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Drift error compensation for vision-based bridge deflection monitoring

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Abstract. Recently, an advanced video deflectometer based on the principle of off-axis digital image correlation was presented and advocated for remote and real-time deflection monitoring of large engineering structures. In engineering practice, measurement accuracy is one of the most important technical indicators of the video deflectometer. However, it has been observed in many outdoor experiments that data drift often presents in the measured deflection-time curves, which is caused by the instability of imaging system and the unavoidable influences of ambient interferences (e.g., ambient light changes, ambient temperature variations as well as ambient vibrations) in non-laboratory conditions. The non-ideal unstable imaging conditions seriously deteriorate the measurement accuracy of the video deflectometer. In this work, to perform high-accuracy deflection monitoring, potential sources for the drift error are analyzed, and a drift error model is established by considering these error sources. Based on this model, a simple, easy-to-implement yet effective reference point compensation method is proposed for real-time removal of the drift error in measured deflections. The practicality and effectiveness of the proposed method are demonstrated by *in-situ* deflection monitoring of railway and highway bridges.

Keywords: off-axis digital image correlation; video deflectometer; reference point compensation method

1. Introduction

Non-contact vision-based optical techniques using a digital camera and advanced image processing techniques have flourished in recent years due to their capabilities of remote, full-automatic and real-time deflection measurement of large engineering structures (Lee and Shinozuku 2006, Ye *et al.* 2016, Ye *et al.* 2013, Ye *et al.* 2015, Feng and Feng 2017). Recently, an advanced video deflectometer based on the principle of off-axis digital image correlation (off-axis DIC) and real-time displacement tracking was proposed (Pan *et al.* 2016, Tian and Pan 2016). Compared with traditional contacting techniques (e.g., level gauges and displacement meters), the advanced video deflectometer offers the following prominent advantages: (1) Convenient installation and simple operation without accessing the test bridges, thus providing higher safety and operability; (2) Remote, non-contact and real-time measurement and visualization of deflection for multi-target measurement; (3) Flexible deflection measurement with adjustable field of view (FOV) and working distance. The camera can adjust the FOV by changing the lens with different focal lengths, thus it can measure the deflection of a bridge with spans ranging from several meters to hundreds of meters. Due to these prominent advantages, this video deflectometer has been increasingly used for deflection measurement of various bridges and large engineering structures in China.

However, in many engineering tests, it was found that there are two kinds of measurement errors (Fig. 1) presented in the deflection results measured by the video deflectometer, i.e., random error and drift error. The random error fluctuates around the truth value and can be effectively mitigated by denoising the measured deflection data using low-pass filtering approaches. As such, it has little influence on the overall measurement. Drift error refers to the overall drift of measurement data from the truth value. Its absolute value usually increases with time, which can be regarded as the systematic error in deflection measurement. Compared with the random error, the reasons behind drift error are miscellaneous and complex. However, due to high correlation between the drift error and camera temperature and camera movement, the measured deflection result could seriously deviate from the truth value, thus lessening the accuracy and practicality of the video deflectometer.

In literature, many research efforts have been dedicated to understanding and correcting the data drift phenomenon in vision-based displacement tracking method based on the use of digital cameras. It has been convincingly demonstrated in different works, including ambient vibrations, wind, ambient temperature variations and camera warm-up effect, can cause considerable errors in the displacements detected by processing the images recorded by a camera. For example, Olaszek (1999) considered that the camera vibration has a great influence on the accuracy of an opto-mechanical system. To realize accurate deflection measurement of bridge structures, the author established a two-channel optical system, which enables simultaneous imaging of the measuring and reference

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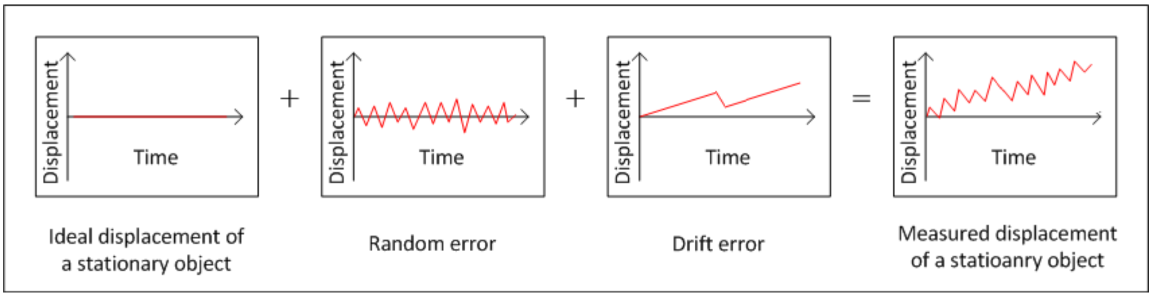


Fig. 1 Schematic showing the influences of random and drift errors

(immovable) points by the CCD camera. With this specially designed imaging system, the corrected displacement is calculated as a result of the subtraction of the positions of the measured point (observed by one channel) and the reference point (observed by the other channel). Yoneyama and Ueda (2012) noticed that the position and the direction of a camera are often changed slightly because of wind, oscillations and the lack of stability of ground in field measurement of bridge deflection using DIC. The slight movement of camera would cause additional displacement error. Based on the displacement maps determined from undeformed regions of the images, they proposed the affine transformation method to correct the effect of the camera movement.

