Oscillation Monitoring Using Ortho-Projected Terrestrial Photogrammetry

Omar A. El Kadi, Adel Y. El Shazly, Khaled Nassar

Abstract— Monitoring of oscillation/ deformation is a raising concern for the benefit of structural health monitoring of historical structures and sensitive facilities. Moreover, the analyzed measurements can be implemented in further structural dynamic analysis (Modal analysis), for repair and remodeling purpose. Moreover, it can aid in structural testing as for static and dynamic bridge loading tests.

The development in the computing powers and cameras' sensors, allow the development of terrestrial photogrammetric model that uses a detected predefined grid to ortho-rectify captured frames in a recorded video; minimizing both radial and tangential lens distortions and allowing the monitoring of oscillating target in subpixel accuracy through the video frames sequence, with the aid of images radiometric corrections.

Such technique allowed market available low to mid cost cameras which provide high video recording rates, and offers high range of optical zoom, to preform monitoring process from a stable platform and with adequate accuracy and rate. which can be done using single market available camera sensor and a developed algorithm that automate the process of video frames or images sequence. Providing simple field setup and remote monitoring without the need of contact or wiring to the monitored structure, such technique allows static and long-term deflection measurement as for structural load testing and collapse hazards detection. In addition, it can be applied for vibration/oscillation monitoring as in modal analysis and structural dynamic testing.

Index Terms— Automation, Deformation monitoring, Image processing, OpenCV, Oscillation monitoring, Structural health monitoring, Terrestrial photogrammetry, Video processing.

1 Introduction

Structural health monitoring and full scale structural tests deformation monitoring, are an increasing demand associated with the modern development and the development of structural systems and materials used in construction, to ensure and evaluate the safety of structures in case of health monitoring or to validate that the structure follows the deformation limitations stated by code of practice or project specifications in case of testing. Such deformations can have high frequencies as in dynamic bridge loading tests or modal analysis of slender structures, while other can have low amplitude as in pile loading tests, also deformations can be cyclic in form of oscillation or time depended deformation as in case of settlement monitoring in tunneling applications.

This raising demand is required in different fields of civil engineering. In construction projects, it is required for monitoring of retaining structures, bridges load tests, structures deformations due to tunneling and to measure the efficiency of supported excavation by surrounding buildings monitoring; In structural health monitoring and structural analysis, oscillation monitoring is required for monitoring oscillation of slender structures and for structural modal analysis. Moreover, in field of Geomatics oscillation monitoring is used to monitor weaving for bathymetric survey.

Oscillation monitoring requires a complex monitoring setup than needs the integration of different techniques to achieve efficient results, where bi-axial or Tri-axial accelometers combined with different sensors and\or high frequency GPS receivers are commonly suggested system for oscillation monitoring, while some recent researches suggested the use of infrared holography; On the other hand, conventional monitoring systems based on trigonometry as robotic total stations are used for monitoring when low oscillation rates are expected and high standard deviations are accepted.

Nowadays, the rapid and high development in fields of photogrammetry and computer vision associated with the offered high computing powers allows the development of terrestrial photogrammetric models that can be used for oscillation monitoring with less complex instrumentation and using on shelf-tools.

2 Problem definition

"The comparison of measured and calculated behavior in order to tune and calibrate mechanical and numerical model assumptions is an essential part of any system analysis" (K. Bergmeister, and U. Santa,2015). The in-market available surveying techniques can monitor deformations in structures with standard deviation of about 11mm, and frequency up to 10hz using differential real time kinematic GNSS receivers and/or robotic total stations. The accuracy of measurements can be increased by implementing different sensors, considering the costs of complex setups, analysis for compatibility between different measuring systems and sensors noise removal. While, yet long term monitoring still can be challenging

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3 METHODOLOGY

3.1 Approach

The target of this research is to use a simple, low cost and reliable monitoring technique, which can be achieved using camera with adequate sensor size and optical zoom to monitor structure form stable platform.
A gridded target is attached to the monitoring spot on the structure, and video / sequential images are used for monitoring while, a program is developed to compute oscillation/ deformation.

