Computer Vision Based Displacement Measurement of Shake Table

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Abstract
In our surroundings, many things move from one place to another; some displace significantly, others only execute a small motion. When it comes to motion estimation, it is easier to quantify large displacements whereas small movements like facial expressions etc. are relatively difficult to detect and measure. Mark Dow at University of Oregon Brain Development Laboratory in February 2009 [1] devised an algorithm to estimate complex small motions in scenes. The algorithm sums pixel wise difference between frames to estimate motion. The proposed framework uses the core of this algorithm to estimate strength of a building structure in laboratory. The framework is a computer vision based and can be used to estimate automatic variation in the building displacement before going it falls. Conventional methods use LVDT Transducers which are expensive and consume much human involvement. The proposed framework was tested using several synthetic data sets and two real data sets taken from shake table installed in an Earthquake laboratory. The algorithm is currently applied for post processing of the data obtained from laboratory; however, it performs fast enough to be used for real-time monitoring of concrete structures like bridges, dams etc.

Index Terms
Shake Table, LVDT

1. Introduction

Even in this 21st century, where, on one hand man claims to rule the universe, exploring skies and travelling the deepest end of the earth; he has not been able to escape natural disasters like earthquakes. The focus from stopping such calamities has therefore shifted towards reducing the number of losses it can cause. Following some basic principles at the time of structure development can reduce the risk factor at the time of earthquake. Many of the past earthquakes wouldn't have cost that much damage to human life as it did, if only the structure designing was up to the standards.

With the concept surfaced that strong structures should be designed, a new area of concern emerged; the testing of these structures before any claim could be made on their strength. Several sensors for structural testing emerged as a result. LVDT (Linear Variable Displacement Transducer) is the most commonly used sensor.

Structural displacement sensors LVDT and dial gauges, are often used to find building displacement while in vibration. They are flexible for measuring displacement and satisfy the resolution requirement for structural testing. However they require a stationary platform which usually has to be close to the structure because the sensor is relatively small in size compared to the size of the structure; but at the same time they must be mounted at a safe distance from the building to avoid any damage to them. To tackle this issue, wire-connection devices are often used at a possible loss of accuracy. LVDTs and their rotary counterpart (RVDTs) use the principle of magnetic induction to determine position. Both require signal conditioning, which can add to cost. Also, these sensors must be accurately aligned inside heavy, expensive packaging and contain wound coils that are expensive to manufacture. LVDTs are sensitive to temperature and cannot be used for longer measurements. They are also not perfectly linear and are commonly used for steady-state and low-frequency vibration.

Successful implementation demands accurate and precise alignment.

Besides LVDT, some promising advanced sensors emerged in the meantime. Examples are Global Positioning System (GPS) [4] [6] [5] [7] and Laser Doppler vibrometer [8]. The use of GPS at the level of resolution we require for building strength measurement is a very expensive proposition. The Laser Doppler vibrometers perform very well but they are also expensive and the laser intensity may become dangerously strong for the distance we envision for remote sensing. Double integration of an acceleration record is a rather unreliable method to obtain a corresponding displacement record even when we use super-precision accelerometers, which by itself is an expensive proposition [10] [9]. Indeed, there is no cost-effective displacement sensor system to remotely measure the displacement of large structures,

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which is reliable, accurate, easy to use, and have real-time capability than the proposed vision-based approach.

This paper focuses on the research and development of a new measurement system to examine fracturing process of concrete structures that are tested in lab using digital image processing techniques. This technique is highly cost effective and easy to implement, but still maintains the advantages of measuring displacement with good resolution. The fundamental measurement accuracy and effectiveness of the measurement system has been confirmed from several tests on synthetic datasets. The performance is finally evaluated by measuring displacement of the building structure and shake table. All experimental work was done in Earthquake department of N.E.D. University, Karachi, Pakistan.

2. Past techniques used for displacement measurement using image processing

Several image processing techniques have been proposed in past to determine structure displacement.

