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Field investigation of contactless displacement measurement using computer vision systems for civil engineering applications

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Abstract

Much of the bridge stock on major transport links in North America and Europe was constructed in the 1950s and 1960s and has since deteriorated or is carrying loads far in excess of the original design loads. Structural Health Monitoring Systems (SHM) can provide valuable information on the bridge capacity but the application of such systems is currently limited by access and bridge type. This paper investigates the use of computer vision systems for SHM. A series of field tests have been carried out to test the accuracy of displacement measurements using contactless methods. A video image of each test was processed using a modified version of the optical flow tracking method to track displacement. These results have been validated with an established measurement method using linear variable differential transformers (LVDTs). The results obtained from the algorithm provided an accurate comparison with the validation measurements. The calculated displacements agree within 2% of the verified LVDT measurements, a number of post processing methods were then applied to attempt to reduce this error.

Keywords: Digital Image Correlation, Camera based Monitoring, Structural Health Monitoring

1 Introduction

This paper investigates the use of computer vision systems for Civil Engineering applications, in particular Structural Health Monitoring (SHM). In essence the goal of SHM is to infer information about the condition or health of a structure by analysing data (often displacement or its time domain derivatives) collected on the structure, and where necessary make appropriate repairs. In the long term, monitoring with cameras is expected to be more broadly utilised for structural engineering purposes because of its potential for inexpensive deployment in real life bridges. Essentially installing sensors on active bridges is logistically difficult and expensive, therefore contactless camera based monitoring is potentially a very useful tool.

A recent example of vision based systems being applied to bridge monitoring is from [Ojio et al., 2016]. In their study a series of vehicles of known weight passing over a bridge were used to determine that changes to deflection can be used a measure of changes to bridge stiffness. In this paper, a set of field trials were carried out to determine the level of accuracy in deflection measurement using a non-contact camera monitoring system. A digital camera was set up to monitor this test and the resulting video images were post-processed to calculate displacements. A modified version of the Kanade-Lucas-Tomasi (KLT) optical flow algorithm [Tomasi and Kanade, 1991] was used to track deflections of the specimen, with these results validated using conventional displacement measurement techniques, such as linear variable displacement transformers (LVDT). The results from directly above the LVDT were compared to readings taken at locations on either side of the LVDT and plotted on a quadratic curve function. In future similar procedures could potentially be used to monitor structural changes in existing buildings and monuments without the need for physical

contact. This novel technique provides simplicity in deployment compared to traditional structural assessment methods which require access and sensor installation. This method is more cost-effective as the response will be measured without any need for sensors attached to the structure overcoming access problems.

2 State of the Art

The methods used for tracking features in a series of images can be categorised under two different headings, optical and normalised cross correlation.

2.1 Normalised Cross Correlation

For this approach, the region of interest (ROI) was defined and then treated as a sub image of the principal image in the sequence. This method is a coarse fine approach to obtain a pixel level displacement. It is performed by mapping the reference sub image on the deformed sub-image. The normalised cross correlation matrix of the two images is then calculated by the use of the `mormxcorr2` [Lewis, 1995] function in Matlab. The peak of this matrix occurs where the sub images are best correlated. If there is a difference in peak locations, the ROI has been displaced and a graph tracking this change can be plotted.

2.2 Optical Flow

The Optical flow (OF) technique is used to calculate an approximation of 3D velocities onto the imaging surface, 2D motion field, using spatiotemporal patterns of images. The surface deflection is extracted by identifying features on the test specimen then tracking them through successive image frames. For the computational time be practical for field usage it is recommended that a region of interest (ROI) is specified in which to extract and track features[Fukuda et al., 2010]. In this study, it was decided that a modified version of the optical flow algorithm would be used to calculate displacements of the test specimen due to its enhanced running time and similar level of accuracy to normalised cross correlation. The method used to extract the features for tracking in this test series was the Harris-Stephens corner and edge detector.

2.2.1 Harris Features

This method uses a combination of edge and corner features to determine points of interest. It measures changes in pixel intensity across an image using an autocorrelation function, and determines the quality and number of edge-corner features in an image[Harris and Stephens, 1988].

