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## Field Testing and Development of Novel SHM systems at Queen's University Belfast

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### Abstract

Ageing and deterioration of infrastructure is a challenge facing transport authorities. In particular, there is a need for increased bridge monitoring in order to provide adequate maintenance and to guarantee acceptable levels of transport safety. The Intelligent Infrastructure group at Queens University Belfast (QUB) are working on a number of aspects of infrastructure monitoring and this paper presents summarised results from three distinct monitoring projects carried out by this group. Firstly the findings from a project on next generation Bridge Weight in Motion (B-WIM) are reported, this includes full scale field testing using fibre optic strain sensors. Secondly, results from early phase testing of a computer vision system for bridge deflection monitoring are reported on. This research seeks to exploit recent advances in image processing technology with a view to developing contactless bridge monitoring approaches. Considering the logistical difficulty of installing sensors on a 'live' bridge, contactless monitoring has some inherent advantages over conventional contact based sensing systems. Finally the last section of the paper presents some recent findings on drive by bridge monitoring. In practice a drive-by monitoring system will likely require GPS to allow the response of a given bridge to be identified; this study looks at the feasibility of using low-cost GPS sensors for this purpose, via field trials. The three topics outlined above cover a spectrum of SHM approaches namely, wired monitoring, contactless monitoring and drive by monitoring.

**Keywords:** Bridge health monitoring; Bridge-weigh in motion; Computer vision; Drive-by monitoring;

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## Introduction

The Intelligent Infrastructure group at Queens University Belfast (QUB) is focused on developing innovative and adaptive sensor systems as well as a protocol for managing structures based on sensor response. The research area is developed in conjunction with some of the leading UK and International Research partners. A strong multidisciplinary steering group was involved in the group development to maximise the research potential for advancing the state of the technology. The sections below present an overview of some of the work carried out by the intelligent infrastructure group at (QUB) in particular, Bridge Weigh in Motion, contactless deflection monitoring and drive by monitoring.

## Next generation B-WIM using fibre optic sensors

Bridge-Weigh in Motion (B-WIM) information on traffic loading can enable efficient and economical management of transport networks and is becoming a valuable tool for bridge assessments. B-WIM can provide site specific traffic loading on deteriorating bridges, which can be used to determine if the load effects are sufficiently below bridge capacity to allow the structure to remain operational and thereby minimise unnecessary replacement or rehabilitation costs and prevent disruption to traffic. Existing B-WIM systems are typically based on electrical resistance strain gauges which can be prohibitive in achieving data for long term monitoring of rural bridges due to power consumption. The system in this study consists of a series of fibre optic sensors (FOS) fixed to the bridge soffit, the strain records are used to determine the loading and provide information on the behaviour of the structure. This is the first B-WIM system to use FOS and also incorporates a new strategy of axle detection, which was investigated and verified in the field.

## System Installation

A full fibre optic B-WIM system was developed at QUB, and was installed at the bridge site shown in Figure 1. The bridge is located at Loughbrickland Co. Down, Northern Ireland. The chosen bridge has span of 18.8 m with a skew of 22.7°. The beam-and-slab structure is typical of many recently constructed short-span bridges across the UK and Ireland. The superstructure consists of 27 no. prestressed concrete Y4 girders, each 1 m in depth, spaced at 1.22 m centres. There is a 0.2m cast in-situ concrete deck which is supported by permanent glass reinforced concrete formwork, spanning transversely between the main beams. The abutments are supported by a pile cap which is integral with the deck beams.

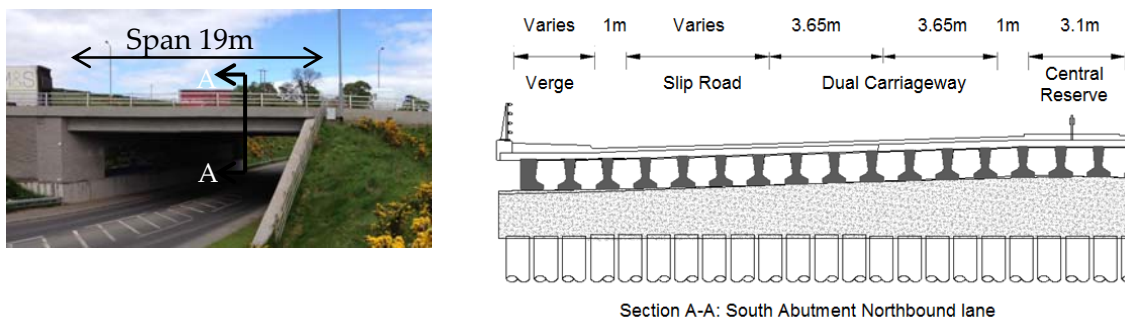


Figure 1: Test Bridge and structural section

A pavement WIM (P-WIM) system was installed on the northbound approach to the bridge. This was very useful as it provided details on the live traffic from an established WIM method and allowed for validation of the B-WIM data. This unique equipment layout is one of the few sites in the world to combine P-WIM and B-WIM at one location. The B-WIM system was

