DEVELOPMENT AND TESTING OF A COMPUTER VISION BASED METHOD OF DISPLACEMENT MONITORING ON REAL WORLD BRIDGE STRUCTURES

[1]DARRAGH LYDON, [2]SU TAYLOR, [3]MYRA LYDON

School of Natural and Built Environment, Queens University Belfast, Northern Ireland
E-mail: [1]D.Lydon@qub.ac.uk, [2]S.E.Taylor@qub.ac.uk, [3]M.Lydon@qub.ac.uk

Abstract - Structural Health Monitoring (SHM) techniques can provide vital information on the performance and capacity of new and existing structures. Generally sensors are embedded or surface mounted to assess the integrity of the structure and provide a means of damage detection or failure prediction. However, existing systems are limited by the need for contact with the structure and demand onerous set up procedures. The lack of a permanent power supply on rural site adds an additional limitation to many existing systems. This paper details the development and testing of a fully portable vision based SHM system. Standard DSLR cameras along with adapted digital image correlation methods are utilized to measure deflections and associate the response to live loading. A series of laboratory investigations have been carried out at Queens University Belfast to develop and validate this system as a viable means of displacement measurement. The system was subsequently trialed at two bridge sites in Northern Ireland, a 20m span truss bridge and a 7m span masonry arch bridge. In each case the structures were identified as showing significant signs of deterioration and the outcome of visual inspections highlighted concerns for the asset owners. Existing SHM systems were not feasible due to access, power and cost limitations, the vision based system allowed for rapid site deployment and real time monitoring of the structures under live loading. The results obtained on site were then compared with theoretical analysis methods to determine the true structural condition.

Index Terms - Computer Vision, Displacement Monitoring, Field Verification,Structural Health Monitoring.

I. INTRODUCTION

Structural Health monitoring (SHM) senor systems are used to monitor deterioration and provide real information on the capacity of individual structures, hence extending life and improving safety. Changes in stiffness are usually measured using strain sensors, but recent research has indicated that measuring displacement changes from repeated known loading can provide an effective means of determining structural condition (Ojio et al. 2016).

This paper investigates the use of computer vision systems for displacement measurement for SHM. 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. While advancing the knowledge by integrating multidisciplinary concepts from theory to application, this research will have direct benefits in areas such as civil infrastructure monitoring which has become a critical societal concern from safety and cost perspectives.

The engineering challenge is significant as structural assets across the country reach the end of their intended operational life, placing an enormous degree of responsibility on structural engineers. The structural behaviour of this infrastructure is randomised due to environmental uncertainties. Successful damage detection from existing sensor based SHM systems is limited by determination of optimum sensor locations. Computer vison systems offer a promising alternative by providing a global analysis of the structure which can be used to determine critical changes in terms of crack propagation or material stiffness.

The initial development and validation of this system has been carried out through a series of laboratory trials proving this concept of non-contact monitoring. The multidisciplinary field of computer vision is developing rapidly and this research validates its applicability for SHM by replacing traditional sensor systems.

A. Background on Computer Vision Algorithms

In recent years camera based monitoring has been introduced to SHM systems, in early applications displacement of several centimetres have been accurately measured by monitoring targets fixed to the bridge [2].
Previous research has highlighted the potential for the integration of imaging devices with traditional SHM technology [3]. Many other SHM applications exist whereby camera based technology is used in conjunction with other sensor types [4-6].

Challenges relating to surface damage of structures have also been addressed using vision based methods [7-9]. Computer vison involves analysing images to determine changing properties of their content. Digital image correlation (DIC) was first proposed by Chu [10] and is now increasing in popularity across science and engineering disciplines. With dramatic improvements in commercially available digital

cameras it is becoming a versatile and cost effective analysis method.
DIC enables non-contact full field measurements of displacements, hence overcoming the access limitations of existing SHM systems. Other non-contact SHM methods based on microwave interferometry can provide an accurate solution for monitoring structures where access is an issue [11].