Lee and Shinozuka proposed a vision-based technique [11] for structure strength measurement based on texture recognition algorithm. This approach begins with marking the measurement point first with a target panel of known geometry. A commercial digital video camera possessing a telescopic lens is considered as a fixed point and is installed at a location away from the bridge. A motion picture of the target is then taken with the help of the video camera. Image processing techniques which involve texture recognition algorithm, projection of the captured image, estimation of the actual displacement using target geometry and the number of pixels moved, were employed to calculate the motion of the target. The paper [11] discusses applying this technology to a large suspension bridge.

Another research was carried out by National Research Institute for Earth Science and Disaster Prevention in Japan [12]. This study proposed the development of a three-dimensional measurement method using an image processing technique to measure the dynamic displacement in shake table test. The main technique used is similar to the J.J.Lee's technique used above that is taking markers on the object of interest and tracing the displacement of these markers to find out the displacement of the moving object. A CCD camera was used in order to capture the dynamic behavior of the marker on the shake table. The marker used for the shake table test was an LED marker having a spherical diameter of 70mm and seventeen red LEDs were placed on it. The method determined the three dimensional dynamic behavior of the shake table in terms of displacement in X, Y and Z directions. However, the measurement error was several millimeters.

[13] Proposed a method for measuring the displacement of vibration of piping structure using image processing. The technique started with marking multiple points on the beam and a camera was used to capture video of these points from a great distance. The recorded images were first converted to grey scale images. Multiple Points in an image were separated using dilation and erosion technique. To estimate the displacement of vibration of these multiple points, a pattern recognition K-means algorithm was used.

3. Proposed framework

The image processing techniques for structure displacement measurement discussed above and most other techniques that exists use markers and measure displacement of these markers through some block matching approach for determining structure displacement. However, there are some limitations associated with using block matching. For very small motion for example the motion of an ordinary building structure while fracturing cannot be precisely determined using block matching of a certain marked point, unless a very high camera were also attached with the building to record building displacement and their output was averaged and taken as a reference for comparison with Image processing results. The Figure 1 shows the experimental set up. It was examined that the maximum displacement produced in the building before it was demolished was only a few (maximum 3 to 4) pixels. Therefore, experimental work done with using block matching and optical flow techniques to measure building displacement did not produce desired results when compared to the LVDT data.

Therefore, an algorithm efficient enough to measure small motions was desired. The algorithm "Estimation of total motion based on absolute differences between frames, without respect to the direction of motion that causes differences" by University of Oregon Brain Development Laboratory created on March 5, 2009 [14] claims to detect complex small motion in scenes. The core of this algorithm was used as the building block of the algorithm which has been used in this project to determine displacement of the structure. This algorithm is the simplest and the fastest among all motion estimation algorithms as it does not require scanning of the entire image for a possible match and yet it produces precise results. Moreover, there is no need to have a marker on the moving object and the solution is general and can be applied on a large scale of civil structures such as building, bridges, beams etc.

In the first phase of the algorithm, video frames are converted to gray scale images and filtered using Gaussian filtering to remove noise due to lighting changes [17]. Then background subtraction is done using Pixel Difference. Pixel Difference also called Frame

Differencing background subtraction techniques compare each video frame against a reference frame; pixels that deviate significantly from the corresponding reference frame pixels above a certain threshold are considered to be foreground (moving object) pixels [15] [16]. Recall the simple translational model, if there is no motion then,

$$I_n(x) = I_{n-1}(x) + e(x) \quad (1)$$

A displacement function d is projected in the above model as:

$$I_n(x) = I_{n-1}(x + dn,n-1) + e(x) \quad (2)$$

In 2D image plane $x = [i, j]$ and $d_{n,n-1} = [dx, dy]$, equation (2) can be written as:

$$I_n(i, j) = I_{n-1}(i + dx, j + dy) + e(i, j)$$

It is expected that intensity variation $|e(\cdot)|$ will be small where $d = 0$ but high where $d \neq 0$. Therefore, we can detect motion by measuring the pixel difference (PD):

$$\text{Pixel Difference} = | I_n(x) - I_{n-1}(x) |$$

The PD is then thresholded to detect motion. Assuming that motion is detected at a site where $m(x) = 1$, the motion detector can be written as:

$$m(x) = \begin{cases} 1 & \text{if } | I_n(x) - I_{n-1}(x) | > E_t \\ 0 & otherwise \end{cases}$$

where E_t is the threshold intensity difference used to flag motion.

