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Real-time, non-contact and targetless measurement of vertical deflection of bridges using off-axis digital image correlation

Bing Pan [a,*], Long Tian [a], Xiaolin Song [b]

[a] Institute of Solid Mechanics, Beihang University, Beijing 100191, China
[b] Train and Track Research Institute, State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu 610031, China

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ABSTRACT

An advanced video deflectometer using off-axis digital image correlation is proposed for real-time, non-contact and targetless measurement of vertical deflection of bridges. To achieve real-time displacement tracking with sub-pixel accuracy, an efficient inverse compositional Gauss–Newton algorithm is employed. The detected image displacements in pixels are converted to physical displacements in millimeters using an easy-to-implement yet accurate calibration technique with the aid of a laser rangefinder. Real translation tests with precisely controlled motions were performed to examine the accuracy of the proposed technique. Real-time deflection monitoring of a railway bridge subjected to train pass-by is also demonstrated to show the practicality, accuracy and application potential of the proposed technique.

1. Introduction

Bridge deflection, directly reflecting the vertical integral stiffness of a bridge structure, is closely related to its capacity to carrying load and ability to withstand external destructive loads (e.g., traffic, earthquake and gusts). For this reason, during the acceptance inspection of newly built bridges and the routine safety evaluation of in-service bridges, static and dynamic bridge deflections are generally considered as basic and essential parameters to be measured. Though various techniques have been developed for this purpose, field measurement of bridge deflection in an easy-to-implement but accurate manner has long been considered as a difficult and challenging task.

It is for sure that the bridge deflection at certain discrete points can be measured by traditional contacting displacement sensors, such as linear variable differential transformers (LVDTs), dial gauges as well as accelerators [1–3]. These contact measuring methods, especially the LVDTs and dial gauges, are capable of detecting displacement in any direction and meeting the resolution requirement for structural testing. However, installation of these contact displacement sensors to the measurement point requires a stationary platform nearby as a fixed reference point. In the field measurement of bridge deflection, this task is generally very difficult, or very costly and time-consuming, or even impossible to accomplish, because most bridges span over active highways, rivers, sea channels, mountainous terrains or deep valleys.

To circumvent the difficulties associated with contact displacement measurement sensors, various non-contact displacement measurement systems, including Global Positioning System (GPS) [4,5], Laser Doppler vibrometers (LDV) [2,6], radar interferometry [7,8] and vision-based (or image-based) optical techniques [9–19] with tailor-made targets, have been developed and applied for bridge deflection measurement. Among these non-contact techniques, vision-based optical techniques seem to be a more practical and promising technique due to following prominent merits:

- *Remote contactless measurement*: By using optical lenses with suitable magnification, the deflection measurement can be accomplished far away from the bridge with a distance ranging from several meters to even more than 200 m;
- *Quick, simple and automatic measurement*: After placing the optical measurement system on the fixed stand and getting a clear image of the test region (having targets or nature texture) of the bridge, the multipoint displacements can be tracked automatically by processing the video images using digital image processing techniques using either feature-based [10–15] or template-based [9,16–19] registration algorithms;
- *Real-time measurement and visualization*: With the aid of high-speed video cameras and high-efficiency digital image processing algorithms, the displacements of multiple measurement points can be tracked and displayed in real-time.

* Corresponding author at: Institute of Solid Mechanics, Beihang University, Beijing 100191.
E-mail addresses: Chinapanb@buaa.edu.cn, panb@buaa.edu.cn (B. Pan).

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It can be easily found in the literature that most of existing vision-based optical techniques for bridge deflection detection rely on the tracking of tailor-made target objects (e.g., circles [9], crosses [10], LEDs [11], spots with known geometry [12–15], or speckle patterns [16–18]) intentionally attached onto the measurement point of the bridge. The live images of the target features (e.g., cross center, circle center, or gray centroid of the LEDs) are then analyzed using digital image processing techniques to retrieve the motions of the target with sub-pixel accuracy. Obviously, using targets with evident characteristics facilitates the image tracking and also helps to improve the measurement robustness and accuracy, but the fabrication, installation, detachment of these targets brings additional cost, complexity and time to the measurement. In this respect, truly remote bridge deflection measurement without using artificial targets and accessing the test bridge seems to be more useful and highly desirable.

It is also noted that digital image correlation (DIC), an image-based optical technique widely used in the experimental mechanics community, has been used by various researchers for bridge deflection measurement [16–19]. Although DIC technique offers the outstanding advantage of tracking natural textures, most of existing works used speckle patterns artificially decorated on or attached to the measured bridge as targets, and also assumed that the optical axis of the camera should be normal to the test surface of the bridge. In addition, the recorded images are post-processed to extract the displacements of points of interests in these published works. Recently, Waterfall et al. [19] reported the targetless precision monitoring of road and rail bridges using video cameras, but they also failed to address the key details regarding the real-time displacement tracking with sub-pixel accuracy and the imaging model used to convert image displacements to real deflections on the bridge.