Aside from camera movement, various experiments conducted by Handel (2009), Yu *et al.* (2014), Pan *et al* (2015, 2018), Zhou *et al*. (2017), and Yu *et al*. (2019) revealed that temperature changes in cameras caused by camera warm-up effect and ambient temperature variations can induce large image drift to even several pixels. And the drift error in measured displacements always shows a highly linear correlation with camera temperature changes. To correct the temperature-induce drift error, several compensation methods were proposed. For instance, Handel (2008) and Yu *et al*. (2014) proposed a compensation method based on the established theoretical model between the camera parameters and temperature variations obtained with the system identification method. Pan and his coworkers (Pan 2018) proposed a generalized reference sample compensation method (RSCM) to correct the thermal errors in DIC measurements induced by camera temperature variations. Adamczyk *et al*. (2018) proposed an improved camera design scheme for thermal compensation at different ambient temperatures.

Despite these advances, there are few efforts devoted to real-time drift error correction of the vision-based displacement tracking methods in outdoor environment. In fact, the compensation methods suitable for laboratory conditions may be difficult or impossible to be realized in the outdoor environments due to more strict and limited testing conditions. Also, the above compensation methods cannot achieve the ideal correction effect for the data with small drift, because it does not fully accommodate the adverse influences caused by camera instability and the experimental interferences. In outdoor measurement, drift error in images often reaches several pixels (the actual error is related to the measurement distance and may reach several tens of millimeters), which seriously degrades the measurement accuracy of deflection. To improve the measurement accuracy and practicability of video deflectometer, it is necessary to analyze the error source of drift error in video deflectometer and propose an effective and efficient compensation method to improve the measurement accuracy of video deflectometer. In the remainder of this work, a brief introduction of video deflectometer is first described. Then, the drift error of the video deflectometer is analyzed and verified. After that, a simple but effective method for real-time drift error compensation is proposed. At last, two applications of the proposed compensation method of a railway bridge and a highway bridge are also demonstrated to verify the practicality and effectiveness of the proposed method.

2. Drift error analysis of video deflectometer

2.1 A brief introduction to video deflectometer

Considering the fact that the system configuration, basic principles and algorithm details of the video deflectometer were all described in great detail in our previous works (Pan *et al.* 2016, Tian and Pan 2016), here we only give a brief introduction of the video deflectometer. As shown in Fig. 2, the video deflectometer consists of a high-speed industrial camera (Genie HM1024, Teledyne DALSA, Ontario, Canada, resolution:1024×768 pixels with 8-bit quantization, maximum frame rate: 117 fps), a fixed-focus lens (the focus length of the lens can be changed as per actual measurement requirement), a laser rangefinder (BOSCH, GLM 250 VF Pro, measuring range: up to 200m, accuracy: 1 mm), an electronic theodolite and a computer (Thinkpad T440p, Lenovo, Intel(R) Core(TM) i7-4700MQ CPU, 2.40GHz main frequency and 8G RAM). The industrial camera is mounted on a horizontal platform of an electronic theodolite. With the aid of the electronic theodolite, the horizontal and vertical angles of industrial camera can be flexibly adjusted. The industrial camera is connected to the computer via a network port and captures the images of a test engineering structure (e.g., a bridge) in real-time. Real-time displacement tracking algorithm based on an advanced inverse compositional Gauss-Newton algorithm is used to process video images and extract image displacements (in pixels) of interrogated targets specified in the test object.

Furthermore, by using a simple calibration method proposed in Pan *et al.* (2016), the physical vertical displacements (i.e., deflection) (in mm) at these

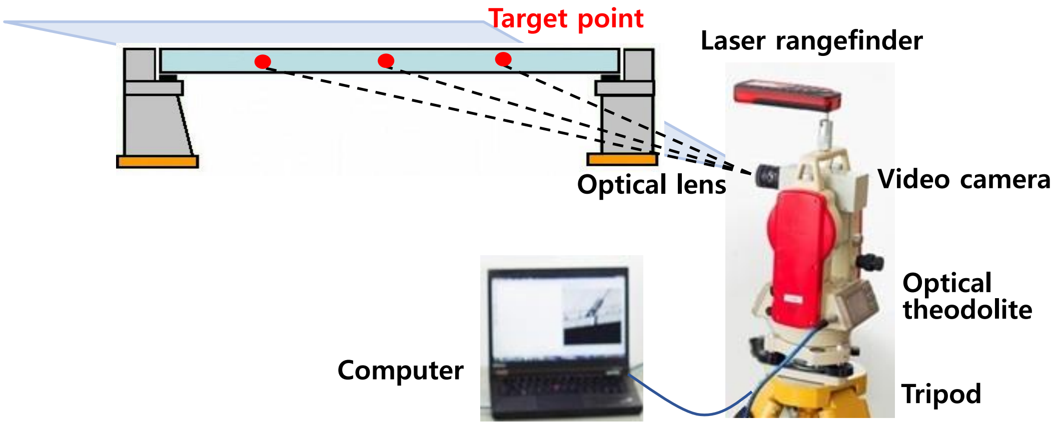


Fig. 2 The established video deflectometer for bridge deflection measurement

measurement targets can be directly converted from the image displacements.