There have been significant advances in both SHM and image processing techniques unfortunately these systems are not heavily utilized in practice. The most significant limiting factors are cost and complex system installation requirements.
The objective of this research is to develop a low cost non-contact SHM system using commercially available cameras. The data collected is then post-processed to determine structural displacement which will in turn be used as a damage indicator for the structure. A series of laboratory trials have been carried out to develop algorithms for displacement measure prior to field applications.

II. ALGORITHM DEVELOPMENT AND TESTING

The computer vision algorithm was developed via a four step process as detailed in this section.

1) Camera Calibration

This step involves obtaining information about the intrinsic and extrinsic parameters of the camera used for testing, in order to accurately convert from pixel units to engineering units. This can range from simply using a reference measurement placed in the field of view of the camera to usage of a camera calibration pattern as developed by (Bouguet 2015).

2) Image Registration

This step involves identifying the elements of the images that will be tracked through the video sequence. The possible elements can be colour based, template based or feature based. The algorithm for this test series used the BRISK feature extraction method. A brief summary of the mechanics of several prominent feature based methods is shown in Table I.

Table I Feature Based Methods Description

Algorithm Name	Method
FAST	Combination of point-based and edge-based tracking systems.
Harris- Stephens	Comparison of Intensity Values in the neighbouring pixels.
SIFT	Difference of Gaussian Method to determine potential interest points.
SURF	Second Order Gaussian partial derivations combined with interval images.
FREAK	Cascade of binary strings is computed by efficiently comparing image intensities.
BRISK	Scale-space FAST Based detector in combination with the assembly of a bit-string descriptor from intensity comparisons.

3) Tracking

Once the features to be tracked have been identified, the algorithm uses a Kanade-Lucas-Tomasi(KLT)(Tomasi & Kanade 1991) tracking method to determine the location of the points in subsequent frames.

This algorithm works by generating an image pyramid, where each level is down-sampled by a factor of two in width and height. The point tracker begins tracking each point in the lowest resolution level and continues tracking until all levels have been checked.

4) Displacement Calculation

The final step of the process is to calculate the movement of the points throughout the video by calculating the Euclidean distance between the location of the features in the first frame of the video and in subsequent frames, this algorithm will be referred to as QUBDisp.

IV. LABORATORY TESTING

A. Steel Beam Testing Series

A series of laboratory trials were carried out to determine the level of accuracy in deflection measurement in a controlled environment using our non-contact camera monitoring system. A Nikon D5300 DSLR camera was set up to monitor a set of laboratory experiments. A Linear Variable Differential Transducer (LVDT) and a mechanical dial gauge were used to verify the results obtained from the tests.

A steel beam was simply supported under an accurately calibrated 600kN capacity hydraulic actuator in the laboratory as shown in Fig. 1.



Fig. 1 Test Setup for Initial Performance Trial

The details of the beam used for the testing are displayed in Table II.

Table II Detail of Steel Beam for Initial Concept Trial

Specification	Detail
Breadth	48mm
Depth	24mm
Modulus of Elasticity	2.05 x 10^5 n/mm^2
Area	1152mm

A speckle pattern was applied to the surface of the beam to provide features with enhanced contrast for the extraction portion of QUBDisp. A series of loading cycles were carried out on the beam. A deflection of 3mm was applied using stroke control at varying rates by the test rig, readings from the dial gauge were extracted from the video at a rate of 2hz. The results from a load cycle is shown in Fig. 2, the Root Mean Square Error (RMSE) between QUBDisp and the verification methods is presented in Table III.

