VISION BASED DEFORMATION MONITORING OF A MASONRY WALL UNDER SIMULATED EARTHQUAKE CONDITIONS

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ABSTRACT
This paper presents the results of the validation of a prototype vision measurement system for use in experiments on civil engineering structures. The system is tested against a uni-axial earthquake shake table designed to hold full-size masonry walls. We compare the reference earthquake signal, the forcing signal, and the observed signal in terms of displacement with time.

1. THE SEISMIC SIMULATION TABLE
In order to test masonry building components under earthquake conditions, a low-cost testing apparatus was designed and built. This seismic simulation table (Shake Frame) is a Single Degree Of Freedom (horizontal displacement) dynamic testing device which consists of four steel I-sections (W360 x 162) with cross-braces to withstand any accidental torque forces in the system. The resulting frame (Figure 1) is 3 meters by 2 meters between respective beam centr lines, and has been designed to handle a maximum load of 300 kN with walls standing up to 6m in height. In order to minimise friction, a bearing and rail system was used as the support and guidance method for the shake frame.

![Shake Frame Diagram](image1.png)

Figure 1 - The seismic simulation table (top view)

The displacement, force capacity and speed of the shake frame are determined by the system’s actuators [1]. These devices can provide a maximum load of 165 kN each, a maximum displacement of ± 125 mm, and can operate without difficulty at the system design frequency of up to 4 Hz. The actuators are independently programmed with a forcing signal requiring the programs to be synchronised. These programming tasks utilise the software development kit of the shake-frame control device, a FlexTest GT Test Controller.

2. THE VIDEOGRAMMETRY SYSTEM
Videogrammetry is a measurement method using triangulation observations from images [2]. The advantages of videogrammetry in the analysis of dynamic structures include non-contact, three dimensional and full-field measurement of an object. The latter is dependent on the number and position of signalised targets that are employed to allow image observations down to 1/10th of a pixel. However, the cost and effort in virtually covering the object with such targets is low, leading to the ability to monitor unpredicted displacements in a structure during testing. In addition to the image observation quality, the measurement accuracy of these systems is determined by the geometry of the camera axes relative to the object, and the use of control points in the area of interest to allow each image to be oriented in a common coordinate system. For essentially planar objects such as masonry walls, a common generic geometry (or network) is shown in Figure 2.

![Generic Network Diagram](image2.png)

Figure 2 - Generic network for a planar structure. Upper figure is front view, lower figure is top view.
The 4 cameras form the corners of a square-based pyramid with their axial intersection defining the central point of the object [3]. The angles between the axes, of 80 to 90 degrees, ensure homogeneity of coordinate estimation in three dimensions. At least 4 non-moving targets are placed around the object to provide the cameras with a common reference coordinate system. The planned system will use high speed (500 full frames per second) CCD cameras. For the prototype system, cameras of standard frame rates were used.

The Vision Measurement System (VMS) from Geometric Software P/L was used to design the network for the masonry wall test. The sensor model was a \( \frac{1}{4} \) inch CCD (640 x 480 pixels), with 6-micron square pixels, which is the type of small format sensor used in cameras of frame-rates around 500 per second. The stand-off distance around the test subject was only around 2.5 meters, so a lens of 4 mm focal length was required to completely cover a test wall of 2 m width by 3 m height. Using the network described in Figure 2, and with four control targets around the test object of 0.2 mm accuracy (standard error), the attainable accuracy of measurement on the object points was predicted to be 0.28 mm standard error in any axis.

For the prototype system four CCD cameras (Imaging Source DMK 21BF04) were combined with lenses of 2.3 mm focal length (Computar T 2314 FICS-3). The cameras were synchronised using a Wavetek 182 function generator producing 5 volt TTL square-wave transferred to the external trigger of the cameras using BNC cables. Images were captured using two Firewire PCI boards (two cameras to each board) mounted in one personal computer. Montivision Workbench 3.0 software was configured to capture four channels on an external trigger saving to the computer’s hard-disc as standard JPEG images. The cost of the prototype system was under US$3500.

2.1 Camera calibration

One of the challenges anticipated in the prototype development was the calibration of optical errors in the camera/lens combination. The calibration used the Vision Measurement System (VMS) software. Since the objects would be points, the collinearity equations were employed (equations 1 and 2). These equations relate the camera orientation and location to the object point through the projection of a line from the object point, through the perspective centre of the imaging system, onto the sensor.