The Kanade-Lucas-Tomasi (KLT) algorithm takes the features extracted by the above approaches and constructs a window (W) based on the points. It then compares each image in a sequence, and tracks the displacement of W through these images and maps it to an affine transformation T. This transformation can then be plotted using Matlab and the displacement of our ROI determined.

2.3 Computer Vision Algorithms Commonly used in Civil Engineering

Approaches for Computer vision in SHM can be broken down into several methodologies, which are detailed in the sections below.

2.3.1 Hybrid Camera-Sensor Approaches

Previous research has demonstrated the feasibility of integrating imaging devices with traditional SHM technology [Zaurin and Catbas, 2010]. This method involves using the computer vision to monitor bridge traffic, while an LVDT is mounted to the bottom of the bridge to measure deflection readings. Another system was laid out in [Yan et al., 2008] where readings from a strain gauge were linked video images of vehicles passing over a test bed setup in order to classify the vehicles into 7 different classes.

2.3.2 Target based Camera only approaches

Replacing the traditional sensors such as LVDT/accelerometers with cameras for measuring displacement is the logical next step in this area. Early work in the field involved the use of a target based system for locating features to be tracked on a bridge as it was not possible to extract targets for tracking from natural features. The study detailed in [Shih and Sung, 2013] compared Digital Image Correlation (DIC) readings to verified measurements from accelerometers that had been attached to the test specimen. Additional work was carried out in the field by [Lee and Shinozuka, 2006] with comparable results to LVDT.

2.3.3 Natural Features based Camera only approaches

With dramatic improvements in commercially available digital cameras, it is becoming increasingly possible to develop computer vision systems for deflection monitoring using natural features of the bridge structure. This would enable DIC to be a non-contact full field measurement of displacement system, hence overcoming the access limitations of existing SHM systems. Work has been done in this area by [Feng et al., 2015, Malesa et al., 2010] using differing methods of deflection calculation, with no clear optimal method as of yet being established.

3 EXPERIMENTAL STUDIES

This section describes the methodology employed to experimentally assess the performance, i.e. the sensitivity and accuracy of the optical method in measuring displacement.

3.1 Test Setup

A full scale experimental investigation was carried out at Banagher Precast Concrete Ltd, Co Offaly on a 10m long concrete floor slab which was prestressed with basalt reinforcing bars. The slab was cast on the 22nd of January 2016 and allowed to cure for over 40 days. The slab was then tested on the 16th of March 2016. The slab member was simply supported and the load is applied at mid-span by a +300 mm stroke mono-directional hydraulic jack counteracting on a strong steel reaction frame. A steel repartition box beam was placed in between the jack and the slab.



Figure 1: Testing Rig



Figure 2: Camera Location

Figure 1 shows a picture of the test rig. Three linear variable displacement transducers (LVDT) were placed at the mid-span section, one in the centre and two at the edges. Two additional analogic displacement transducers were placed at about 800 mm from the edges to be able to clear the mid-span deflection from the shortening of the timber slats. A manually controlled hydraulic pump provided with an analogic pressure gauge supplied the pressurised oil to the ram. A Nikon 810 camera was set up 6m from the beam to provide a means of determining the slab deflection using fully contactless methods, as shown in Figure 2.

3.2 Testing Plan

A series of loading cycles were carried out on the slab, the details have been presented in table 1. A load of 10bar was applied to investigate the precracking behaviour; the load was then increased to induce cracking, and finally the load was then increased to failure of the specimen.

Test Number	Pressure applied(bars)	Notes	LVDT
1	0-10-0	Video and photo	YES
2	0-10-0	Video	YES
3	0-30-0	video	YES
4	0-30-0	photo	YES
5	0-30-0	photo	YES
6	0-35-0	video	YES
7	0-40-0	photo	YES
8	0-40-0	photo	YES
9	0-50-0	photo/video	YES
10	0-50-0	photo	YES
11	0-58-0	photo	NO
12	0-58-0	photo	NO
13	0-62-0	video	NO

Table 1: Test Details.