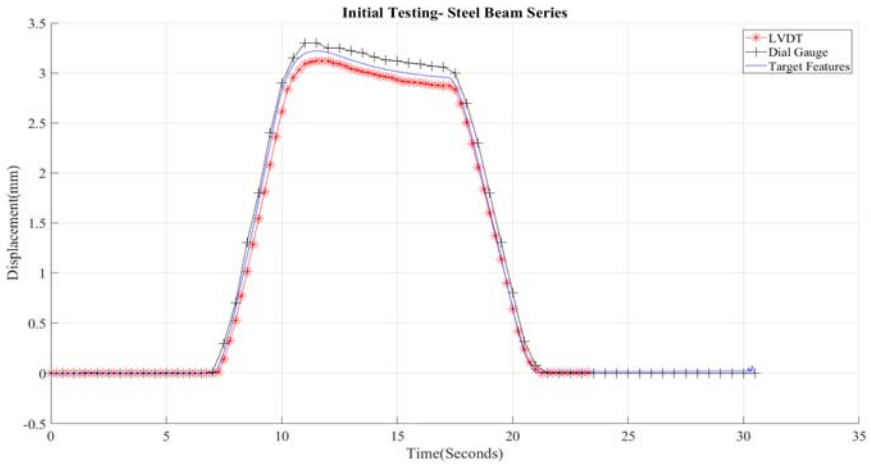


Fig. 2 Results from Initial Testing of QUBDisp

Table III RMSE of QUBDisp vs Verification Methods

Verification Method	RMSE vs QUBDisp
Dial Gauge	0.1863
LVDT	0.1792

The results shown above provided confidence in the initial performance of QUBDisp. The next step in algorithm development was to test the efficacy of the algorithm in a simulated field trial on a scale model of a bridge structure.

B. Concrete Beam Test Series

The aim of this test series was to determine the difference in algorithm accuracy between using natural features of the beam vs an applied target. A scale model of a bridge was simply supported and loaded using an accurately calibrated 600kN capacity hydraulic actuator in the laboratory spreader beam was used to simultaneously apply the load at both 3rd span locations as shown in Fig. 3.



Fig. 3 Concrete Beam Test Rig in the Laboratory

The specifications of the bridge are shown in Table IV:

Table IV Details of Concrete Beam Model

Specification	Detail
Cross Sectional Area:	30.238 x 10^3mm^2
Depth	250mm
Width:	230mm
Neutral Axis	137.09mm
E-Value:	26.6 x10^3N/mm^2
I-value:	4.05 x 10^9mm^3

As shown in Fig. 4, a pattern was marked on the beam under the points that load would be applied at in order to compare the accuracy of the target based feature extraction against natural feature extraction. Three LVDT's were also placed in series at these points on the beam, they were spaced 1168mm apart and set to a scanning rate of 2Hz. The Nikon D5300 camera was set up 2m from the beam and set to record at 25fps.



Fig. 4 Monitoring Locations for Concrete Beam

V. RESULTS

The results for natural vs target features trial are shown in Fig. 5; the data from LVDT 4, target and natural based feature readings have been included.

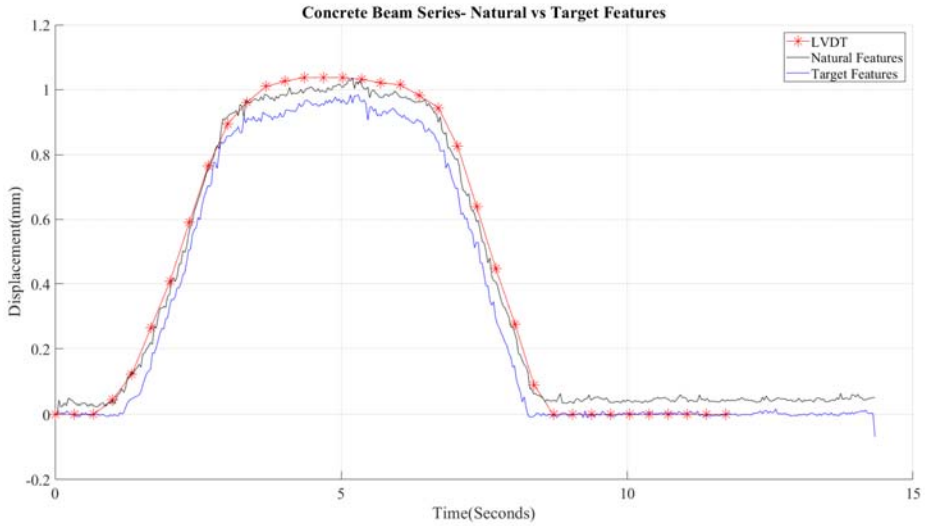


Fig. 5 Comparison between Natural and Target Features

The RMSE between the natural and target features versus LVDT-4 is presented in Table V.

