3-D DISPLACEMENT MEASUREMENT IN LARGE STRUCTURAL TESTS USING VIDEO CAMERAS

Yuan-Sen Yang(1) , Fu-Pei Hsiao (2) , Yuan-Tao Weng (3)

(1) *Professor, National Taipei University of Technology, Taiwan. ysyang@ntut.edu.tw*
(2) *Division Director, National Center for Research on Earthquake Engineering, Taiwan.*
(3) *Associate Researcher, National Center for Research on Earthquake Engineering, Taiwan.*

Abstract

Image analysis techniques is a feasible method to measure three dimensional displacements of structures. However, when measuring dynamic responses of large structures in a structural laboratory, it is difficult to carry out camera calibration because it is impractical to manufacture a large rigid camera calibration board. In addition, the stereo triangulation results are sensitive to the time difference between two video cameras.

To demonstrate the solutions of the aforementioned issues, this paper presents the following contents:

(1) This paper introduces two camera calibration approaches that can be applied for large structural experiments. Either one of them can be used to complete extrinsic camera calibration which is difficult to carry out in large laboratories using conventional methods.

(2) This paper introduces a synchronization method that is designed to minimize the time difference between two video cameras in order to minimize the stereo triangulation errors.

(3) Several structural experiments are presented to demonstrate the calibration approaches and the aforementioned synchronization method.

(4) The procedures of the 3D displacement history measurement are presented and explained in details.

The descriptions of the procedures of image analysis and measurement aim to ease the complexity of 3-D dynamic responses measurement using video cameras by presenting the basic theory and the procedures of measurement.

Keywords: structural experiments, response measurement, camera calibration, signal synchronization

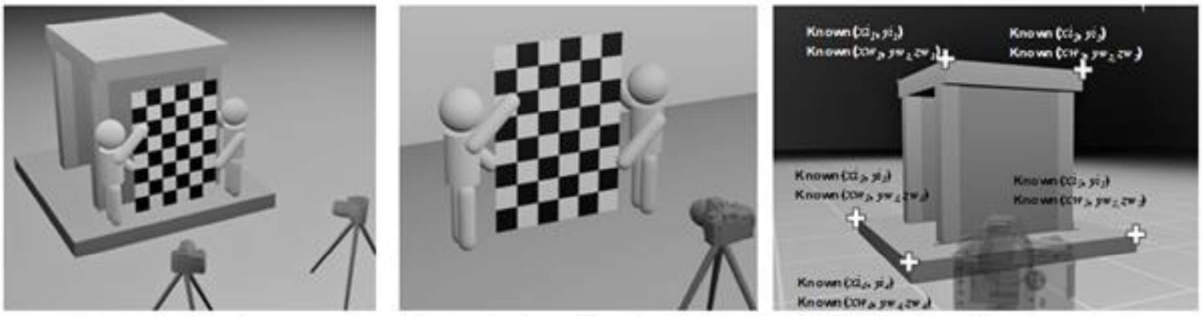
INTRODUCTION

Image analysis for structural experiments using stereo triangulation based techniques encountered challenges on stereo calibration and synchronization [1]. Measurement of a large region makes it difficult to do camera extrinsic calibration, because the difficult to produce and operate an equivalent sized rigid calibration board, making it impractical to carry out image measurement using conventional camera calibration procedure [2]. Dynamic experiments further make it difficult to synchronize video images taken by different video recorders.

This paper presents experiments on using previously proposed methods to reduce the errors induced by the aforementioned difficulties. Two types of calibration approaches: (1) Two-stage calibration method, and (2) Single-image calibration are employed. A software solution is also tested to improve the synchronization between two video cameras [1].