Motion estimation is done to find the motion (displacement) produced in the structure in terms of the total pixels moved. An advantage of this algorithm is that the motion is estimated the same time at which the background is subtracted and no additional image processing is required to find motion, so algorithm performs really fast. Since it is fast, it is appropriate for real time processing and comparable to parallel processing methods both in software and hardware.

In the last phase, displacement in unit of pixels is transformed to the actual real world displacement in engineering unit of distance. A simple relationship can be given as:

$$x_p = x_i \times k \quad (3)$$

where,

x_p = real 3D world physical displacement in millimeters (mm)

x_i = normalized value of displacement in the image plane

k = transformation constant.

By experimentation and comparison, it is found that the transformation factor for positive lobes is 0.14091/128 and the transformation factor for negative lobes is -0.14091/128. The transformation factor remains the same as long as the camera position remains fixed

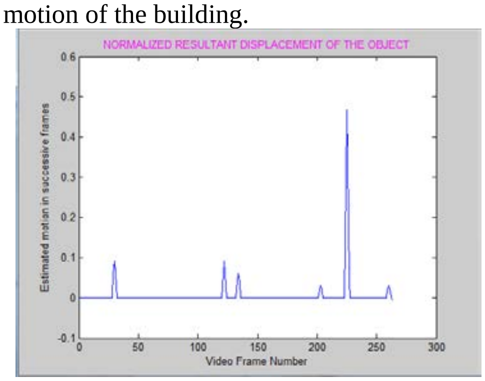
Figure 1: Experimental Setup

A. Finding Building Displacement

When finding building displacement using this technique, first a proper threshold was set. To set a proper threshold a segment of the video was taken where there was no motion of the building. The algorithm should also give a zero resultant displacement for this section of the video. Figure 2(a) shows that when threshold is set at 10, there remains some noise although the building is stationary. However when the threshold is increased to a value of 20, the noise is entirely removed as shown in figure 42(b). Hence a threshold value of 20 was selected.

B. Horizontal and vertical displacement of the building

The algorithm was applied on the sequence. The motion of the building is oscillatory so a single cropping rectangle was selected which defines the region of motion of the building. Since the building is a rigid body so motion estimation at one portion of the building would be equal to actual motion of the building.



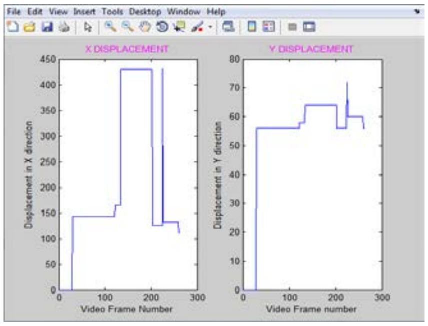


Figure 2 (a): Threshold set at 10 for building vibration video

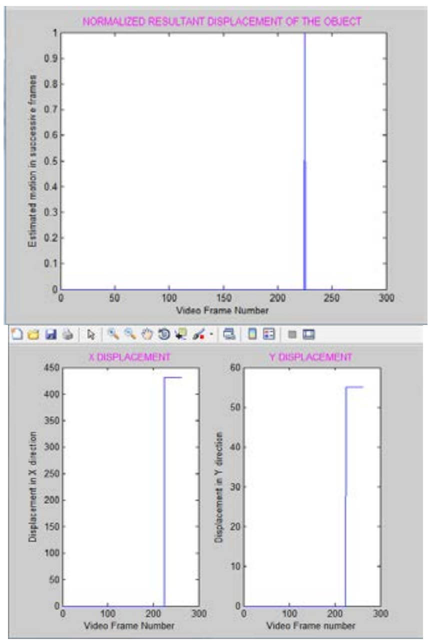


Figure 2 (b): Threshold set at 20 for building vibration video

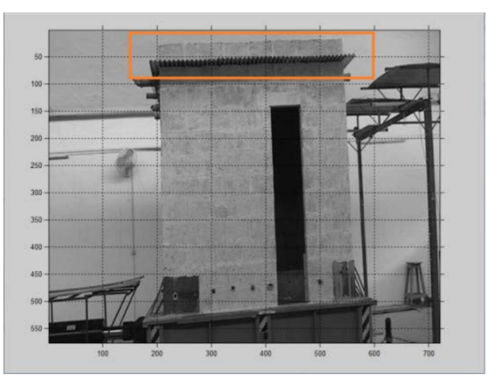


Figure 3: Full Frame of the building with cropping rectangle shown

C. Total motion estimation

LVDT data taken from two LVDT channels was averaged and normalized so that it can be plotted against the data obtained from image processing algorithm and the results could be compared. The graph in Figure 4 below shows the comparison between the two results.