Table V Results from Natural vs Target Features Comparison Trial

Method	RMSE vs LVDT-4
Target Features	0.0353
Natural Features	0.0753

The resulted presented above provided confidence in the performance of the algorithm in extraction of natural features of a structure, this was an important step in the development of a fully contactless solution for displacement monitoring. The next step was to trial the monitoring method in field conditions.

VI. FIELD TESTING

A. Verners Bridge

A bridge which was identified for repair by the local roads authority, Transport NI, was made available for testing in order to validate the performance of the algorithm in field conditions. Verners bridge, Co. Tyrone, is a steel truss bridge with a clear span of 20m, the structure carries a single lane of traffic on a minor road. The response of the bridge under a series of passes by a truck of known weight (40t) was recorded. The displacement was calculated using the QUBDisp algorithm – the results from a series of passes are shown in Fig. 6.

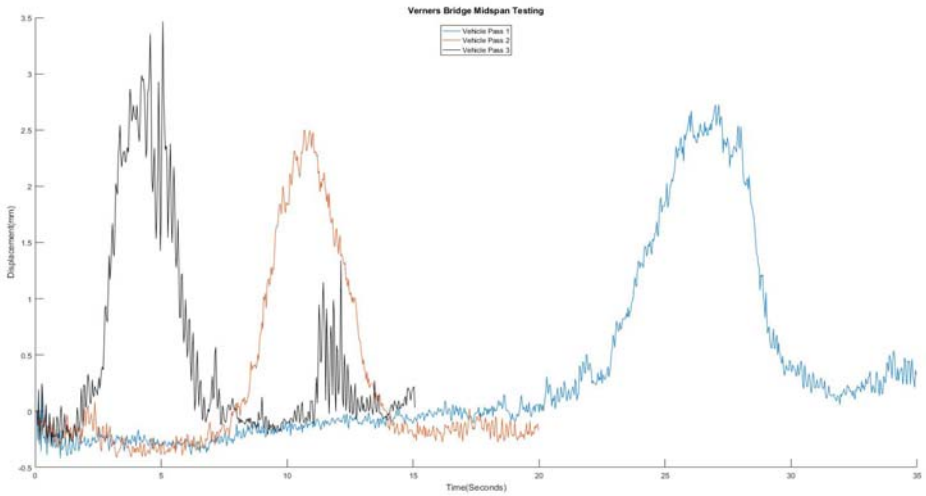


Fig. 6 Results from Midspan Monitoring on Verners Bridge

Due to an error with calibration, the results from the accelerometers used for ground truth verification were not available; nevertheless, there is a close correlation between readings of the camera solution for subsequent passes on the same location. The difficulty with accelerometer setup provides a further validation of the validity of vision systems as a viable method, with no issues occurring with setup or monitoring with the camera equipment.

B. Majors Bridge

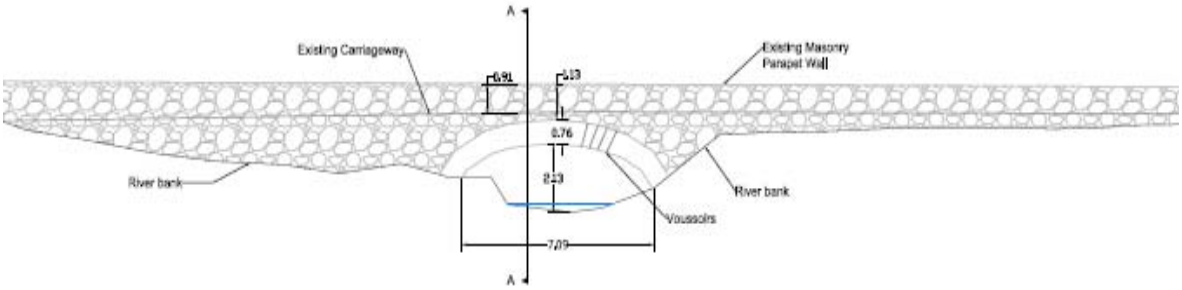
Majors Bridge is a masonry arch bridge which carries two lanes of traffic on the A34 Lisnagole road north of Lisnaskea, Co Fermanagh. The bridge has a cumulative span of 7.41m, Cover to arch ring 0.11m (approx. 0.2m measured on site recently) and a deck width 9.0m.