CALIBRATION METHOD

Conventional stereo calibration requires a rigid calibration board which is about the same size with the measurement region, which is an impractical method for large scale experiments. The proposed method first carries out intrinsic calibration in a relatively small indoor laboratory without need to be done in a large space, as shown in Figure 1(a). The extrinsic parameters of the camera(s) can be carried out after the cameras are firmly setup in the large laboratories as shown in Figure 1(b). In the stage of extrinsic parameter calibration, more manual operations could be required on defining corners or feature points where their 3D points can be obtained from experimental design drawings, as shown in Figure 1(c). Separating calibration into two stages makes calibration suitable for large experiments yet without need to produce a large calibration board. The details of the calibration methods can be found in [1].



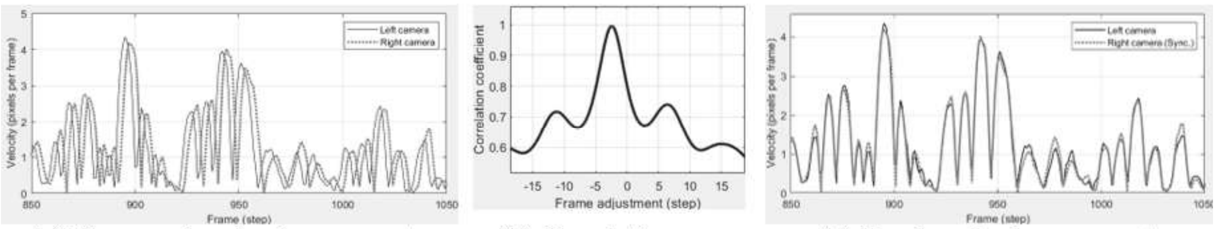
(a) Conventional stereo calibration (b) Intrinsic calibration stage in a small laboratory (c) Extrinsic calibration stage on site

Figure 1. Different camera calibration approaches and stages. The proposed two-stage calibration includes intrinsic calibration in a small laboratory and extrinsic calibration on site.

SYNCHRONIZATION

Non-synchronized signal (as shown in Figure 2(a)) would result in significant error in stereo triangulation. To synchronize the time axis of images taken by two video cameras with a precision much smaller than one frame (i.e., 1/30 s when 30-frames-per-second video cameras are used), a cross correlation based method is used, as shown Figure 2(b). Based on an assumption that the peaks of motions of a target occur at the same time in both cameras, cross correlation helps to accurately determine the time difference between two cameras, as shown in Figure 2(c). The details of the cross-correlation based synchronization can be found in [1].

While the aforementioned assumption is not always true and can contain a certain level of error, it is probably one of feasible ways to figure out the time difference between cameras. If two cameras are setup faraway with each other and observe the target from quite different angles, the assumption can lead to sufficient error in synchronization.

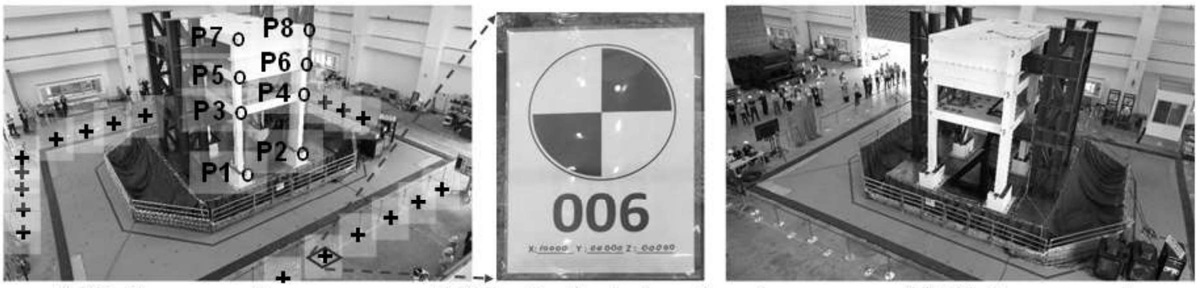


(a) Non-synchronized movement (b) Correlation vs. time lag (c) Synchronized movement

Figure 2. Synchronization by shifting image coordinate histories of the right camera. The proposed synchronization method estimates the time difference between cameras by applying cross correlation on analyzed moving velocity.