2.2 Drift error analysis of video deflectometer

Drift error presented in the deflection-time curves measured by the above-mentioned video deflectometer is mainly due to the following two reasons. One reason is the instability of the video deflectometer in out-door conditions caused by the instability of ground, environmental vibration, wind load and other factors. These adverse issues would lead to small changes in the position and orientation of the camera in the video deflectometer, and further induce measurement error. The other reason is the temperature variations in the camera due to self-heating (warm-up) effect of cameras and ambient temperature variations. As comprehensively interpreted in a recent review paper (Pan. 2018), temperature variations in a camera could cause a small relative motion of the sensor target in the camera (including the in-plane motion perpendicular to the optical axis and the out of plane motion along the optical axis). This will cause the overall translation and small expansion of the recorded images. The small temperature-induced movements in camera target can be detected by advanced DIC algorithm with sub-pixel accuracy and were designated as thermal errors by Pan (2018). Due to the ambient temperature variations or camera self-heating phenomenon, the position of sensor target will slightly change. In practical application, other minor environmental interferences can also be seen as tiny movements of the sensor target or camera, thus the effects of these interferences on the imaging system are similar.

Video deflectometer is a video-based optical metrological instrument for deflection measurement. In real applications, the test object surface is often not perpendicular to the optical axis of the video deflectometer. Moreover, to realize multi-target measurement, the distances from different measuring targets to the measurement device are generally not the same. These two factors indicate that video deflectometer has its unique characteristics. In the remote measurement of the deflection of various large civil structures in outdoor environments, the image displacement generated by the experimental load in the images is relatively small due to the large field of view, and the real displacement is easily submerged in the noise. Therefore, the potential sources of the drift error should be identified, and these errors should be mitigated or corrected to ensure accurate measurement.

2.3 Drift error verification of video deflectometer

In the previous literature (Pan *et al.* 2015), drift errors caused by camera self-heating and ambient temperature variations have been verified and explained by detailed experiments. The conclusion pointed out that the virtual displacement and virtual strain is highly correlated with the camera temperatures variations. However, different from conventional optical measurement systems (2D-DIC, 3D-DIC) (Pan 2018), video deflectometer is generally used in outdoor scenarios with large field of view. Due to the limitations of field conditions, it is difficult to ensure that the camera axis is perpendicular to the measured object. Furthermore, measured targets are generally not in the same plane when measuring multiple targets. Therefore, an experiment that simulates the actual deflection measurement was conducted to verify the drift error model and provide an experimental support for the compensation method.

Fig. 3 shows the experimental arrangement for the verification test. The video deflectometer equipped with a 50 mm fixed-focus lens was mounted on a sturdy tripod fixed on the ground, and the angle between the optical axis and the ground was measured as 4 degrees. The two target plates were fixed on the vibration-proof platform, and their distances from the video deflectometer were measured as 4.372 m and 2.041 m, respectively. Blue LED light sources were placed in front of the two target plates for illumination, and a coupled optical filter with the same wavelength was installed in front of the deflectometer lens to eliminate the possible adverse influence of ambient light changes on the experiment (Pan *et al.* 2013). At the same time, a temperature sensor was installed on the camera housing of the deflectometer to monitor the camera temperature in real time. As shown in Fig. 3, the region of interest (ROI) where the two target plates are located can be seen on the real-time acquisition screen.

