6-DOF Measurement of a Vibrating Structure Using Digital Close-range Photogrammetry

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ABSTRACT
The objective of this paper is to simulate the dynamic behavior of a structure using digital close-range photogrammetry by a stereo-camera system and a single-camera system. An inexpensive stereo-camera system recorded a vibrating structure with multiple marked-target points, and then the displacements in spatial coordinates of the target points were computed via space-intersection theory. A less than 1.0 mm error of 3D coordinates calculation was obtained from the stereo-camera system of the proposed method. The six degrees of freedom (6-DOF)-based dynamic motion of the structure could then be systematically attained by an absolute orientation of set points on the vibrating rigid structure. The motion of the structure was also simulated using a single camera or stereo system in the same experiment. The method using a single camera was based on a space-resection algorithm with a suitable camera position and object size, and ended with an inverse resection to 6-DOF of the structure. By applying the proposed methods, an experiment was successfully performed to monitor the motion of a vibrating structure.

Keywords
dynamic structure, 6-DOF, space resection, bundle adjustment, displacement, DLT

1. INTRODUCTION
As the knowledge basis of vibration-based structure health-monitoring techniques, dynamic measurement plays an important role in the whole process, including modal parameters identification, efficacy validation of maintained work, etc. The measurement of the operation and response of the structure to track and evaluate the symptoms of operation or deterioration may affect serviceability and safety reliability.

At present, several methods are commonly used to measure the displacement and motion of a structure; these can be classified as contact types or non-contact types. Contact-type sensors include accelerometers and GPS (real-time kinematic global positioning systems), and non-contact sensors include Laser Doppler Vibrometry (LDV).

Accelerometers are commonly used to perform dynamic tests on structures. However, these sensors are sensitive to lightning and electromagnetic fields. In addition, even small errors in the measured acceleration will yield a rapid increase of errors due to error accumulation [5].

GPS sensors are proposed to be used in civil engineering to capture the dynamic displacement of long-span cable-supported bridges subjected to wind excitation [21]. Although GPS has been proved to be suitable for displacement measurement of large-scale structures, some limitations cannot be avoided in field dynamic tests. On the other hand, GPS automatically calculates the distance between satellites and receivers to determine the structure displacement position. Therefore, many aspects affect the accuracy of dynamic measurement, such as sampling rate, satellite convergence, and atmospheric effects. A field study by Wieser and Brunner [19] also concluded that GPS was not practical for monitoring deck displacement of a cable-supported bridge due to the multi-path and diffraction effects associated with the steel cables.

The Laser Doppler Vibrometer is a device that provides a non-contact vibration measurement system [20]. Though this instrument is non-contact and can provide accurate displacement measurements at locations within its applicable distance, it is much more expensive than other equipment.

Due to practical limitations for motion-recording of the above-mentioned sensors, the motivation of this study is to seek an effective alternative for measurement in order to avoid the foregoing difficulties of conventional sensors. With the advent of inexpensive and high-performance cameras and associated imaging techniques, photogrammetry, a measurement technique of digital close-range photogrammetry, has become a popular tool of great interest for wide applications. The objective of this study was to exploit a close-range photogrammetry technique involved with commercial cameras for movement measurement of dynamic structures. This study proposes two measurement systems to monitor the dynamic motion of a rigid structural model: a stereo-camera system and a single-camera system.

2. CLOSE-RANGE PHOTOGRAMMETRIC MEASUREMENT TECHNIQUES
Photogrammetry is a technology for measuring 2D or 3D shapes from photos. In this study, an image-based measurement system is proposed for monitoring the dynamic behavior of a structure. For an investigation of the dynamic movement of a structure, various approaches and experimental studies have been primarily addressed. A method to measure multi-point displacement responses using a digital image-processing technique was suggested by Kim and Kim [11]. Digital image correlation was applied to the developed algorithm and the image-transform function to correct the movement and errors between the images, without deformation and with deformation, was also used to increase the resolution of displacement responses. One shaking-

table test and several field tests were carried out to validate this algorithm, which can measure multi-point displacement responses of structures by using digital image-processing techniques [11].

Pure photogrammetric solutions for object tracking based on two or more synchronized cameras have the advantage of providing the absolute object coordinates of targets. Ozbek et al. monitored a large wind turbine, applying a photogrammetry method that required a PONTOS system consisting of four CCD cameras [16].