installed under lane one of the northbound carriageway. The B-WIM sensors had two different functions, (i) weighing sensors and (ii) axle detecting sensors. Each weighing sensor consisted of a non-metallic 10 mm gauge-length Fibre Bragg Grating (FBG) sensor mounted on a 5 mm stainless steel dog-bone plate which had the effect of amplifying the bridge beam strain [1]. The plate was attached to the soffit of the longitudinal beams and orientated to measure strain in the longitudinal direction. As illustrated in Figure 2, six beams have been instrumented to allow for the measurement of change in strain in the longitudinal direction. Eight sensors were installed for NOR (nothing on the road) axle detection [2], these are indicated as sensors AD1-AD8 in the diagram. Additional axle detecting sensors were installed to test a new strategy for axle detection. This involved the installation of four additional 10 mm gauge length FBG sensors which were located near the support, details of this can be found in the literature [3].

### System Calibration

The P-WIM system was calibrated prior to the completion of the B-WIM installation to allow for the accuracy of the B-WIM system to be assessed at various stages of the installation. The calibration of the P-WIM system was carried out using a pre-weighed calibration truck and conformed to the 'full repeatability' condition of COST 323. As further calibration days of this nature were excessively expensive, an alternative method of calibration was required. A cost-effective alternative was to calibrate the B-WIM system by comparing the results with those obtained from the calibrated P-WIM system. This method of assessing accuracy of one system using an inaccurate measurement has been long established in medical literature [4]. This allowed the accuracy of the B-WIM system to be checked on any given day without the need for prearranged calibration trucks. Both systems were time-synchronised to allow for easy comparison of the results. An additional independent accuracy check was developed in conjunction with the DVA-NI (Driver Vehicle Agency of Northern Ireland), whereby the results from both P-WIM and B-WIM system could be compared with those obtained from a certified static weigh bridge. The comparison of the two WIM technologies was used as an error 'indicator' for day-to-day monitoring while the DVA-NI measurements provides 'ground truth' data for assessing the accuracy of both systems. The final calibration of the B-WIM system was carried out using the measured static weight of a heavy goods vehicle (HGV) selected from the live traffic at the site. The vehicle was identified by the DVA-NI and directed to the static weigh bridge. An influence line for the structure was determined from the response of this vehicle crossing. As the calibration truck was selected from live traffic, only one calibration run was completed.

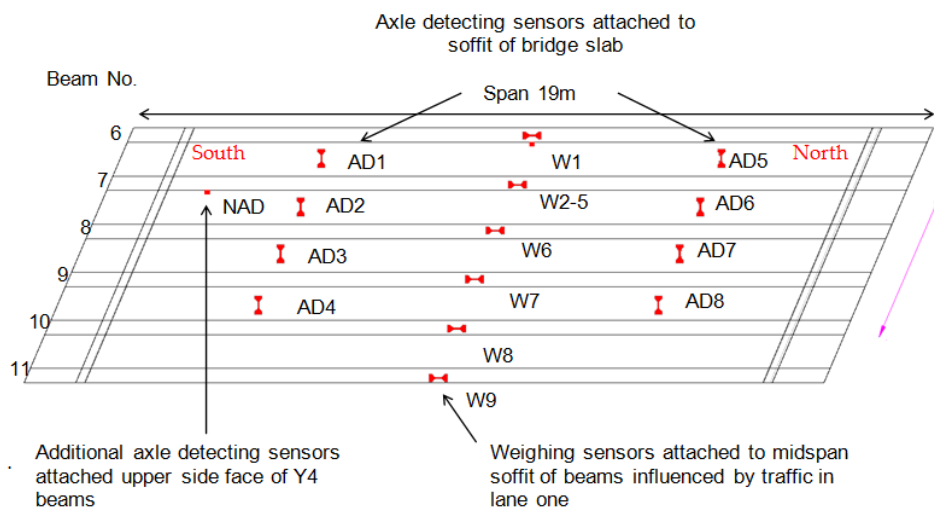


Figure 2: Equipment Layout

### **B-WIM System Accuracy and new method of axle detection.**

The accuracy classification of the B-WIM system was determined from a number of vehicles from the live traffic which were statically weighted by the DVA-NI. The test was considered to be carried out under “full reproducibility conditions (R2)”, that is, a large sample of traffic representative of the traffic flow. The condition R2 from the COST 323 specification is the closest representation of the true conditions of the site test, however this condition states that 10 to 100 vehicles should cross the site to give an accurate estimation for a variety of loading conditions. Since the calibration for this system was limited to only one vehicle, this condition is considered conservative. Future testing of this system would require a more rigorous calibration to measure the effect of varying vehicle speed and configuration and vehicles in other lanes, hence improving the accuracy of the system.

The new method of axle detection was found to increase the accuracy of B-WIM systems by increasing the number of correctly identified axle configurations. Successful axle detection is dependent on the transverse position of the vehicle on the bridge; the findings of this research indicate that the ideal system is one which combines axle detection sensors at both NOR and the new location close to the supports identified in this research.