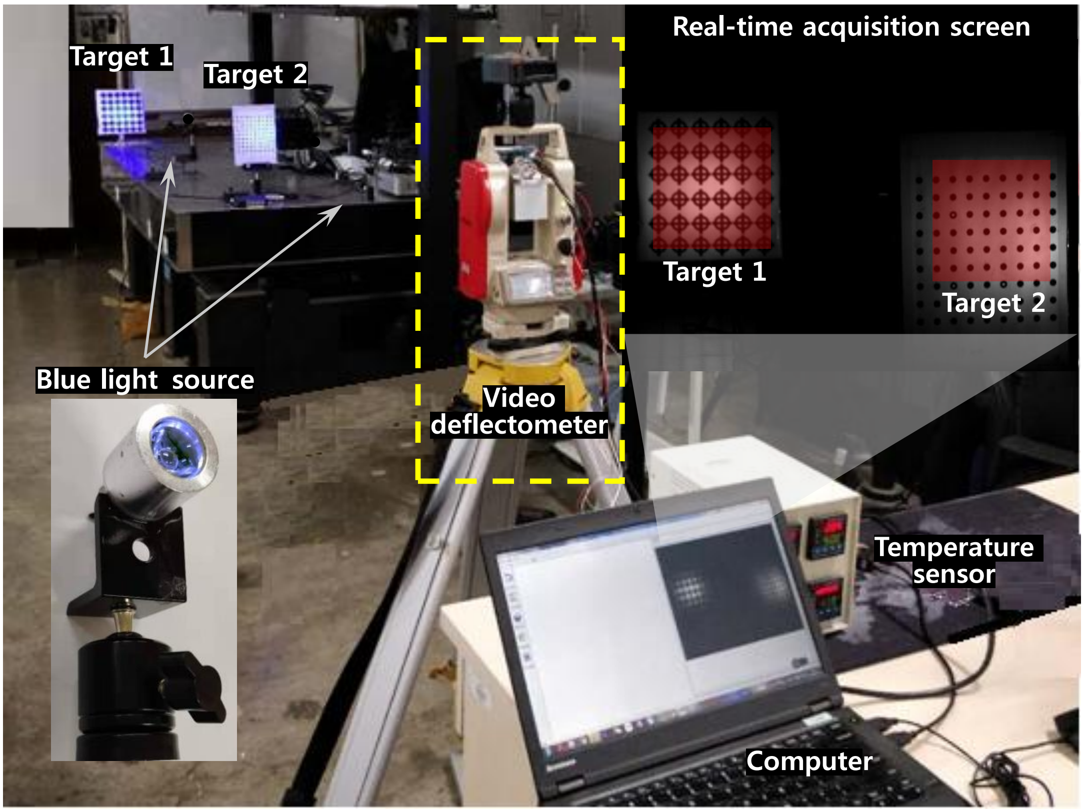


Fig. 3 A picture of the experiment

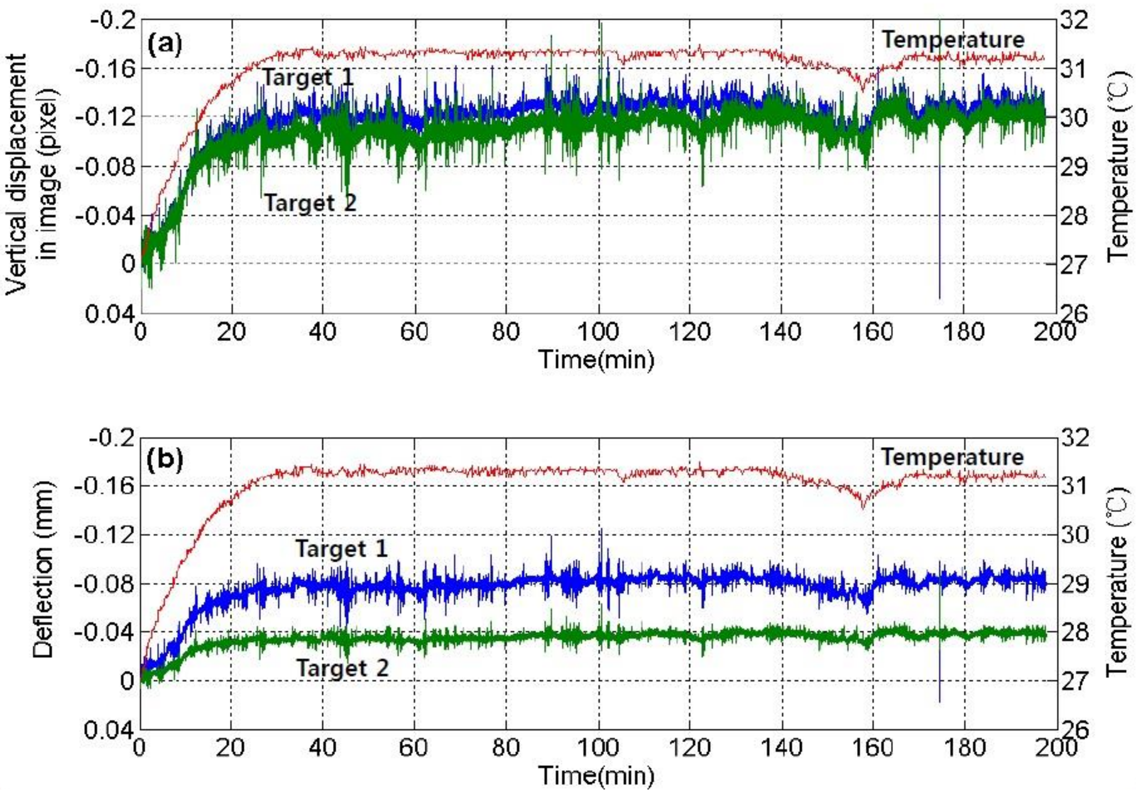


Fig. 4 Measured deflection-time curves of the two targets in the Y direction and the recorded camera temperature-time curve

A subset of 41×41 pixels is selected in these two ROIs at an interval of 10 pixels. According to the oblique optical axis calibration method (Pan *et al.* 2016), the calibration coefficients of the two ROIs in the vertical direction are calculated as 0.640 mm/pixel and 0.295 mm/pixel, respectively. During the experiment, the frame rate of the image acquisition was set as 25 fps, and the average displacements in the two ROIs were calculated in real time.