Another study introduced a dynamic displacement system, which proposed a digital video-image resizing method to monitor the dynamic motion using an adjusted camera in a shaking-table test of building structure specimens. The researchers evaluated the usability of the displacement-sensing by the rigid frame specimen, then the dynamic displacements of an earthquake-loaded masonry specimen and a two-story steel frame specimen were measured as applications of this method [4].

Ji and Chang introduced a non-target image-based displacement measurement technique to measure small cable vibrations [10]. The technique analyzes an image sequence of a vibrating cable segment captured by a camera. The proposed method was validated both in the laboratory using a rigid pipe and in the field on a small pedestrian bridge cable. Results showed that the technique is able to accurately measure 1D vibrations of cables.

An application of an image-based technique to measure vibration displacements of a beam and for modal testing using one camera was also introduced by Jeon et al. [9]. However, their research was limited to measuring 2D vibrations of the beam.

For a 3D measurement using an image-based system, Benetazzo proposed a six degrees of freedom (6-DOF) motion-measurement technique for a small-scale floating model based on analysis of image sequences from one camera [2]. The suggested system consisted of one camera and one target, and the method estimated the 3D rigid motion following the time evolution of the target of a known pattern fixed to the moving body and framed by the camera. In particular, the rotation matrix and the translation vector of the 3D rigid motion between the initial still position and a generic moved position were calculated by assuming the existence of a planar homography between the camera's CCD plane and the plane passing through the flat target's surface body. The geometrical relationship allowed for the calculation of the wanted 6-DOF for every point of the model. The image-based technique was illustrated on some tests carried out in an experimental multipurpose wave basin [2].

An image-based dynamic-motion-measurement technique using multiple targets was proposed to measure the 3D dynamic motion of floating structures. A scheme was also suggested to determine an appropriate threshold value to discriminate the background by minimizing an estimation error index. The method was applied to field measurements of the dynamic motion of a large concrete floating structure under various wave conditions, and the results were compared with those from a conventional real-time kinematic global positioning system and a motion reference unit (MRU). The researchers reported that the image-based system was much better than the other two systems for measuring transverse motions [22].

In this article, the problem of determining the dynamic motion of a rigid structure was performed based on mathematical relationships established between the 3D position of an object and its 2D representation in an image system [14]. The problems of both space resection and bundle adjustment are mentioned in this study. In a single-camera system, the estimation of camera orientation can be obtained by linear or non-linear solutions, based on the measurement of image coordinates of appropriate reference points. The linear resection method is based on direct linear transformation (DLT) [1] or projective geometry [7]. The linear functions require a minimum of six control points, without the need for approximate values of the unknown orientation parameters. Accordingly, the best-known non-linear method of space resection based on the least squares solution of linearized collinearity equations can be performed with the initial values provided by DLT. In the stereo-camera system, bundle adjustment based on the collinearity equations was used to determine the camera orientation parameters, then 3D coordinates of target points were computed by applying the space-intersection theory.

In this paper, the proposed methods and explanations of procedures are made clear in Section 3. The experimental verification to investigate the algorithm and analysis of the results are discussed in Section 4. Finally, a comparison of the 6-DOF-based dynamic behavior of the structure using the two proposed methods is performed.

3. METHODOLOGY

3.1 Stereo-camera solution

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In order to measure 3D vibrations of a structure by stereo photogrammetry, the interior and exterior orientation parameters of two cameras must be precisely identified. These parameters can be determined by the bundle adjustment with spatial and image coordinates of fixed reference points. The bundle adjustment is based on the collinearity Eq. (1), which refers to the alignment of the perspective center of the camera, the points on the photograph, and the points in the object space, which coincide with the bundle of rays [15].