Geometric corrections are calculated from reference frame, by applying fourth degree two-dimensional polynomial transformation, to allow on spot projection of skewed object plan and minimize the effect of radial and tangential lens distortion. gridded pattern target was used as per (Zang,1998); the equal spaced pattern is used as control points for the sake of the polynomial projection, which in this case requires a minimum of 30 points.

The estimated polynomial coefficients are then applied to project the successive frames, while a detected intermediate point in the target is used for the oscillation monitoring, to avoid the distortion that may be residual at the outer projected zone, using Harris corner detector (Chris Harris,1998).

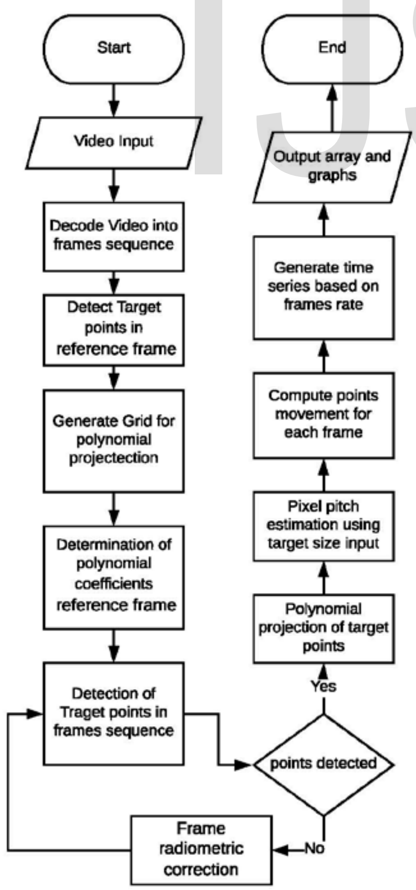


Fig. 1. Flow chart used for developed script.

3.2 Photogrammetric model

The photogrammetric model used is based on polynomial function from 4th degree, which is used to minimize the effect of radial and tangential distortion in captured frames. The polynomial coefficients are estimated using correlations to reference/ initial frame, then projection of following frames is applied using estimated coefficients.

Resulting a rectified ortho-photo parallel to the target's plane, while the maximum displacement is assumed to be smaller than half the target width, to ensure that the tracked points are all occupied in the projected zone of frame.
The estimated polynomial can be represented as following

$$U = a_1 x^4 + a_2 y^4 + a_3 x^4y^4 + a_4 x^3 + a_5 y^3 + \ldots \quad (1)$$
$$V = b_1 x^4 + b_2 y^4 + b_3 x^4y^4 + b_4 x^3 + b_5 y^3 + \ldots \quad (2)$$

Where U, V = image coordinates
x, y = object coordinates
a_n, b_n = polynomial coefficients

The resulting 30 polynomial coefficients be estimated by least squares can as:

$$\mathbf{A} = \begin{bmatrix} 1 & u_1 & v_1 & \cdots \\ 1 & u_2 & v_2 & \cdots \\ \vdots & \vdots & \vdots & \ddots \\ 1 & u_K & v_K & \cdots \end{bmatrix}, \mathbf{a} = \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_{N-1} \end{bmatrix}, \mathbf{b} = \begin{bmatrix} b_0 \\ b_1 \\ \vdots \\ b_{N-1} \end{bmatrix}, \mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_K \end{bmatrix}, \mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_K \end{bmatrix} \ldots \quad (3)$$

$$\mathbf{a} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{x}, \quad b = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T y \quad \ldots \quad (4)$$

The developed Python program implemented NumPy and SciPy for array, math, and linear algebra computations, while OpenCV and SCIKIT- image processing libraries were used for image processing and objects detection, Sub pixel refinement algorithm for corner detection based on gradient direction and neighborhood search is implemented from OpenCV library to increase detection accuracy and reduce the effect of image noise.