3.3 Algorithm Development

The code used for the calculation of the deflection is based on a modified version of a face tracking algorithm contained in the Image Processing toolbox of Matlab. The Harris feature extraction method was used to find the features to be tracked through the video. A ruler was attached to the test specimen in order to give a pixel-mm calibration for the deflection plots. Affixing the ruler will give an accurate calibration factor for pixel-mm conversion, however a system for determining pixel values based on focal length of camera/distance from target is currently being developed in order to present a truly contactless approach. An area directly above the LVDT was chosen for feature extraction, and the 40 strongest features were chosen to be followed. Once these values had been tracked throughout the series of frames, the Euclidean distance between the features in the original reference frame and each subsequent frame was calculated and averaged over the number of points, with the resulting values plotted in the graphs below.

4 Results

The results for Test 2 are shown in Figure 3, both the LVDT and camera based data have been included. The graph validates that the camera based monitoring corresponds to the established LVDT measurements. The result from the camera based monitoring are continuous for the test duration, however the LVDT readings have been taken at discrete times during the test, the markers indicate the actual readings. An optical flow algorithm has been used for the post processing of the test videos; the graph shows the LVDT recorded a maximum deflection of 3.044mm compared to a calculated deflection of 2.98mm from the vision based method. As the error was less than 2% the vision based method has been validated as a viable method of measuring deflection and the results from the other tests confirm this correlation. In an attempt to reduce the error below 2% a number of different post processing methods were then applied to the video image from test 3. As previously stated the optical flow algorithm requires a ROI to be chosen for analysis, the results presented in Figure 3 were determined for a ROI directly above the LVDT location but the following results have been determined by various methods from the ROI highlighted in Figure 4 with ROI3 being located directly over the LVDT. Initially the results from ROI 1,2,4 & 5 were averaged, they were subsequently plotted on a graph and a 3rd

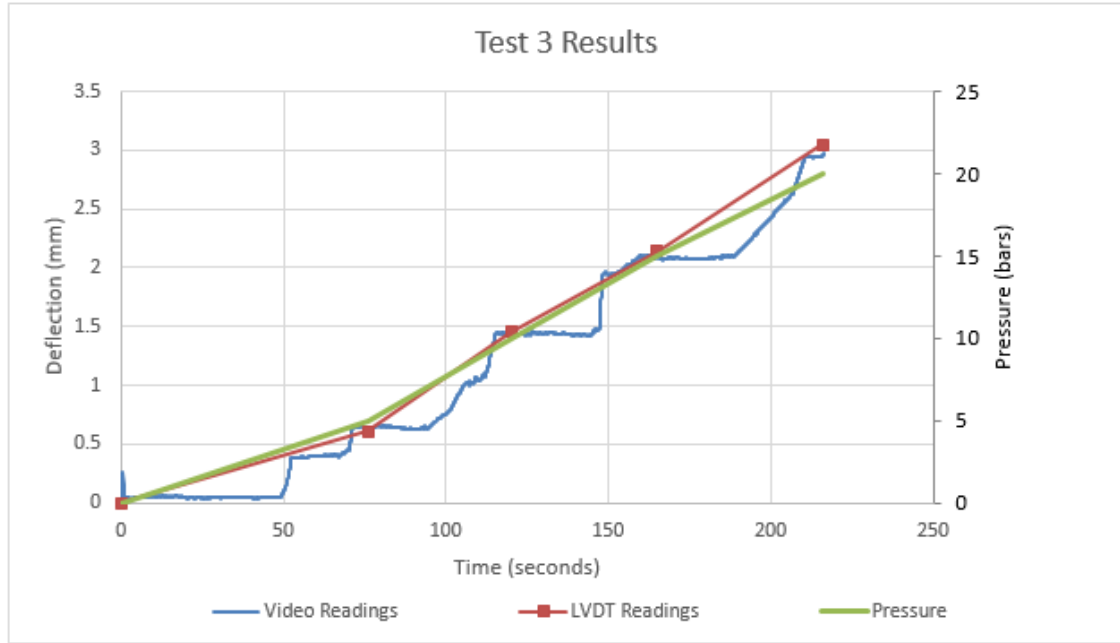


Figure 3: Test 2 Results

order polynomial trend line was added to determine the midpoint deflection. The results for the maximum deflection are presented in Table 2.