$$x = x_{0i} - f_i \frac{m_{i,11}(X - X_{Li}) + m_{i,12}(Y - Y_{Li}) + m_{i,13}(Z - Z_{Li})}{m_{i,31}(X - X_{Li}) + m_{i,32}(Y - Y_{Li}) + m_{i,33}(Z - Z_{Li})} \qquad (1)$$

$$y = y_{0i} - f_i \frac{m_{i,21}(X - X_{Li}) + m_{i,22}(Y - Y_{Li}) + m_{i,23}(Z - Z_{Li})}{m_{i,31}(X - X_{Li}) + m_{i,32}(Y - Y_{Li}) + m_{i,33}(Z - Z_{Li})}$$

where i is the number of the camera station; x and y are the coordinates of points in the image coordinates; x_0 and y_0 are the coordinates of the principal point in the image plane; X, Y, and Z are the coordinates of the object point; X_L, Y_L, and Z_L are the coordinates of the exposure station; f is the camera's focal length; ω, ϕ, and κ are the rotation angles with respect to the x, y, and z axes; and m_{11}, m_{12},… m_{33} are the elements of the rotation matrix.

Figure 1 shows the schematically detailed procedure of the method to measure the dynamic motion of a vibrating structure using two digital cameras. A number of circle-shaped targets were placed on the body of the structure. Consecutive photos of the vibrating structure were taken and stored by two inexpensive cameras.

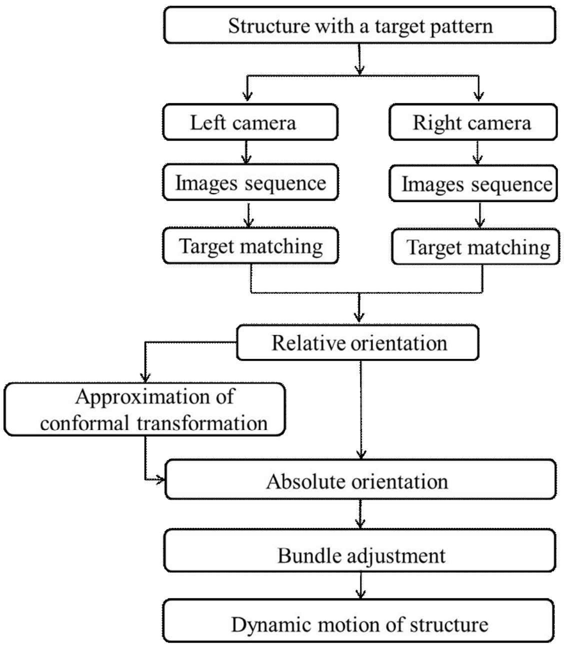


Figure 1. Dynamic motion measurement procedure using two cameras.

3.1.1 Image-based tracking of control points

In this experiment, a circular shape made with a high-contrast marker was selected to be used as the target attached to the structure because of the radial-symmetric design to measure the actual 3D point. Circular targets are not only useful for manual interaction, but also for automatic digital target detection and measurement [13].

The edges were detected on the target based on the approximation position. Similar to other operations in digital image processing, there are various methods to find edges in images. Among them, an advanced edge-detection method developed by Canny can detect edges in the presence of noise even if they are weak or not clearly visible [3]. Once a target is detected and its approximate position is known, the center of the circular target can be calculated with subpixel precision, and then a circle can be fitted to the edges to obtain a precise target center

3.1.2 Photogrammetric calculation

The relative orientation of two cameras can be calculated using tie points of the image pairs. An approximation of conformal transformation needs to be executed in order to provide initial approximation values of absolute transformation calculation [6]. The exterior orientation parameters of the two cameras are then determined via the results of absolute orientation combined with relative orientation. The above procedure provides the generation of approximate values of bundle adjustment. Based on the bundle adjustment, the interior and exterior orientation parameters of the two cameras can be precisely computed.

Since the camera's position and orientation do not change during the whole video acquisition process, the obtained camera parameters can be used for all pairs of images. Using these fixed parameters, the object coordinates of targets can be calculated for the entire sequence. Additionally, since the structure is a rigid body, the 6-DOF-based dynamic motion of the structure can be obtained using the displacement of the control point pattern. The process of 6-DOF determination is based on a closed-form solution of absolute orientation using unit quaternions [8].

3.2 Single-camera Solution

Figure 2 shows the schematically detailed procedure of the method to measure the dynamic motion of a vibrating structure using a single video camera. The following approaches were implemented to calculate the position and orientation of the camera, then the 6-DOF of the structure.