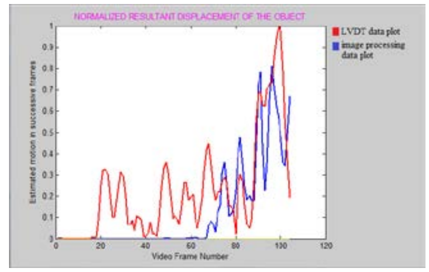


Figure 4: normalized resultant displacement of the building

The results obtained from LVDT were very noisy as is clear from the graph above. This could be because the displacement of the building is very small which is more likely to be affected by the noise in the surroundings. Hence, this cannot be used as a good reference for the image processing algorithm verification. The displacement of the building from its reference position in terms of pixels is shown in the figure below:

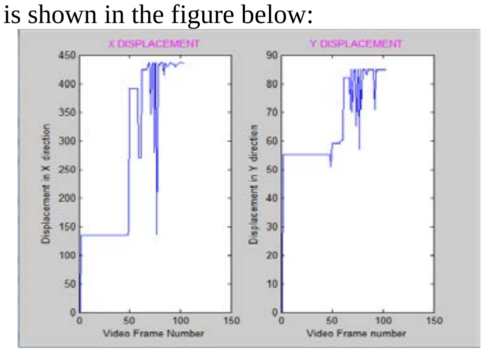


Figure 5: X and Y displacement of the building

It is also clear from the above graph that the displacement in X and Y direction is very small and mostly dominated by noise. Hence for small motion, it is better to refer to the resultant displacement estimation curve which filters out most of the noise since the resultant displacement estimation considers all the pixels which are moving instead of considering the pixel at a particular point.

The total estimation graphical representation is graphically shown in the Figure 6. It shows which pixels in the picture actually moved.

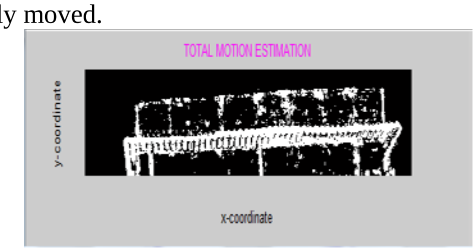


Figure 6: Total motion estimation of the building (pictorial representation)

D. Experimenting with finding shake table displacement

Since the LVDT data obtained from building vibration experiment was very noisy and also the duration between the time building started to shake and the time it got demolished was very small so a promising decision could not be made upon the results of image processing algorithm after they were compared with this LVDT data. Hence, another experiment was performed; this time with no building but instead shake table was taken as the moving object.

Shake table was vibrated 10 times to and fro. Two LVDTs were attached to it to take readings of its displacement with time. For imaging system, camera was positioned at a safe distance from the shake table and was fixed so that it remains stationary. Video of the shaking table was processed after taking a suitable crop rectangle as shown in the Figure 7with the above algorithm to yield the results of shake table motion estimation.

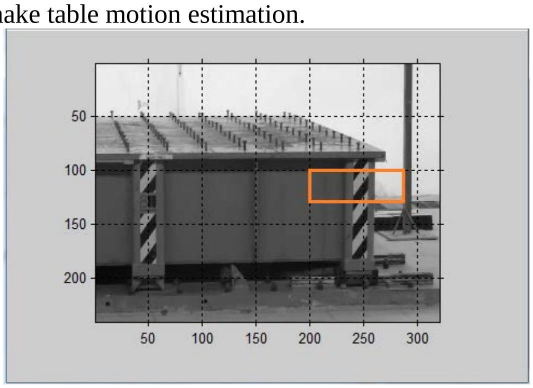


Figure 7: Full Frame of the shake table with cropping rectangle shown

E. X and Y displacement of the building

The estimated X and Y displacement of the building from the image processing method is shown in the Figure 8. The displacement in Y direction is zero as the building only displaces in X-direction and the graph also shows almost zero Y displacement with some added noise component. The displacement in X direction however is very smooth and it clearly shows 10 cycles of oscillation of uniform magnitude which is in accordance with the set experiment conditions.