The whole experiment lasted for 200 minutes, and the temperature changes of the camera and the deflection changes of the two ROIs were observed. As shown in Fig. 4, the temperature of camera surface increase from 27℃ to 31.3℃ in the first 30 minutes and then stabilized approximately at 31.3℃. The average displacements in the two ROIs also rose to -0.088 mm and -0.039 mm, respectively, and then reached equilibrium. During the period from the 140th minute to the 180th minute, due to the ambient temperature variations, the camera temperature and the average displacements of the two ROIs also fluctuated in the same trend. By observing the average displacements of the two ROIs in Fig. 4(a), it is found that the image displacements of the two ROIs are roughly equal, and in Fig. 4(b) the physical displacement (deflection) of the target 1 is about twice that of the target 2.

From the above experiments, it is concluded that: (1) the change of camera temperature will cause the data drift in the deflectometer. (2) the drift physical displacements at each target with different distances are different, but the drift image displacements are roughly the same. Since we have

$$V = k \cdot v \tag{1}$$

where V represents the actual physical displacement, k is the calibration coefficient, and v is the image displacement. Since the calibration coefficient k generally is a large value in remote measurement of bridge deflection, the data drift V caused by the camera temperature variations will greatly magnified. In addition to the camera instability, other issues such as soft ground, instrument vibration, ambient light changes, etc., also contribute to data drift errors. To reduce or even eliminate drift errors in real-time deflection measurement, a real-time and accurate compensation method is required.

3. Drift error compensation method and experimental verification

3.1 Compensation method for drift error

A reference point compensation method (RPCM) using fixed reference points to correct the measured data is proposed in this work, which is based on the analysis of drift error in video deflectometer. As shown in Fig. 5, aside from the measuring targets, several fixed points located on static sceneries (e.g., pier, ground) are selected as reference points in the recorded images. The actual displacement of the fixed reference point should be zero, thus the measured displacements of these reference points are completely treated as measurement errors within the acceptable error range. By neglecting thermal expansion of camera sensors, the error caused by image expansion is ignored and only the error caused by image translation is considered. Thus, the displacement at a measuring target can estimated as

$$V_{\mathrm{m}} = K_{\mathrm{m}} \times \left(v_{\mathrm{m}} - \frac{\sum_{i=1}^{n} v_{ri}}{n}\right) \tag{2}$$

where V_m (unit: mm) is the actual displacement of a measuring target, K_m (units: mm/pixel) is the magnification factor of the measuring target, v_m is the measured image displacement of the target (units: pixel), and v_{ri} is the measured image displacement (units: pixel) of the ith reference point. It is seen that the proposed drift error compensation method is simple and easy-to-implement. It only needs to calculate the image displacements of reference points and then get the average of the measured results at these discrete reference points. It does not need to estimate the calibration coefficient of these reference points. However, in practical implementation, the reference points should be chosen as much as possible to close to the measuring targets, because the proximity to the measuring targets can not only eliminate the image translation effect, but also can eliminate the image expansion effect effectively.

3.2 Compensation experiment for single target

A bridge deflection measurement experiment performed on Shuiguan bridge of Shuohuang railway was first used to verify the validity and practicability of the proposed drift error compensation method. Shuohuang railway is the first heavy freight railway in China and has important strategic significance and economic value. Because of the onerous detection and heavy maintenance tasks of Shuohuang railway, efficient and accurate bridge deflection monitoring method is highly necessary. Thus, it is necessary to eliminate or reduce the drift error to guarantee the accuracy and reliability of the measuring results while measuring bridge deflection using the video deflectometer.