(1) Image-processing-based tracking control points

(2) Space resection using DLT

(3) Adjustment of camera parameters

(4) 6-DOF by inverse resection

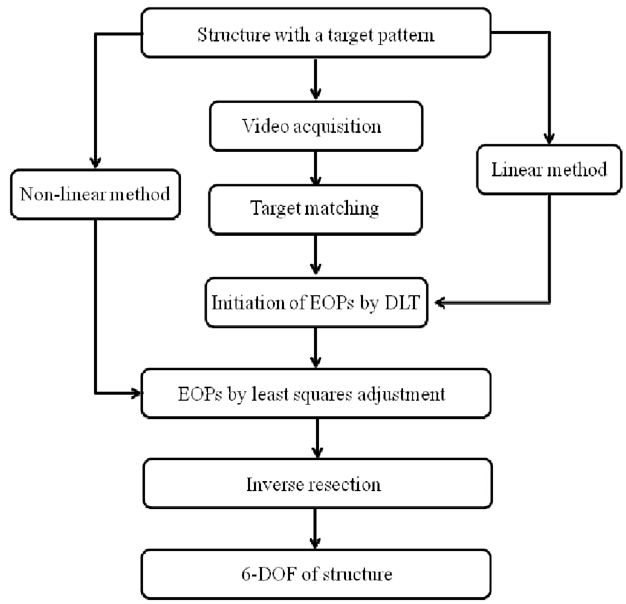


Figure 2. Movement-measurement procedure using a single camera.

3.2.1 Exterior orientation parameters of the camera

Since the camera is stationary during the experiment, in order to recover the translation and rotation of the object, the position and orientation of the camera must be determined. The DLT method is used to accomplish this. The equations of DLT are linear and can be solved with standard least square estimation (LSQ). To solve the DLT parameters, a minimum of six well-distributed reference points is required. The transformation equation of the DLT is given by Eq. (2)

$$x = \left(\frac{L_1 X + L_2 Y + L_3 Z + L_4}{L_9 X + L_{10} Y + L_{11} Z + 1} \right) \qquad (2)$$
$$y = \left(\frac{L_5 X + L_6 Y + L_7 Z + L_8}{L_9 X + L_{10} Y + L_{11} Z + 1} \right)$$

where x and y are the measured comparator or image coordinates; X, Y, and Z are the 3D coordinates of the reference points; and the coefficients L_1 to L_{11} are the DLT parameters [13].

It is well-known that the non-linear method, based on the least squares solution of linearized collinearity equations, is considered the most accurate solution of space resection. If a suitable number of control points are available, the calculated exterior orientation by DLT can be applied as initial values of unknown parameters in the least squares adjustment solution to determine the six exterior orientation parameters. Accordingly, the general least squares adjustment method was utilized to adjust the exterior orientation parameters. The collinearity equations can be rewritten as Eq. (3):

$$F_1 = (x - x_0) + f\frac{U}{W} = 0 \quad (3)$$
$$F_2 = (y - y_0) + f\frac{U}{W} = 0$$

The image coordinates x and y are considered the observation or measurements, while the elements of interior orientation, x_0, y_0, and f, are considered known from calibration. The remaining variables are considered unknown parameters. Consequently, the linearized form of collinearity equations is given by Eq. (4) [14].

$$v + B\Delta = f \quad (4)$$

where $v = [v_x \; v_y]^T$ are the image coordinate residuals, B is the matrix of partial derivatives of the two functions in Eq. (4) with respect to each of the six exterior orientation elements and the three coordinates of the object point, and Δ is the vector of nine corrections to approximate the parameters.

3.2.2 Six degrees of freedom by inverse resection

The relationship between the coordinate of a point X in the object system and x* in the camera system [13] is given by Eq. (5):

$$X = X_0 + Rx^* \quad (5)$$

The translation vector X_0 and rotation matrix R form the 6-DOF of the camera, with respect to the object system. The coordinates x^* of a control point on the object, with respect to the camera system, are calculated by Eq. (6):

$$x^* = R^{-1}(X - X_0) \quad (6)$$

Since the camera remained still during the entire video acquisition, the change in spatial position and orientation of an object with respect to the camera coordinate system can be obtained by repeated inverse space resection, as in Eq. (6).