This work aims to develop an advanced video deflectometer for truly remote (non-contact), real-time, targetless and multipoint vertical bridge deflection measurement. In the proposed technique, the live frames of a test bridge are recorded by a high-speed video camera with non-perpendicular alignment and tracked using a high-efficiency, robust subset-based matching algorithm to determine image motions of the bridge with sub-pixel accuracy. The image motions are later converted to real displacements of the bridge using a simple but accurate calibration model based on the ideal pinhole camera model. To the authors' best knowledge, real-time measurement of multiple-point dynamic displacements of a bridge using off-axis DIC has not be reported so far. In the remainder of this work, the measurement system used to image the test bridges is first described. Then, the principles of the fast, robust and accurate DIC algorithm for real-time image displacement tracking from live video frames are detailed. Next, the calibration model that converts image displacements in pixels to physical displacement in millimeters is presented. After that, real rigid-body translation tests with precisely controlled motions are carried out to verify the proposed technique. At last, an application of the proposed technique for real-time deflection measurement of a railway bridge passing by a freight train is also demonstrated.

2. System configuration and measuring procedure

2.1. System configuration

The proposed vision-based bridge deflection measurement system comprises a high-speed area scan monochrome camera (Genie HM1024, Teledyne DALSA, Ontario, Canada), a fixed-focal optical lens (the focus length of the lens can be changed as per actual measurement requirement), a laptop computer (Thinkpad T440, Lengend, Intel(R) Core(TM) i7-4700MQ CPU, 2.40 GHz main frequency and 8G RAM), a laser rangefinder (BOSCH, GLM 250 VF Pro, measuring range: up to 200 m, accuracy: 1 mm) and an optical theodolite. The camera allows for a maximum image capture rate of 117 fps in 1024×768 pixels resolution with 8-bit quantization. The camera equipped with an optical imaging lens with fixed focal length is connected to the laptop computer using a Gigabit Ethernet standard LAN wire. The laser rangefinder is employed to determine the distance from the camera sensor to each measurement point as well as the pitch angle of the camera, and the optical theodolite is used to provide a firm support and supply electricity for the video camera. Fig. 1 shows a real picture of the established video deflectometer.

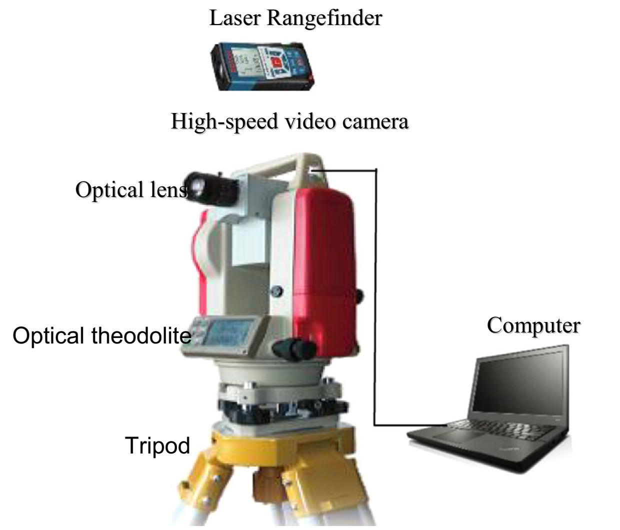

Fig. 1. The established video deflectometer for bridge deflection measurement.

2.2. Measurement procedure

The measurement of bridge deflection using the established system involves the following three steps:

(1) *Measurement preparation*:

a) Place the measurement system on the ground that permits imaging the test bridge far away. In general, the optical axis of the video camera is oblique to the test bridge surface, leading to an off-axis imaging configuration. Note that the measuring system should be kept stationary during the whole measurement period, because small vibration of the camera can lead to considerable unwanted displacement errors [10,17]. Then, tune the imaging distance and aperture of the lens to get a clear image of the bridge with sufficient contrast and without overexposure.

b) Define discrete measurement points in the live image of the test bridge. Then for each measurement point a subset with proper size should be chosen, which should contain sufficient local nature texture to allow an accurate subset-based pattern matching. For each measurement point, a proper subset size can be selected according to the value of a parameter called sum of square of subset intensity gradient (SSSIG) as suggested in our previous work [20]. Generally, a subset with larger SSSIG leads smaller random errors in the detected displacements.

c) Measure and record the distance D from the camera sensor to each measurement point using the laser rangefinder. Thus, the objective distance of the point (*i.e.*, the distance from optical center to the measurement point) L can be estimated as $L = D - f$ with f denoting the focus length of the camera lens.