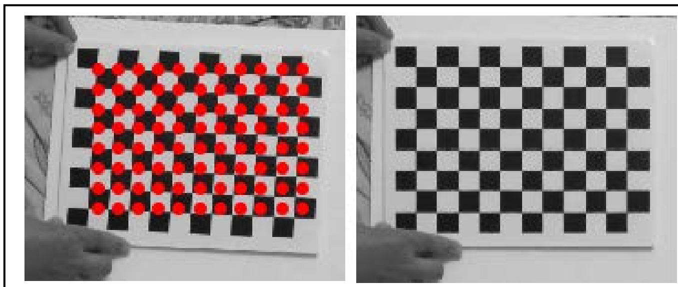


Fig. 2. Detection of grid points used for polynomial projection (left) and resulting projected frame (right).

3 Testing

Two sets of experiments were conducted to examine the proposed approach of oscillation monitoring, then the approach was examined in outdoor condition. The first set of experiments based on moving the target on a predefined grid in X, Y and XY directions, then the target was fixed to a small metal ruler moving on a groove, formed in a horizontal fixed wooden board to control displacement. While the second set of experiments monitored a dynamic actuator in structural laboratory and compared monitoring results with actuator's LVDT measured data. Then the proposed monitoring approach was used to measure deformations for a wooden structure tested for graduating students' thesis project conducted at outdoor condition (House in a bag, AUC, 2017).

3.1 Predefined grid Movement

3.1.1 Movement along X-axis

8 marks at 20mm intervals was marked on a white board, a video is captured using camera mounted over tripod, while the target is attached on a board and moved by hand from initial mark in x direction to last mark and back, to have a movement of about 160mm in X direction, the recorded video had a length of 59 seconds, and decomposed in to 1770 frame.

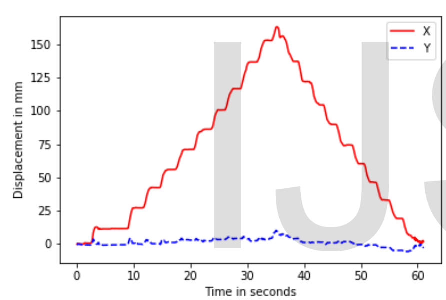


Fig. 3. Detected oscillations along X, Y direction, for moving target along X axis.

3.1.2 Movement along Y-axis

4 marks at 20mm intervals was marked on a white board, a video is captured for 25 while moving the board from initial position to 4th mark and back, the 754 frames of 1920 x 1080 pixels' size needed about 70 seconds for analysis using a modern business edition Laptop of 16 GB ram and i7 processor.

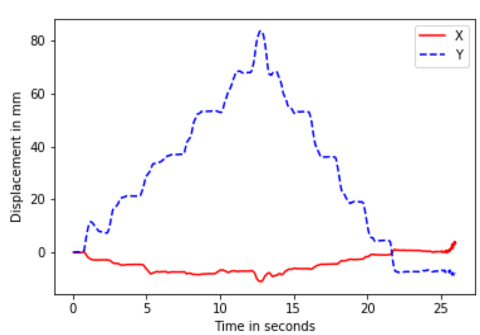


Fig. 4. Detected oscillations along X, Y direction, for moving target along Y axis.

3.1.3 Movement along X-Y axis

A video is used to monitor, while target is moving on a board with predefined points along diagonal direction of about 40 degrees from y axis. To avoid coincided x and y graph representations.

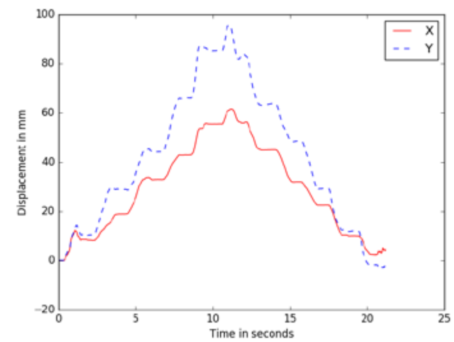


Fig. 5. Detected oscillations along X, Y direction, for moving target along X-Y axis.