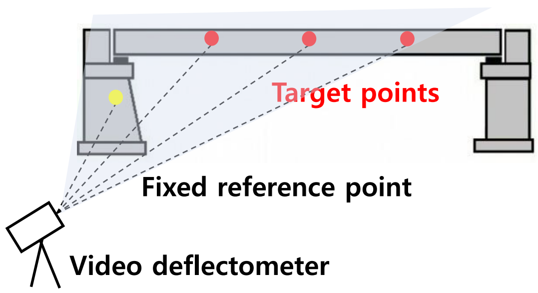


Fig.5 Schematic diagram of compensation method

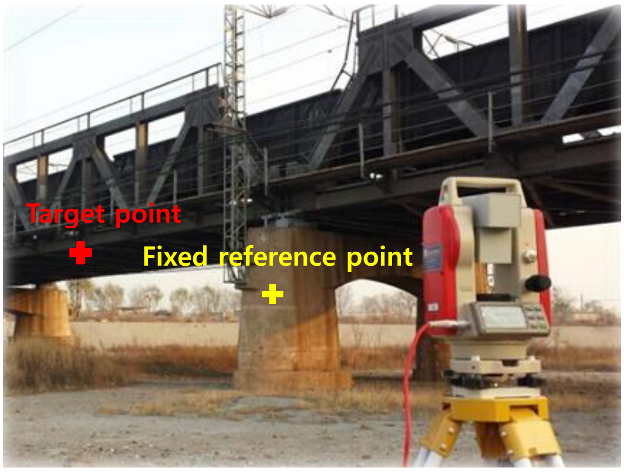


Fig. 6 Field experiment of Shuiguan bridge of Shuohuang railway

As shown in Fig. 6, conventional train loading experiment was carried out on Shuiguan bridge of Shuohuang railway to measure the deflection of the middle point of the north third span in real-time during the 90-minute continuous deflection monitoring. A tripod tightly fixed on the ground was used to hold up the video deflectometer, which was 96m away from the measuring target. The pitch angle of the video deflectometer was measured as 5.2° and a camera lens of 50 mm fixed focal length was used. A total of 5 trains passed in the loading process. Two C70 railway trucks (standard load: 70 tons) passed through the bridge firstly and then three C80 railway trucks (standard load: 80 tons) followed. The measured results demonstrate obvious data drift due to the *in-situ* continuous measurement. The marker on the bridge pier showed the position where a fixed reference point was specified to compensate the drift errors for the measuring target in this experiment. Note that the natural texture on the bridge pier was used for subset-based displacement tracking for the fixed reference point.

The deflection values of the target point with and without using the proposed drift error compensation method and the vertical displacement measured in image of reference point are computed in real-time, and the results are shown in Fig. 7. Fig. 7(a) depicts the directly measured displacement-time curves of the target point. The drift phenomenon is clearly seen in the data with the maximum drift reaching 3.85 mm at the end of the measurement. Fig. 7(b) gives the measured vertical displacement-time curve of the fixed reference point located on the stationary piers, whose the actual displacement should be zero. However, obvious data drift is observed in the measured results possibly mainly due to the temperature variations of camera and/or ambient vibration. By subtracting the drifts at the fixed reference point, the drift errors of the target point can be eliminated, and reasonable results are obtained with the maximum random error less than 0.05mm as showed in Fig. 7(c).

Table 1 Measuring results before and after drift error compensation

Load	Average deflection (mm)	Maximum deflection (mm)	Impact coefficient
C70	7.502/8.092	7.893/8.586	1.052/1.021
C70	7.034/8.189	7.421/8.624	1.055/1.026
C80	8.145/10.348	8.563/10.760	1.051/1.040
C80	7.579/10.377	7.913/10.849	1.044/1.045
C80	7.241/10.336	7.747/10.575	1.070/1.023

Table 1 lists the measured average deflection values and impact coefficients, which are obtained by analyzing the measured deflection results before and after compensation in the loading process of 5 different trains. Before compensation, it is seen that the difference of the average deflection value and the maximum deflection value of two C70 loads is quite large. Also, the difference of the average deflection and the maximum deflection of three C80 loads is more than 10%. These results are inconsistent with the actual situations. After compensation, the difference of the average deflection values is less than 0.10mm and the difference of the maximum deflection values is less than 0.05 mm for two C70 loads. Meanwhile, the difference of the average deflection values is less than 0.04mm and the difference between the maximum deflection values is less than 0.30 mm for three C80 loads. The measuring results after compensation match well with the real situation. These results show that the compensation method can well eliminate the drift error, thus confirming the accuracy and validity of the measuring results of video deflectometer.

3.3 Compensation experiment for multiple targets

A multiple targets deflection monitoring experiment of a highway bridge was carried out in Xi County of Xinyang City in Henan province. As shown in Fig. 8, four targets were selected as the measuring points on the mid-span and target 5 is on the fulcrum. At the same time, one target of the bridge pier was selected as the fixed reference point. The detection distances were measured as 4.58 m for target 1, 9.858 m for target 2, 11.725 m for target 3, 13.537 m for target 4, 16.185m for target 5 and 16.189m for the fixed reference point, respectively.

High-brightness LED targets were installed at the observation points because the experiment was carried out at night. The experiment had three stages of loading and the whole process lasted for 12 minutes. Fig. 9(b) shows the vertical displacement measured in image of the reference point whose position was fixed actually. However, it can be seen from the Fig. 9(b) that the measured image displacement is not zero, and the curve drifts downward firstly and then drifts upward, which is not completely consistent with the camera self-heating effect. It indicates that the position of the camera of video deflectometer had a slight change. In other words, there were other uncertain interference factors except the camera temperature variations causing drift error.

