *close-range photogrammetry*: Springer Berlin Heidelberg, 2014.
[9] F. B. Bales, "CLOSE-RANGE PHOTOGRAMMETRY FOR BRIDGE MEASUREMENT," *Transportation Research Record,* vol. 1, 1984.
[10] K. Leitch, "CLOSE-RANGE PHOTOGRAMMETRIC MEASUREMENT OF BRIDGE DEFORMATIONS," *https://www.lap-publishing.com/,* 2010.
[11] R. Jiang, D. V. Jáuregui, and K. R. White, "Close-range photogrammetry applications in bridge measurement: Literature review," *Measurement,* vol. 41, pp. 823–834, 2008.
[12] M. A. R. Cooper and S. Robson, "HIGH PRECISION PHOTOGRAMMETRIC MONITORING OF THE DEFORMATION OF A STEEL BRIDGE," *Photogrammetric Record,* vol. 13, pp. 505-510, 2006.
[13] C. Forno, S. Brown, R. A. Hunt, A. M. Kearney, and S. Oldfield, "Measurement of deformation of a bridge by Moire photography and photogrammetry," *Strain,* vol. 27, pp. 83-87, 2008.
[14] J. I. Jeong, S. Y. Moon, S. G. Choi, and D. H. Rho, "A study on the flexible camera calibration method using a grid type frame with different line widths," in *Sice 2002. Proceedings of the Sice Conference*, 2002, pp. 1319-1324 vol. 2.
[15] C. Mingzhi, Y. ChengXin, X. Na, Z. YongQian, and Y. WenShan, "Application study of digital analytical method on deformation monitor of high-rise goods shelf," in *2008 IEEE International Conference on Automation and Logistics*, 2008, pp. 2084-2088.
[16] A. S. Kilgore and A. D. Mittleman, "Camera stand having an unlimited range of motion along an axis of rotation," 2017.