3.1.4 Manually controlled movement along X-axis

This set of tests is performed to examine the accuracy of measured deformations. Still images of 4608 x 3456 and 1920 x 1080 pixels' sizes were used. Where 150mm target is moved along x direction with small displacements that varied form sub-millimeter to 30 mm. The target was attached to a steel ruler that is moved in marked notch over a horizontal wooden board.

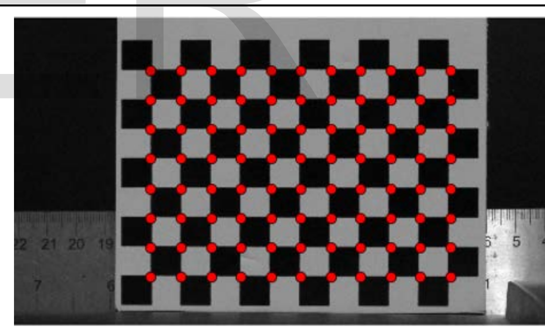


Fig. 6. setup of manually controlled movement along X axis, showing target detected points.

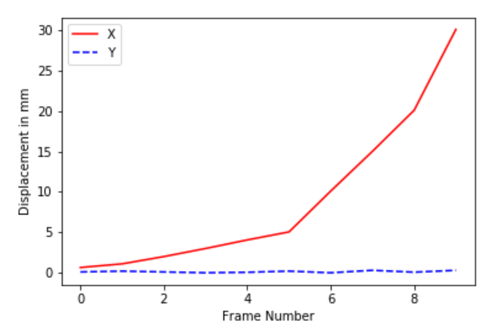


Fig. 7. Detected oscillations along X, Y direction, for manually controlled moving target along X- axis.

TABLE 1 APPLIED VS MONITORED MANUALLY CONTROLLED TARGET MOVEMENTS IN (TEST 1)

Applied

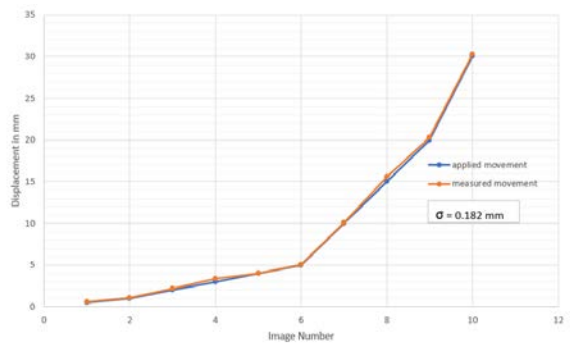


Fig. 8. Detected manually controlled target movements along X axis, (Test 1)

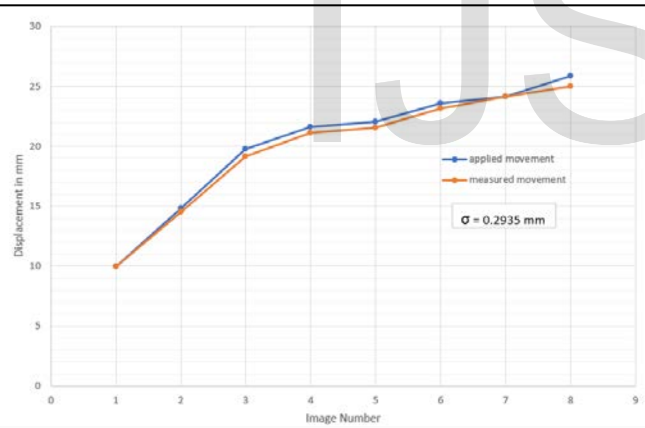


Fig. 9. Detected manually controlled target movements along X axis, (Test 2)

3.2 Monitoring dynamic actuator movement

This set of tests were conducted at the structural laboratory, at Construction engineering department at the American university in Cairo. A DTE dynamic actuator of maximum stroke of 250mm is used, which is powered by a hydraulic power unit and controlled by PC attached to data controller. The actuator was mounted to the strong wall and supported by a rope connected to an overhead crane, and different protocols were applied to allow the actuator head to oscillate.