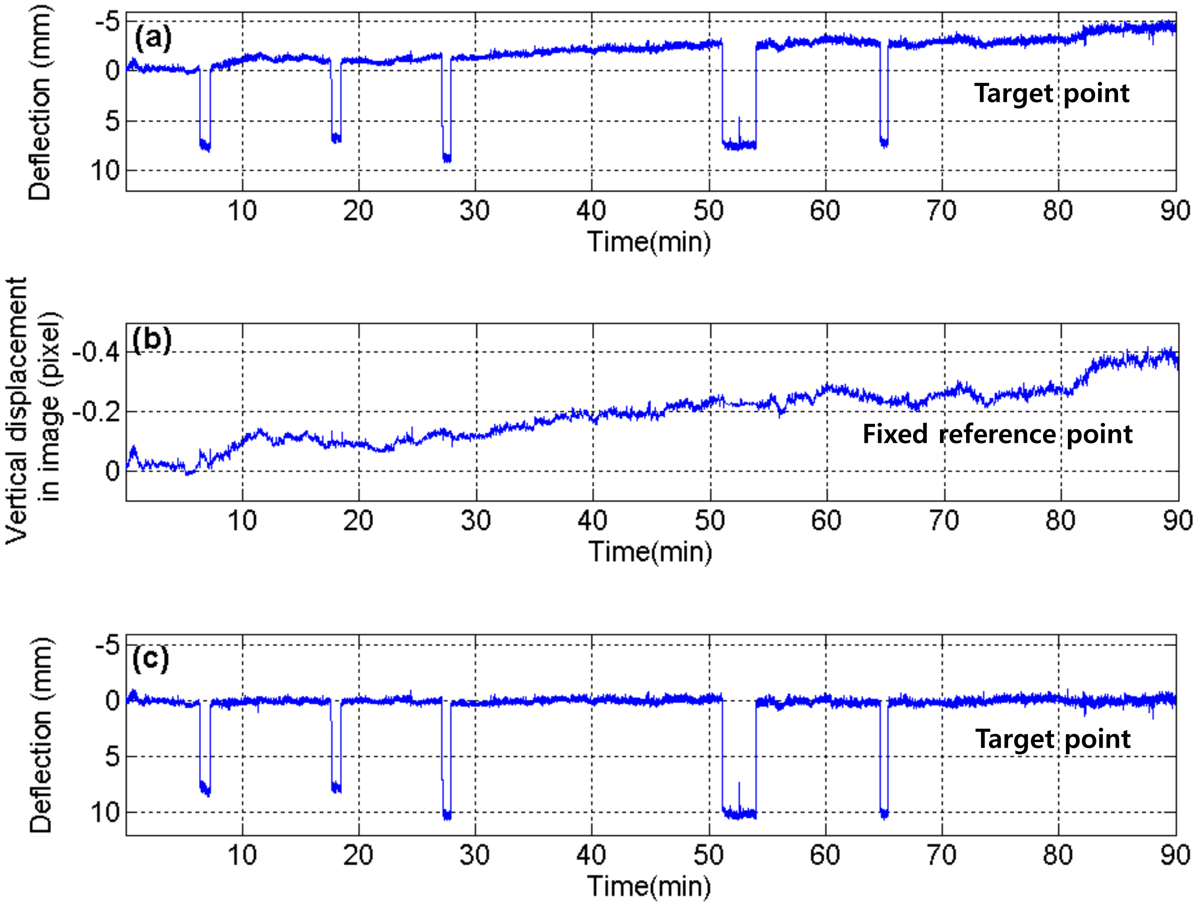
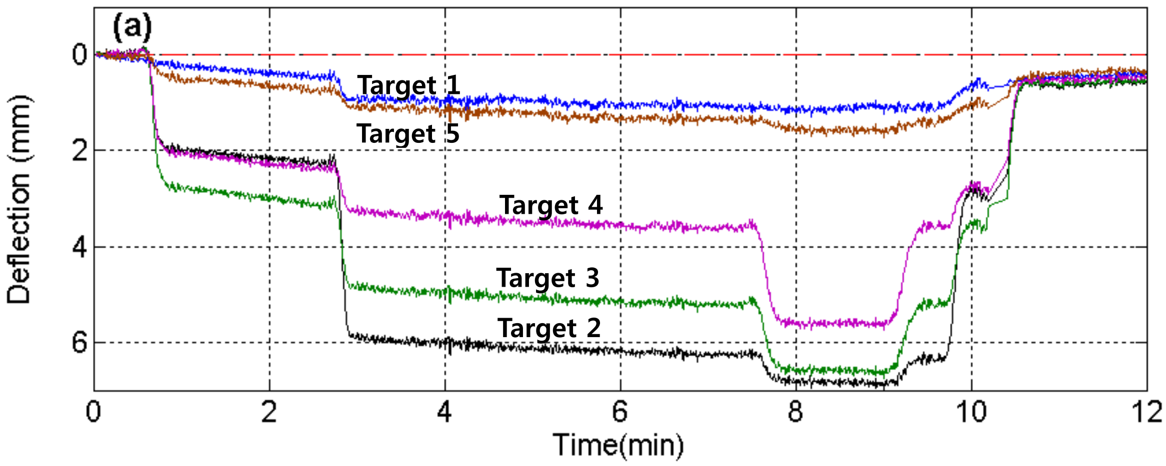
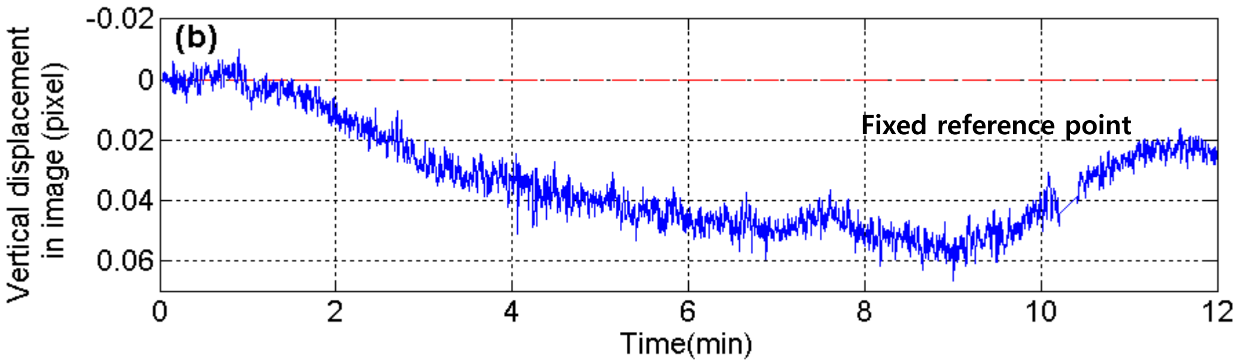