4. EXPERIMENT AND RESULTS

4.1 Experiment

In order to validate the method using two cameras, a moving-object experiment was performed. Two video cameras (Nikon D800) were simultaneously used for the image sequence acquisition. Each camera could record high-definition images with a pixel resolution of 1920×1080 at 30 fps. They were equipped with fixed lenses of F1.8 and focal lengths of 85 mm and 50 mm. The two cameras were systematically calibrated prior to the experiment using the checkerboard pattern as shown in Figure 3. A stopwatch monitor was used to synchronize the two cameras during the experiment; the two recorded image-sequences were manually synchronized when the times appearing on the stopwatch was absolutely identical.

In this experiment, a large number of target markers were placed on the structure. The structure could be moved in three directions with an arbitrary amplitude and frequency. The first camera was placed at about 3.3 m away and the second one was placed at about 2.8 m away from the target (see Figure 4(b)). For stereo calibration, the checkerboard pattern was placed in front of the target object. Twenty-three images were recorded by the two cameras under the fixed focal lengths, and each image pair corresponded to a different orientation of the checkerboard pattern. The camera calibration calculation was performed with the camera calibrator application of the Matlab program.

After calibration, the structure was moved in three directions in a sinusoidal motion of arbitrary amplitude and frequency. The position of the stereo-camera system with respect to the interest object is schematically illustrated in Figure 4. The motion of the vibrating structure was acquired in 33.50 seconds, recording a total of 1,000 frames per camera.

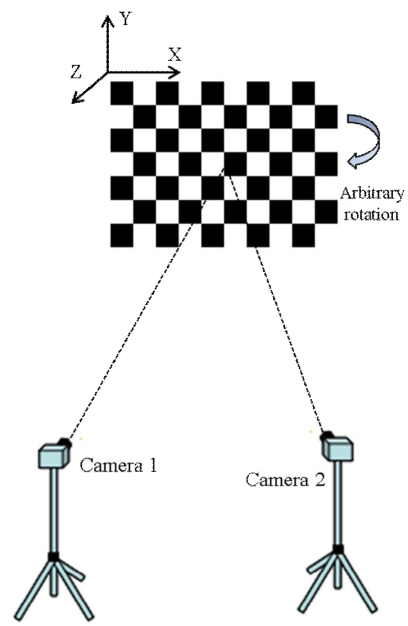
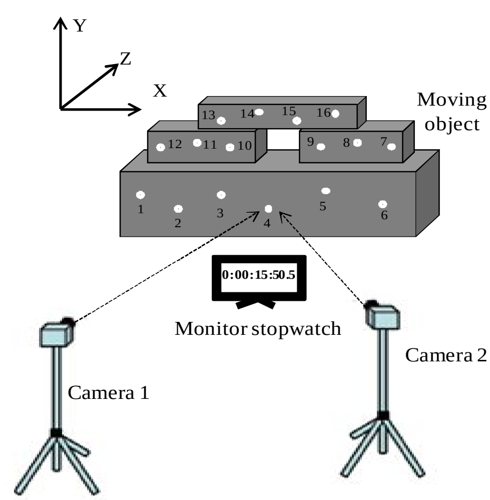


Figure 3. Checkerboard and two cameras for stereo calibration.



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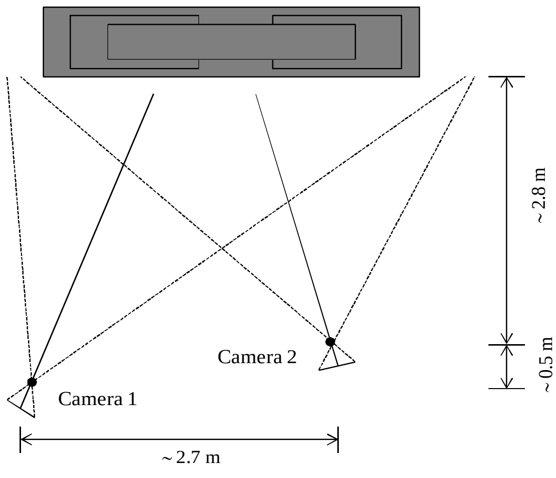


(b)

Figure 4. Schematic overview of experimental setup; (a) configuration of measurement system and (b) position of cameras with respect to object.