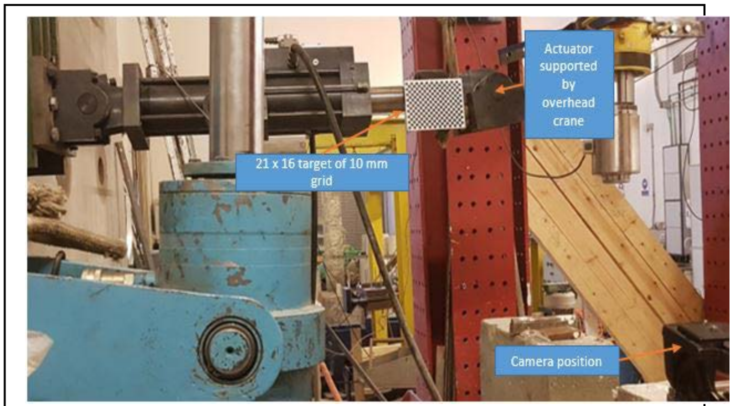


Fig. 10. Configuration used for testing using dynamic actuator.

The different applied loading/oscillation protocols had a maximum stroke of 100mm and were all monitored by video of full resolution (1920 x 1080 pixel), the applied tests can by summarized as per following table

TABLE 2 APPLIED OSCILLATION FOR DYNAMIC ACTUATOR

Setup No.	Stroke Time	Oscillation Frequency	Video Capture rate	Data acquisition rate	Max speed (mm/sec)
1	4 Sec	0.125 Hz	30 fps	20 Hz	25
2	1 Sec	0.5 Hz	30 fps	50 HZ	100
3	0.5 Sec	1 Hz	30 fps	50 Hz	200

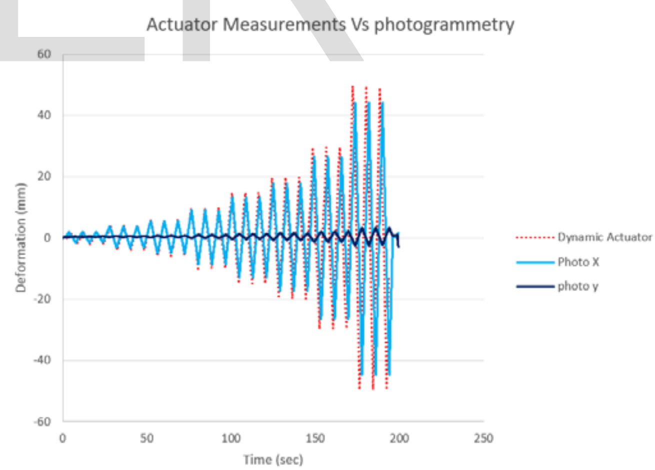
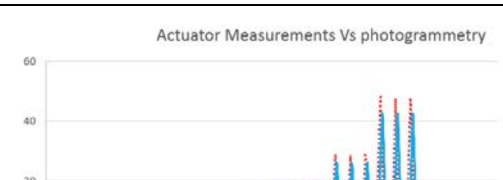


Fig. 11. Video Detected vs LVDT measured actuator oscillation at setup No. 1

As shown in figure 10, the LVDT measured the oscillation along the actuator movement direction, while the applied monitoring technique resolved the movement into target's X and Y axis direction, the small motion in Y direction is a result of the rotation of the wire supporting the actuator moving part around overhead crane fixed position.