Fig. 7 Real-time measuring results of the single target experiment: (a) directly measured deflection-time curve for the target point, (b) measured image displacement-time (drift error) curve of the fixed reference point, and (c) corrected deflection-time curve of the target point after drift error compensation

Fig. 8 Multiple targets deflection experiment of the highway bridge



(a)



(b)

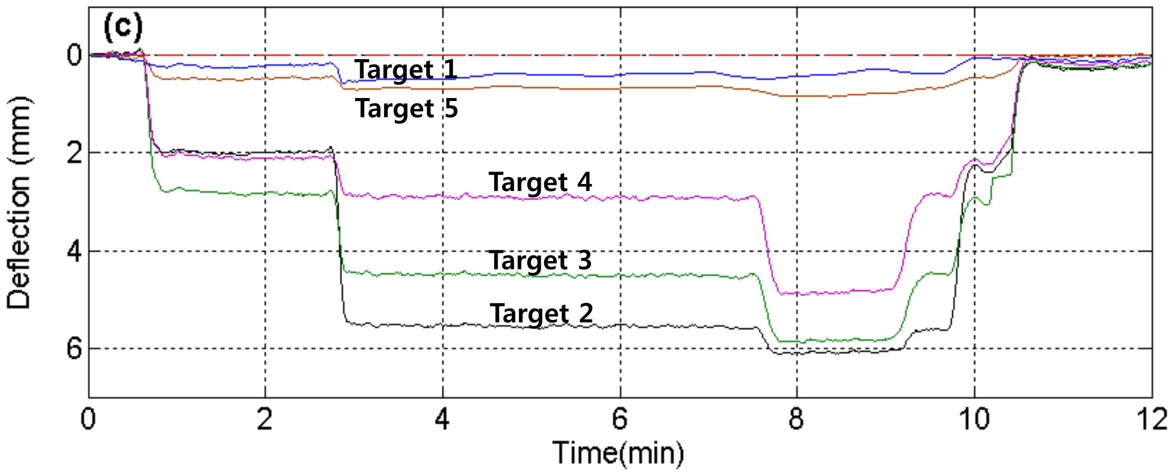


Fig.9 (a) Directly measured deflection-time curves of five target points, (b) Measured drift error-time curve of the fixed reference point and (c) Corrected deflection-time curves for the five target points after drift error compensation

Figs. 9(a) and 9(c) give the curves of each measuring target before and after the compensation. it can be seen that the measuring curve before compensation is not a horizontal curve, but has a downward movement trend after the completion of the first and second loading. The deflection of each target is still about 0.51mm after unloading. Fig. 9(c) shows that the curve of each measuring target which was compensated using fixed reference point is very stable after the completion of loading and all curves return to zero basically after unloading. The measured curve after compensation is more consistent with the actual situation, indicating that the proposed compensation method can effectively compensate multiple targets and has good universality.

4. Conclusions

Drift phenomenon always presents in vision-based bridge deflection monitoring, which is generally considered as the most detrimental error source and greatly lessens the accuracy and reliability of the measured deflection results. This work analyzes the potential sources of drift error and verifies a simple temperature-related drift error model using an indoor experiment. A real-time drift error compensation method based on the use of fixed reference points is proposed, which was verified via two real experiments. The proposed compensation method has two significant advantages: (1) Real-time error compensation and correction. It can display the deflection measuring results after eliminating the drift error in real time during the measurement process, without complicate and time-consuming data post-processing. (2) It can not only compensate the errors caused by temperature variations of camera, but also can compensate the measurement errors caused by ambient interference (wind or ambient vibration) and other uncertain reasons. Despite the simplicity, efficiency and effectiveness of the proposed drift error compensation method were well proved, further work should be carried out to study the influences of individual error source to thoroughly understand the complex mechanism of drift errors presented in vision-based deflection monitoring.

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