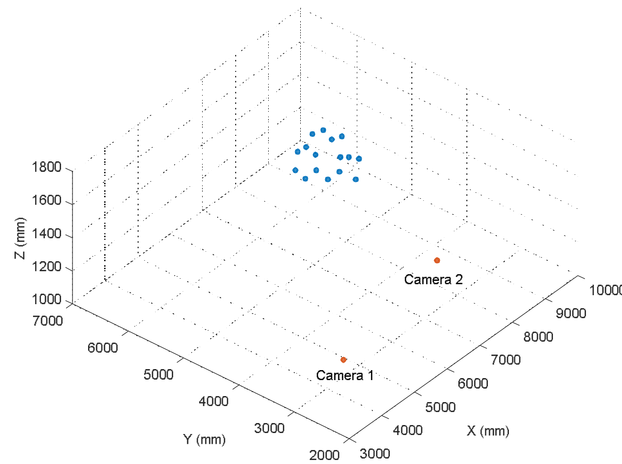


Figure 5. Positions of the cameras and control points

4.2 Results and Analysis

4.2.1 Stereo-camera system

Table 1 shows the interior parameters of the two cameras, and the accuracy of the calibration procedure is presented with the mean reprojected values of 0.336 pixels and 0.315 pixels, corresponding to the first camera and the second camera, respectively. It can be seen that the means of reprojection errors were all smaller than one pixel. It is noted that to record the image of the pattern at a distance roughly equal to the distance between the camera system and the object and the checkerboard should fill at least 20% of the captured image [18]. This is because the pattern becomes smaller and covers fewer pixels as the distance increases, and the calibration achieves a low reprojection error but the distortion estimation is incorrect.

Following the proposed procedure for the stereo-camera system, after bundle adjustment, the camera parameters and 3D coordinates of the control points were derived by calculating the first image pair of the image sequences, as shown in Figure 5. The blue dots illustrate the calculated object coordinates and the red dots are the calculated coordinates of the two cameras in the object space. In order to verify the accuracy of the determined camera parameters, a common method is to compare the 3D coordinates of the check points reconstructed from the stereo-camera system with those measured by a total station. A quantitative comparison of measurement results is shown in Table 2. Using the fixed parameters of the two cameras, the 3D displacements (X- horizontal direction, Y- vertical direction and Z- in-depth direction) at all target positions from point 1 to point 16 can be obtained. As the structure is rigid and vibrated in a fairly sinusoidal oscillation relative to its vertical symmetry axis, the displacements in the vertical direction of points 1 to 3 and points 10 to 14 are relatively symmetrical to those of points 5 to 9 and points 15 and 16. Assuming that the first images of the sequences denote the beginning of the vibration test, the displacement at each target point relative to its initial state is demonstrated in Figure 6.

4.2.2 Single-camera system

Following the proposed procedure for the single system as shown in Figure 2, assuming that the camera is moved and the structure is stationary, after adjustment of space resection, the translation and rotation of the camera were obtained for all images in sequence and given in Figure 7.

4.2.3 Comparison of 6-DOF

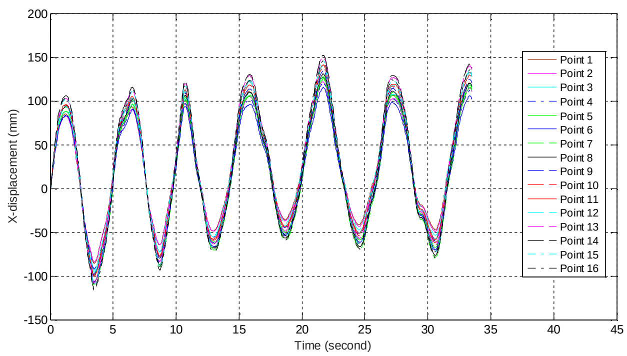
Since the structure was a rigid body, the 6-DOF-based dynamic motion in the stereo-camera system could be obtained by applying absolute orientation in the set of target points on the structure using 3D displacement results. The 6-DOF of the structure from the single-camera system was computed by repeating the inverse resection. A 6-DOF-based comparison of the two measurement systems is shown in Figure 8 in terms of translation and rotation with respect to the three axes coordinates, X, Y, and Z. The comparison shows that a similar translation in the X and Y directions can be obtained by the two measurement systems. Assuming that the results of the stereo-camera system were more accurate than those of the single-camera system, a large error is seen in Z-directional translation (in-depth direction relative to the cameras). The increase of error is possibly due to the insufficiency of the single camera to accurately determine the absolute depth. The problem of depth estimation from a single monocular image is a difficult task that requires taking into account the global structure of the image, as well as the use of prior knowledge about the scene [17]. In terms of the rotation angles of the structure, Figure 8(b) shows the comparison of omega, phi, and kappa corresponding to the X, Y, and Z directions. Among them, the rotation angle of the Y direction resulting from the single camera matched quite closely with that measured by the stereo cameras. However, it shows less accuracy in the rotations about the X and Z directions. Using a single camera, Hartley and Zisserman suggested that the field of view is small; on the other hand, a long focal length should be used for image acquisition [7]. The calculation of exterior orientation from a single camera is weaker when the figure formed by the perspective center and object points becomes narrow [12]. The vibration of the structure in the frequency domain is also presented in Figure 9.