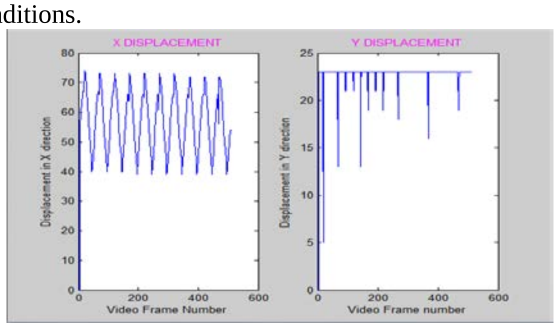


Figure 8: X and Y displacement of the shake table

The data taken from LVDT channel 1 was absoluted, normalized and plotted with normalized resultant displacement data from image processing algorithm. The Figure 10 shows the results. The two graphs almost completely overlap with each other. This shows that Image Processing can be rightly used as an alternate to the traditional LVDT sensors for measuring displacement.

F. Total motion estimation

Now the data from second LVDT is taken, made absolute, normalized and plotted with the same Image processing data as shown in Figure 9. The data obtained from this LVDT channel is very noisy as shown in Figure 10. Hence, if such as LVDT is used for structure displacement measurement then the results are most likely to deviate from their true values and will have a big margin for error. Hence LVDT due to aging and noise in surrounding may produce noisy results, whereas, this digital solution is free from all such limitations since the software will not be affected by aging and the noise factor for image processing solution can also be easily controlled by keeping the camera fixed at one position and avoiding any extreme light intensity variations. Hence it is clear that the image processing solution gives a consistently accurate result for all the experiments done above. And it even provides good results even when the LVDT fails to do so. Hence, it can be concluded that image processing used for building displacement provides comparable, in fact a better solution than a traditional LVDT.

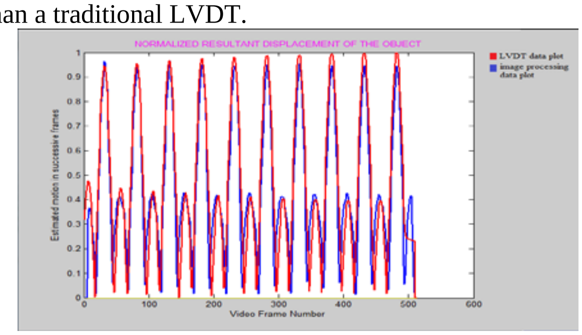


Figure 9: normalized resultant displacement of the Shake table (data taken from LVDT channel1 and image processing algorithm)

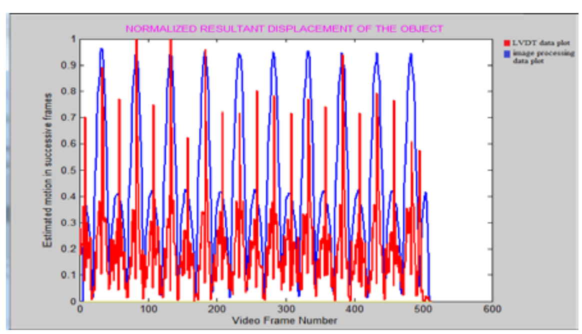


Figure 10: normalized resultant displacement of the Shake table (data taken from LVDT channel2 and image processing algorithm)

4. Conclusion and future work

The transformation to real world displacement can be found by the *transformation constant*. The *transformation constant* is found by comparing the results of image processing and LVDT channel 1 data which is shown above. A simple relationship is given in equation (3)

Eq.(3) $x_p = x_i \text{ x } k$

with transformation constant = 0.14091.

Some more experimentation could be done with testing this algorithm in different areas like finding speed of a moving vehicle, analysis of cracks in concrete beams, bridges etc. X and Y displacement can be more worked upon to make up smooth and noise free even for oscillatory motion. The area of transforming image plane values to real physical world values can also be further evaluated and improved.

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