ROI	Vision	LVDT	Error
Above LVDT	2.99	3.04	2%
Average 1,2,4 & 5	3.00	3.04	2%
Polynomial	2.99	3.04	2%

Table 2: Calculated Deflections(mm).

The data in Table 2 shows that an error still exists between the LVDT and camera based deflections, the most accurate calculated deflection was determined from ROI 3(the region directly above the LVDT), where a vision based deflection of 3.03mm was calculated eliminating the error. Based on this it was assumed that since the camera was not perpendicular to the test specimen the accuracy of pixel to mm calibration was inversely proportional to the distance between the ROI and the ruler. Further modifications were then carried out to attempt to minimise this error, the post processing algorithm was then adjusted to compensate for this by applying a normalisation factor to the x coordinates of the measured deflection points. Deflections from the 5 ROI were then recalculated and the results are presented in Table 3. The data in Tables 2 and 3 confirm that the tested method did not



Figure 4: ROI Locations.

ROI	Vision	LVDT	Error
Above LVDT	2.95	3.04	3%
Average 1,2,4 & 5	2.96	3.04	3%
Polynomial	2.95	3.04	3%

Table 3: Calculated Deflections after Perspective Correction(mm).

improve the accuracy of the deflection calculation, based on all of the findings included in this paper it has been

determined that the most accurate deflection calculation can be detected by locating the reference measurement scale close to the desired ROI. Future work is now underway to quantify the effect of varying the camera angle in relation to the test specimen. A series of lab trials will be used and the findings will then be applied to the monitoring of a real bridge structure on our regional road network. These initial trials have indicated that camera based monitoring has the potential to provide accurate deflection measurements and can be used as a suitable alternative to LVDTs. The applicability of this can be seen in the data obtained from the two fail tests in this experimental program. During tests 12 & 13 the LVDTs were removed from the test set up as there was a risk of total failure which would result in critical damage to the equipment. However as the deflection measurements were still of significant interest the vision based monitoring was carried out during these tests. The results for test 12 have been presented in Figure 5.

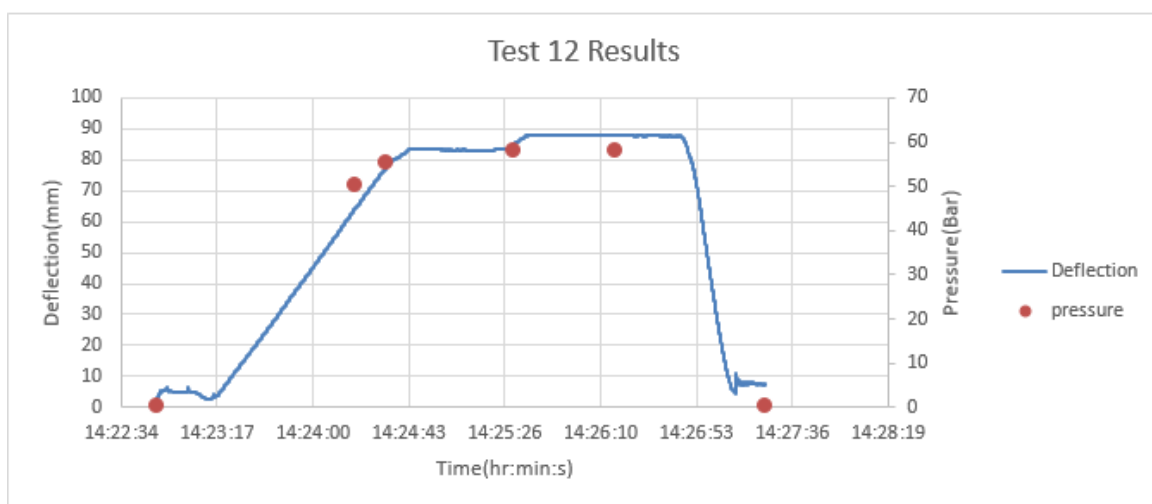


Figure 5: Test 12 Results

5 Conclusions

The results presented in this report confirm vision based monitoring to be a viable method of tracking deflection. This approach has been validated and provided results in a testing situation which would not have been possible using LVDTs. Based on the application of vision based measurement across other engineering disciplines significant further work is now required to realise the full potential of vision based monitoring for civil and structural applications.

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