SHAKE TABLE TEST OF A 3-STORY RC EXPERIMENT

The experiment involves a three-story reinforced-concrete (RC) building specimen (see Fig. 3) with one span in the x direction (north–south) and two spans in the y direction (east–west). The second and third floors have shear walls on the south side, while the first story is entirely open without walls. The building is subjected to a uniaxial near-field ground motion.



(a) Left camera view (b) Physically deployed marker (c) Right camera view

Figure 3. The 3-story RC building specimen and known calibration points marked. Points data in these photos are used for the second stage of the two-stage calibration approach.

The aforementioned two-stage calibration method is employed to estimate the intrinsic parameters and extrinsic parameters. The positions and orientations of cameras with respect to the structural specimen (Fig. 4) are estimated by the extrinsic parameters.

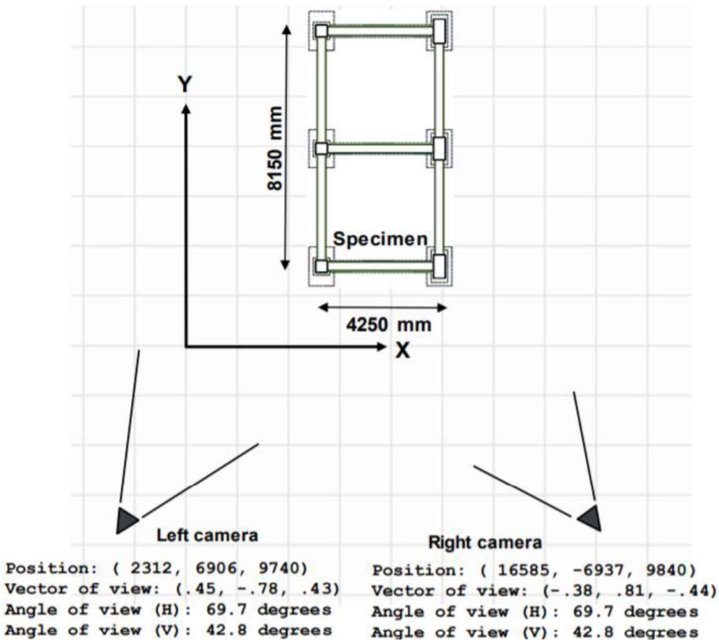


Figure 4. Camera positions and viewing directions based on calibrated extrinsic parameters. Calibrated extrinsic parameters represents the positions and orientations of cameras in the experiment.

The image measurement results were used to estimate the time history of the story drift of the first floor and were compared with the optical tracking device and contact displacement sensors (a linear variable differential transducer, LVDT). The first-floor drift was estimated using the time history of the world coordinates of points 1, 3, and 4 analyzed from the images. These measurement approaches are all capable of capturing the general response of the story-drift history. One of the largest differences is at the response peak around 42 s, which reached a difference of 4.7 mm between the image analysis (55.6 mm) and LVDT results (60.3 mm), as shown in Fig. 5. Most of the differences between the image analysis and LVDT results at the response peaks were within 2 mm.

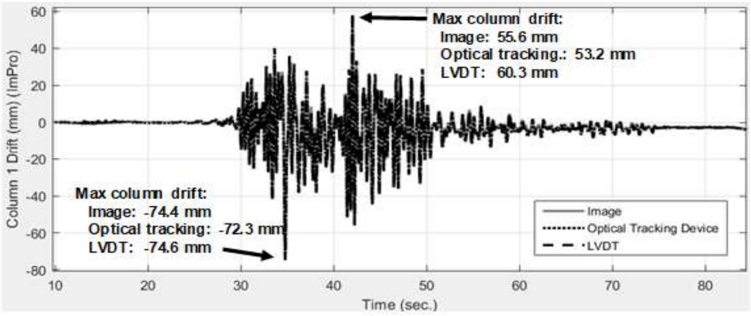


Figure 5. Comparison of three different measurement system results for first-story drift history. Image analysis gives satisfactory accuracy comparing with other sensors.