\[
x_y = -c_x \times \frac{m_{11} (X_j - X_i) + m_{12} (Y_j - Y_i) + m_{13} (Z_j - Z_i)}{m_{31} (X_j - X_i) + m_{32} (Y_j - Y_i) + m_{33} (Z_j - Z_i)}
\]

\[
y_j = -c_x \times \frac{m_{21} (X_j - X_i) + m_{22} (Y_j - Y_i) + m_{23} (Z_j - Z_i)}{m_{31} (X_j - X_i) + m_{32} (Y_j - Y_i) + m_{33} (Z_j - Z_i)}
\]

where \( x_j \) and \( y_j \) are the image coordinates of point \( i \) in camera \( j \), \( (X_j, Y_j, Z_j) \) are the coordinates of the perspective centre of camera \( j \), and \( m_{11} \) - \( m_{33} \) contain the orientation parameters for rotations between the camera coordinate system and the object coordinate system, \( (X, Y, Z) \) are the coordinates of point \( i \), and \( c \) is the axial distance (principal distance) from the perspective centre to the image plane. In the method of intersection (triaignulation) the parameters of the camera (principal distance, orientation and location) are generally known, and the coordinates of point \( i \) are sought. For these 3 unknowns, a minimum of two cameras is required to give four equations \( (x_{ij}, y_{ij}, x_{kj}, y_{kj}) \), which are then solved in a least-squares solution.

Due to distortion and decentering of lens and camera elements, the collinearity condition is not likely to exist. The left hand sides of the equations are therefore extended to include parameters to model radial and decentering distortion, as well as non-orthogonality and affinity of the sensor plane [4] (equations 3 and 4).

\[
\begin{align*}
(x_j - x_{0j}) + (x_j - x_{0j})^2 dR / r + dx &+ a_1 (y_j - y_{0j}) + a_2 (x_j - x_{0j}) \\
(y_j - y_{0j}) + (y_j - y_{0j})^2 dR / r + dy &
\end{align*}
\]

(3)

where:

\[
dR = k_1 r^3 + k_2 r^5 + k_3 r^7
\]

(5)

\[
dx = p_1 (r^2 + 2 (x_j - x_{0j})) + 2 p_2 (x_j - x_{0j}) (y_j - y_{0j})
\]

(6)

\[
dy = p_3 (r^2 + 2 (y_j - y_{0j})) + 2 p_4 (x_j - x_{0j}) (y_j - y_{0j})
\]

(7)

And the parameter descriptions are given in table 1.

| Table 1 - Additional calibration parameters in the collinearity equations |
|-----------------|-----------------|
| \( x_{0j} \)    | \( x \)-image coordinate of the principal point |
| \( y_{0j} \)    | \( y \)-image coordinate of the principal point |
| \( k_1, k_2, k_3 \) | 3rd-4th and 5th terms of the polynomial for radial distortion |
| \( p_1, p_2 \)  | 1st and 2nd terms of decentering distortion |
| \( a_1 \)       | Orthogonality of the image coordinate system |
| \( a_2 \)       | Affinity of the image coordinate system |

The challenge lay in the relatively cheap construction of the components, and the assumption that, for instance, radial lens distortion would be symmetrical about the optical axis. For each camera, a network of six camera stations was constructed similar to the geometry of Figure 2 with two extra stations midway between the upper and lower station on each side of the ‘pyramid base’. The target field consisted of 20 signalised targets similar to those shown in Figure 4. Three images were collected at each station. The images were upright, 90 degree roll clockwise, and 180 degree roll anti-
clockwise. The roll angles help to decouple the otherwise highly correlated radial distortion parameters. Each object point was measured using centroid computations on the signalised targets, and appeared in every image, giving high redundancy of observation. On completion of the construction of each network, and computation of initial approximations for all of the unknown parameters, an ‘inner constraint’ solution was undertaken, whereby the coordinates of the targets are also allowed to vary. The constraint is therefore based only on the geometry and quality of the observations, which gives the inner, or ‘best’, precision for all parameters. An interesting by-product of this final adjustment is that the residual errors from the model are an unbiased estimate of the quality of the image observations.

The calibrations showed that one of the cameras demonstrated an image measurement accuracy of 0.9 microns, whilst the other three showed accuracies between 3.95 and 5.1 microns. Unable to explain this difference between nominally similar cameras, the calibrations were repeated on another test range using the same network. The results showed the one camera with image measurement accuracy of 0.46 microns (the same camera as before), whilst the others had accuracies between 3.4 and 4.1 microns. Since the test was immanent, the design simulation was altered to these figures giving revised design accuracy for the system of 0.51 mm.

3. EXPERIMENTAL DESIGN

The test specimens for the experiment were two 200 mm concrete block masonry walls, 1 m wide by 1.60 m high (Figure 3). The walls were built in place, on the side beams of the shake frame, and were attached to the frame using two threaded rods grouted in the first course [5]. No other reinforcement was used in the walls, so they were categorised as un-reinforced masonry.

| Image of the experiment showing signalised targets and object coordinate system

For each camera, the six targets were identified in the first image of the video sequence by thresholding a region of interest (ROI) created by the user. Their centroid and bounding box were then computed. Subsequently, the target centroids were tracked in all frames of the video sequence using the cross-correlation method described in [6]: given a target \( T_i \) in image \( i(t) \), neighbourhoods of \( T_i \) in image \( i(t) \) (the template) and in image \( i(t+dt) \) (the ROI) were created using its bounding box. The ROI in image \( i(t+dt) \) must be bigger than the template. Then the best matching neighbourhood was found, i.e. the one that has the smallest energy in the squared difference image. This method was chosen since the amount of the target movement was limited. The four non-moving targets were also identified in all frames of the video sequence for each camera. On the first image, the user created a ROI for these targets. A thresholding within this ROI for each frame was then applied to find the targets and their centroid computed.