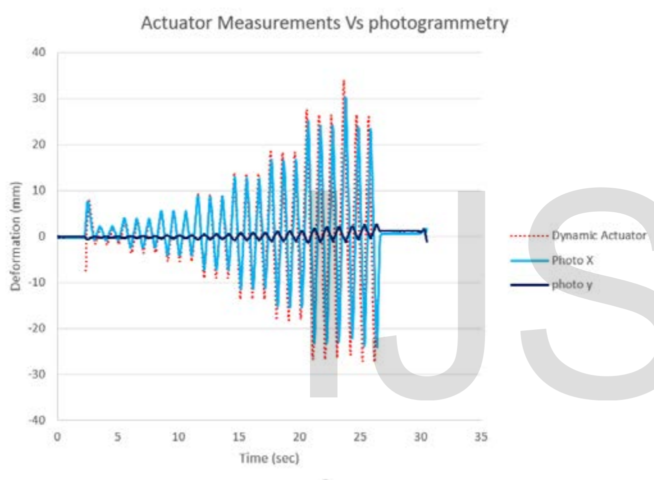


Fig. 13. Video Detected vs LVDT measured actuator oscillation at setup No. 3

The captured videos properties had a rate of 29 frame per second (fps). While from signals matching, it was concluded that captured videos have frame rate of 29.5 frame / second (i.e. frame each 0.034 second). The measured and monitored oscillation didn't match the input protocol due to HPU flow limitation, however this won't affect the test results as the measured LVDT movements can be used to validate the proposed monitoring technique.

3.3 Monitoring deformation of wooden structure at outdoor condition

Outdoor condition can be challenging for image /video processing, due to the expected variation of lighting conditions. Moreover, direct sun light reflection on nearby surfaces can cause errors in image detection process.

To examine the ability of proposed oscillation monitoring technique to monitor outdoor structures, a test conducted by graduating students at the American University in Cairo was monitored for their thesis project. The thesis introduced a low cost portable wooden shelter, that can be transported in a bag to be used as refugees' shelter.

The target of the test is to measure lateral deformation of wooden house subjected to lateral load, to be compared to conducted numerical analysis.

Fig. 14. Outdoor Setup configuration for loading a wooden structure

As shown in figure 13 a pulley fixed to the ground was used to apply load on the structure, while a digital luggage scale attached to the pulley was used to determine the applied force. The deformation was monitored via proposed monitoring technique as shown in next figure, while video was used for load-deformation synchronizing.

Fig. 15. Monitoring target attached to tested structure

The monitored target required radiometric corrections to enable target point detection. The need of radiometric corrections is automatically detected by programed python script if target

points were not detected in a specific frame, in such case the ongoing process is paused and radiometric corrections function is called and applied to the frame.
The radiometric correction is performed by changing the grayscale image into binary image, while the threshold value of the conversion is calculated via histogram matching between region of interest in the monitored image and a stored image for the target. The region of interest is determined by the inputted target dimensions at the start of program. Where, an offset of half of the target dimension is considered to insure including the target with minimal target surrounding features in the histogram matching process.

Fig. 16. Wooden structure measured load deformation vs numerical model (House in a bag, AUC, fall 2017.)

4 Conclusion

The proposed oscillation monitoring technique using ortho-projected terrestrial photogrammetry successfully monitored oscillation and deformations in various environments, as the analysis results had precision less than 0.2mm when using video at 30fps in full HD resolution.

The proposed approach can theoretically achieve sub – millimeter precision for monitoring objects more than 100m apart using low cost camera senor of bridge type. Moreover, high speed data acquisition rate can be achieved (up to 240 fps at full HD video capturing) with on shelf cameras.

However, it important to examine real sensor video capturing rate and consider extreme outdoor conditions.

Acknowledgment

The authors wish to thank the construction department at The American university in Cairo for allowing the usage of facilities, and thank Mr. Ahmed Gaber, Mr. Ahmed Madbouly& Ms. Zahra Zayed for their help with tests setups and programming debugging.

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