The acceleration responses of structures can be estimated from the second derivative of the displacements. The ground acceleration and roof acceleration histories are estimated and compared with the results of an accelerometer installed on the specimen, as shown in Fig. 6. The acceleration history from image analysis generally matches the acceleration measured by the accelerometer. It also includes relatively larger high-frequency noise. The high-frequency noise could be induced by the central difference calculation, as the numerical derivative is typically sensitive to small errors. With a simple low-pass filter, the high-frequency noise in Fig 6a can be eliminated. The user can select her/his preferred filter to do the signal processing, thus is not discussed here.

The procedures of the measurement are presented here to ease the implementation. The major procedures include: (1) video cameras installation, (2) targets deployment, (3) camera calibration, (4) experiment execution with video recording, (5) target tracking, (6) signal synchronization, (7) stereo triangulation, and (8) data post-processing. They are introduced as follows.

(1) Video camera installation: Video cameras are to be placed so that they are capable of capturing clear videos of the experiment. Cameras need to be firmly setup or fixed so that they do not move or vibrate during the experiment. Setup of safety fence or strips around cameras can be considered to prevent accidentally move or touch after calibration. Cameras should be able to remotely triggered so that operators can start and stop the recordings without touching the cameras. If the camera encounters vibration or accidently touch, some methods can be used to partially correct the errors [3].

(2) Target deployment: There are two types of targets: targets for tracking and targets for calibration. Targets for tracking are which displacements are of interests. They can be at beam-column joints, base isolators, connections of dampers, or any points which displacements are of interests. They can also be densely distributed over a region such as walls, roofs, or floors. Targets for tracking need to be visible during the entire experiment. The image clearance of each target should be examined before the experiment. The pattern of targets can be black-white intersected squares, as shown in Fig. 3(b) so that the accurate position of the target can be unambiguous. Targets should be avoided to be placed at where they appear near the boundary of video images because image boundary may have violent image distortion which may lead to higher errors even if camera calibration is carried out. In addition, moving targets which are too close to the image boundary could be out of range of video imaging during the experiment. Targets for calibration should be placed at where their global coordinates can be accurately measured (by conventional manners such as rulers, total stations, or any other surveying methods). Targets for calibration should also be surrounding the measurement regions of the specimen as much as possible in the viewpoint of cameras, so that the calibration parameters (which are based on the image coordinates and global coordinates of the targets for calibration). Procedures (1) and (2) could be iteratively carried out so that targets can appear clearly at decent locations in the images.