3.1 - Sinusoid

The shake frame was programmed with the force signal of a sinusoid of 0.05 Hz, with amplitude of 38 mm. The cameras were triggered at 1 Hz. The initial results of this test are shown in Figure 5.

Since no movement was anticipated for this test in the X and Z axes, there was clearly a problem in the system. The pixel tracking was giving results with a standard deviation of 0.060 pixels (0.37 microns), and the camera pixel positions remained at a standard deviation of 0.095 pixels (0.57 microns) from start to end, indicating their stability over the test.

Figure 3 – Shake frame with test specimen (side view)

The design for the vision system was as shown in Figure 4, where there are four non-moving targets around the test specimen. These targets were to act as the control to determine the orientation and location of the cameras. Figure 4 shows the view from the top left camera (refer to Figure 2). The coordinate system of the control targets was established such that the y-axis of the right-handed system coincided with the axis of the wall in the direction of displacement. The labels show the six signalised points that were tracked over time to produce their trajectory in 3D.
The variable responsible must therefore be the timing of the images. Tests demonstrated that the time of the captures had a random element in the addition of 30 milliseconds or 130 milliseconds without any discernible pattern. An extra image was also sometimes added at a 550-millisecond offset. The time additions appear to be multiples of the exposure time of the cameras (1/32 second). Only one of the cameras collected extra images compared to the other three (6 extra images in 175 seconds). It was relatively straightforward to identify the erroneous images by scaling the tracked pixel locations of that camera and identifying the outliers. Once these were removed the intersection routine was repeated, with the result shown in Figure 6. Only the Y displacement is shown since the other axes had negligible displacements after correction.

The random addition could not be removed, however, and is evident in the increasing separation of the measured and shake-frame command signals (standard deviation of the points in the first cycle is 0.33 mm, and in the last cycle 9.46 mm).

### 3.2 - El-Centro earthquake

The Imperial Valley 1940-05-19 04:37 earthquake had a magnitude of 6.95 on the Richter scale; the epicentre was located at 32.7601° latitude, -115.416° longitude, and at a depth of 8.8 km.

Using the MultiPurpose TestWare (MPT) software, the displacement time history data from the Imperial Valley 5/19/40-04:39, El Centro Array #9, 180 (USGS Station 117), was programmed in the Hydraulic System. The maximum acceleration, velocity and displacement are 0.313g, 298mm/s and 133.2mm respectively. Due to limitations on the maximum displacement capacity of the actuators, the earthquake input signal was modified. The signals maximum displacement was changed to 125 mm.

The vision system was triggered at 5 frames per second. A potentiometer was used to determine the reference displacement of the frame with an accuracy of ±1 mm.
Post-analysis showed capture intervals with random multiples of 160 ms and 260 ms, although 5 frames were collected each second. The result is shown in the offset of the signal in Figures 8 and 9.

Analysing the discrepancies between the extrema of the potentiometer and videogrammetry signals, there was a 0.832 mm average error between the values of maxima and minima. This is surprisingly good considering the low sampling frequency used, and the rate of change of displacement that reaches 60 mm/s in places.

The ability of the system to find out-of-plane movement is demonstrated in Figure 10, where the displacement in X (in m) is plotted against time. The peaks shown are higher than our noise level of approximately 0.3-0.5 mm, and so significant. The differential x-displacement of a point further from the wall foundation is clear.

4. ANALYSIS

1. We are satisfied that the system accuracy is of the order predicted in simulation. The calibrations of the camera / lens combinations were therefore sufficient, although we do not yet know the time-stability of the calibrations.

2. The sinusoid test indicates an accuracy similar to that predicted by the simulated design for an image measurement of 1/10 pixel. This would indicate that the problems with the calibration in terms of estimated image measurement accuracy differences between cameras lies with the calibration network, or the calibration software.

3. The camera captures were synchronised and collected the number of frames required per second, but the time intervals were seemingly random multiple of the exposure time for the cameras. This caused unpredictable shifts in the measurement times. The synchronising signal passed to the cameras was as specified by the camera manufacturer. It was not a storage issue since the storage rate was only 260 kb per second, and the problem was evident in a single camera capture at this rate.

4. The tracking of the targets was sufficient for the test masonry wall moving in a single axial direction. Further development for more complex movements is planned.

5. CONCLUSIONS

A prototype vision system was developed to test the concept of videogrammetry in the monitoring of civil engineering structures. The accuracy of the calibrated system using signalised points was tested and found to be of the same order as a simulated design for the system based on constraints of test object dimension and available stand-off distance from the object. Synchronisation remains the biggest issue facing the use of such a system. Nevertheless, the advantages to be derived from this non-contact, three dimensional, full-field method have been shown to be possible to implement. The full system will be developed based on the lessons learned using the prototype.

REFERENCES