Table 1. Camera calibration parameters

Camera	f (mm)	x_0 (mm)	y_0 (mm)	Mean reprojection error (pixel)
Camera 1	88.570	-0.261	0.229	0.336
Camera 2	53.496	-0.817	0.1778	0.315

Table 2. Positioning error of check points

Direction	Mean (mm)	RMSE (mm)
X-direction	-0.2245	0.6364
Y-direction	-0.1573	0.2222
Z-direction	0.0625	0.2350



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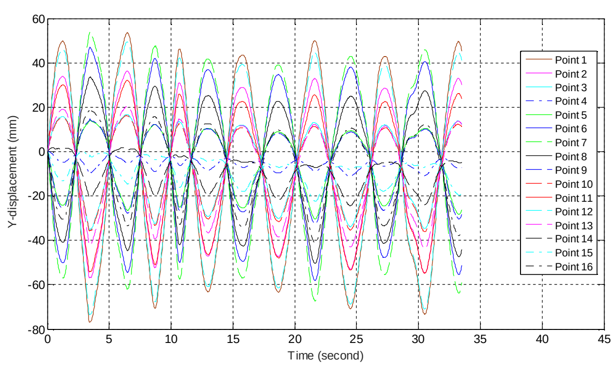

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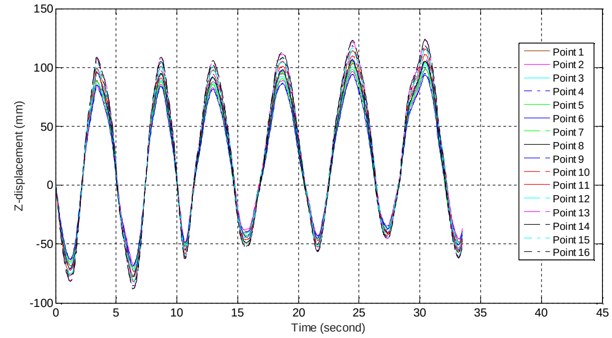
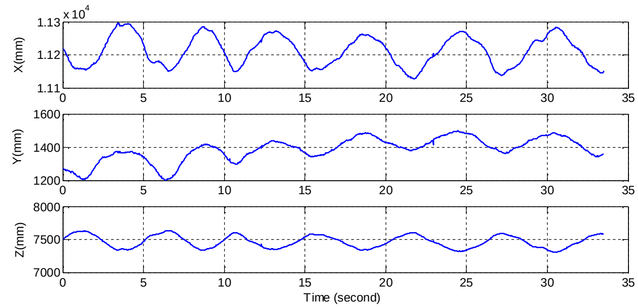


(c)

Figure 6. Displacement of target points on object; (a) X-displacement, (b) Y-displacement, and (c) Z-displacement.