(3) Camera calibration: One-stage calibration [1] can be performed only based on the targets for calibration, while two-stage calibration [1] requires a separate intrinsic calibration which needs an additional calibration object (such as a chessboard). The 3D global coordinates and the image coordinates of all targets for calibration need to be accurately determined. For one-stage calibration method, these coordinates are used to acquire camera intrinsic parameters (i.e., representing a mathematical approximation of how a camera transforms 3D objects into planer image) and extrinsic parameters (i.e., the orientation and position relationship between world coordinate and each camera) by computer vision subroutines such as OpenCV function calibrateCamera. For two-stage calibration method, these coordinates are used to acquire camera extrinsic parameters by computer vision subroutines such as OpenCV function solvePnP. Cameras should be kept unmoved and untouched after camera calibration.
(4) Experiment execution with video recording: All video cameras should record the entire duration of the experiment. Starting and stopping recordings should be operated remotely, by cable lines, inferred control, or any other remote manners so that physical touch of cameras can be avoided.
(5) Target tracking: This procedure acquires the image coordinates of all targets for tracking. There are many image algorithms for object tracking, for example, template match, enhanced correlation coefficient (ECC), optical flow (OF) method, feature extraction with homographic estimation, machine learning based object tracking, etc. [2]. They are mostly available from open resource on the Internet, such as the OpenCV functions matchTemplate, findTransformECC, calcOpticalflowPyrLK, etc. Template match basically gives image coordinates at a pixel based precision (integers), which requires further post-processing methods to improve them to sub-pixel precisions. ECC and OF methods requires a decent initial guess or result would diverge. Feature extraction based methods require each target having sufficient number of key points of features, which is not good for relatively small targets in typical structural experiments. Machine learning based method also gives pixel based (integers) and requires post-processing for sub-pixel precisions.
(6) Signal synchronization: Since all video cameras do not precisely start recording at the same time, there are time differences between images. By assuming the differences can be simplified to a single constant time lag, we can estimate the time lag by numerical cross correlation. Image coordinate histories are the signals used for cross correlation, with an assumption that the image coordinate histories are approximately appearing in similar patterns between cameras. The implementation of cross correlation should be either available over public resource, or can be home implemented based on the numerical analysis textbooks. Actually the OpenCV functions for image tracking such as matchTemplate can be properly employed for cross correlation if we consider signal history as a single-pixel height image.
(7) Stereo triangulation: After synchronization, image coordinate histories of each target for tracking from different cameras can be used to do stereo triangulation. Assuming the cameras are unmoved during the experiment (unchanged extrinsic parameters), and unchanged intrinsic parameters of cameras, stereo triangulation gives us the theoretical 3D position of a target. This can be executed by using computer vision subroutines such as OpenCV function triangulatePoints.
(8) Post-processing: This procedure is to convert the calculated 3D position of all targets to the information required. For example, inter-story drift histories calculated by subtraction operations of two sets of points, acceleration estimated by double differentiation, surface strain by finite difference manners, noise reduction by low-pass filtering, or wavelet transform for time-frequency analysis.

The above procedures can be slightly modified to satisfy actually experimental requirement. For example, camera calibration can be carried out after the experiment if these cameras remain untouched before the completion of camera calibration.

CONCLUSIONS

This paper introduces two stereo camera calibration methods and a synchronization method which is suitable for measuring 3-D displacement histories of tracking points in structural experiments. The two-stage approach separates conventional stereo calibration into intrinsic calibration in a relatively small laboratory and extrinsic calibration on-site, is suitable in cases where the region of measurement is much larger than available calibration objects. By using the two-stage approach, the intrinsic parameters were estimated by performing conventional intrinsic calibration using a relatively small calibration board, where the cameras' configurations were set the same as they were in the shake table tests. The single-image approach, meanwhile, is suitable for older experiments where videos were taken but no calibration was performed and the cameras are no longer available for calibration. A synchronization method can minimize the stereo triangulation error induced by a time difference between two videos. While manual video editing can roughly synchronize two videos, this method adopts cross-correlation analysis of the velocity histories from both videos for the same selected moving point. This method was verified through two experiments.

ACKNOWLEDGEMENT

The author of this paper would like to thank the National Center for Research on Earthquake Engineering (NCREE) in Taiwan for providing experimental resources and data of the shake table experiment, as well as financial supports. This work is funded by the Ministry of Science and Technology [MOST 106-2625-M-027-002, MOST 107-2625-M-027-003, MOST 108-2625-M-027-001, and MOST 109-2625-M-027-002].

REFERENCES

[1] Yang, Y.S. (2019), "Measurement of Dynamic Responses from Large Structural Tests by Analyzing Non-Synchronized Videos," *Sensors*, **19**(16), 3520.

[2] Kaehler, A. & Bradski, G. *Learning OpenCV3: Computer Vision in C++ with the OpenCV Library*, O'Reilly Media, 2016. (ISBN: 978-0596516130)

[3] Yang, Y.S., Xue, Q., Chen, P-Y, Weng, J.H., Li, C.H., Liu, C.C., Chen, J.S., Chen, C.T. (2020). "Image Analysis Applications for Building Inter-Story Drift Monitoring," *Applied Sciences*, **10**:7304.