All of the available geometric properties for the bridge presented in

Table VI and the east elevation can be seen in Fig. 7.

Table VI Majors Bridge Details

Measurement	Detail
Voussoir depth at keystone:	0.77m
Soffit to top of parapet wall	1.87m
Parapet wall to road surface:	0.9m
Parapet wall thickness	0.48m



East Elevation

Fig. 7 Site layout elevation at Majors Bridge

Concerns about the bridge condition were raised subsequent to a traditional bridge inspection carried out by Transport NI. Excessive movement of the arch ring was reported under normal traffic loading. In order to assess this, a field test using the camera based system and QUBDisp algorithm was carried out.

Access was gained to the through a housing development on the south east of structure, this area provided a safe location of parking and setting up of equipment. As shown in the cover photo the area surrounding the bridge is overgrown but the water level under was low enough to allow safe easy access to the underside of the bridge. During this site visit some short- term monitoring was carried out using the camera-based system. It was also intended to use a dial gauge system to provide validation of the results, this was not possible during this visit due to the very uneven ground conditions.

Monitoring Setup

The camera was set up at 2.9m from the spandrel wall on the south east side of the structure as shown in Fig. 8. Monitoring was carried out under live traffic to determine if the system could provide information on the bridge behavior.



Fig. 8 Camera monitoring location

Targets were attached to the underside of the bridge using a non-destructive adhesive. The target locations are shown in Fig. 9 and this allowed for accurate calculation of the movement based on the known geometry of the target.



Fig. 9 Targets attached to bridge soffit

Trial Data Collection

The results shown in Fig. 10 show the measured response of the bridge structure under traffic loading. The actual weight of the vehicles is unknown, but images of the vehicles have been embedded on the graph to give an indication of vehicle type. In this case a maximum deflection of ~1.2mm was measured at the mid span.

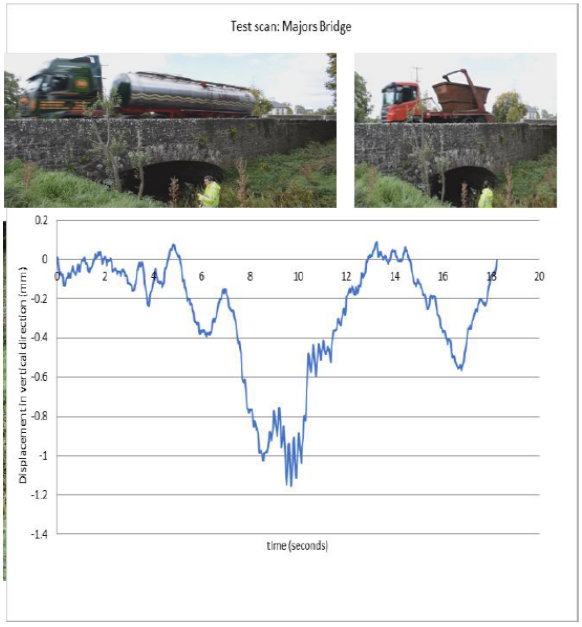


Fig. 10 Midspan displacement in vertical direction due to live traffic as shown in embedded picture.

The purpose of this visit was to determine the suitability of the site layout for camera based monitoring. The trial monitoring carried out indicates this method of assessment is suitable for this site. Future work would include a method for analyzing the traffic crossing the bridge to allow for correlation of applied load to measured displacement.

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