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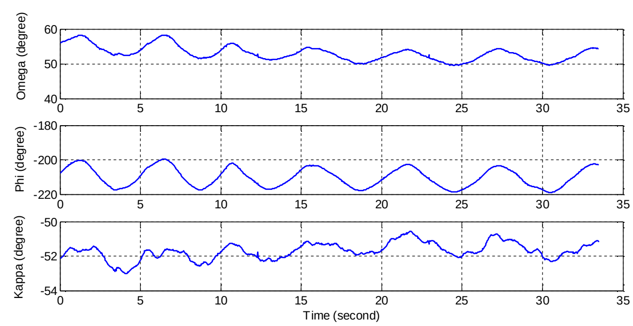
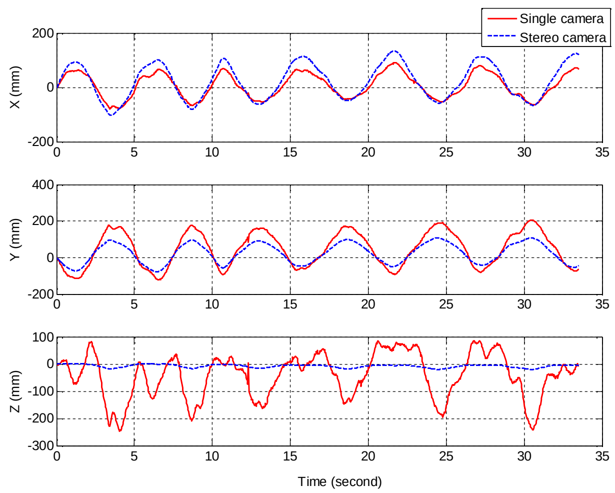


(b)

Figure 7. Camera translation and rotation; (a) translation and (b) rotation



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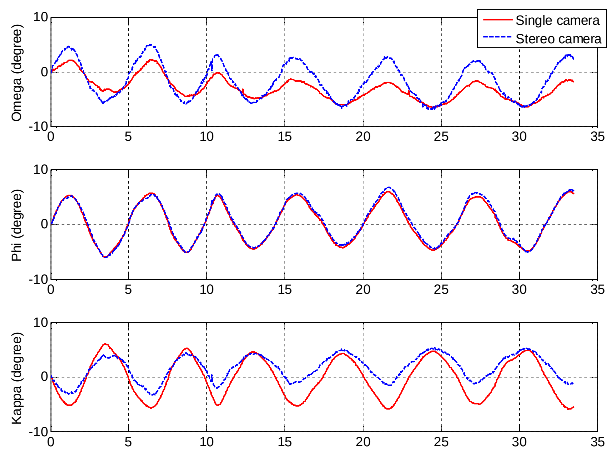

(b)

Figure 8. The 6-DOF of the structure using the two measurement systems; (a) translation and (b) rotation

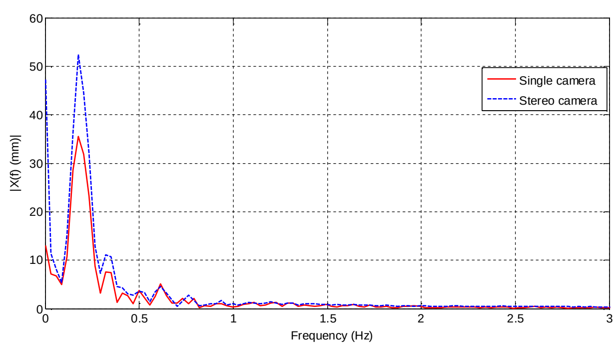

Figure 9. Spectrum of X-translation of structure

5. CONCLUSION

This paper proposed two measurement systems to simulate the dynamic behavior of a rigid structure using digital close-range photogrammetry with inexpensive cameras. Using the stereo-camera system, the 3D dynamic displacement of a structure can be effectively measured by the proposed method. This is meaningful for the requirements of measuring the displacement of multiple points or for monitoring a non-rigid structure. The 6-DOF-based dynamic behavior of the structure was also computed with a single-camera system using a space-resection algorithm. With the single-camera method, it should be noted that the object must be acquired in a large field of captured view and a suitable number of control points must be available in the measurement system.

An experiment was successfully performed to measure the displacement of a vibrating structure using photogrammetric measurement systems. A comparison based on the results of the two proposed methods was also presented in this study.

The proposed photogrammetric techniques have many advantages compared to conventional sensors and provide a prospective solution for determining the dynamic behavior of structures using low-cost equipment. Further research will investigate and analyze other factors in 6-DOF measurements, e.g. lens distortion of the camera and the range of using a single camera for measuring distant structures.

6. ACKNOWLEDGMENTS

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