The data set for the accuracy classification consists of vehicles which were statically weighed during the two separate DVA-NI days. Therefore, the test was deemed to be under limited environmental reproducibility conditions (II) from COST 323. The overall accuracy of the system is C(15), groups of axles and single axles being the governing criteria. Class B(10) accuracy has been achieved for GVW and axles of a group. As already mentioned, future testing of this system will involve more rigorous calibration of the system to allow for this. The mean errors for all vehicle axle groups are negative which means that the system is under-weighting. It is acknowledged that this is a small sample, particularly for gross weights and groups of axles.

### **Camera based SHM**

Despite its limitations, the most common method of data collection for bridge assessment is still visual inspection. However, bridge assessments can be overly conservative which can lead to costly and sometimes unnecessary repair or replacements. At the design stage the cost of conservatism is relatively small. However when the same degree of conservatism is applied to bridge assessments, some bridge structures may be deemed unfit for purpose when they are in fact safe. Structural Health Monitoring (SHM) Systems can provide valuable information on the bridge capacity and objectively identify the structural condition. One of the impediments to implementing such systems is the difficulty in accessing parts of the structure to install in the instrumentation. Currently research is under way at QUB to investigate the use of computer vision systems 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 on real life bridges.

### **Contactless displacement measurement**

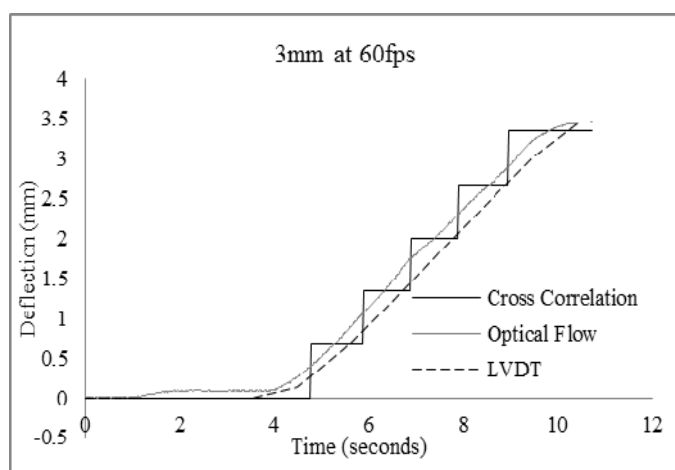
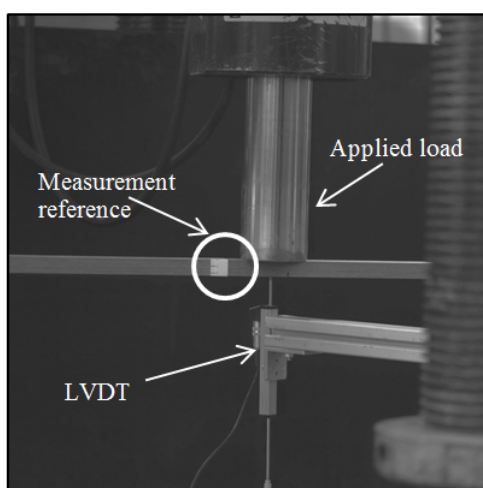
An initial set of laboratory trials were carried out to determine the level of accuracy in deflection measurement using a non-contact camera monitoring system. A digital camera was set up to monitor two sets of laboratory experiments. Video images of the tests were recorded and the images were post-processed to calculate displacements. In each of the techniques used for post processing, the displacement was extracted by tracking the movement of a textured pattern on the surface of the test structure. The results were validated against the displacement response measured using conventional linear variable displacement transformers (LVDT). Computer vision techniques and post-processing algorithms, such as Lucas-Kanade optical flow, could potentially be implemented to

determine structural changes in existing structures without the need for physical contact. In relative terms, computer vision techniques provide simplicity in deployment compared to traditional structural monitoring approaches 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. Previous research has highlighted the potential for the integration of imaging devices with traditional SHM technology [5]. Digital image correlation (DIC) was first proposed by Chu et al. [6] and is now increasing in popularity across science and engineering disciplines. With dramatic technological 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. In this research two DIC methods are tested against contact measurements determined by LVDT.

The two methods used were the optical flow algorithm and the Normalised Cross-Correlation approach. The images from the experiments were processed using both methods and the results were then compared.

### Experimental testing

In the experimental test a timber beam was simply supported and was loaded at mid-span using a hydraulic actuator as shown in Figure 3(a). The timber beam had a cross section of 47mm x 23mm and a clear span of 2300mm. The load was applied to the beam using displacement control; the maximum displacement for each test was selected and applied at a rate of 0.2mm/s. The load was applied at the mid span of the beam and the displacement was verified with the LVDT. Each test was recorded using a camera which was placed opposite the test set up and it was set to record at a frame rate of 60fps. The purpose of the test was to determine the accuracy of both image processing methods for deflection measurement. A reference measurement was attached to the face of the timber beam to allow for the pixels to be scaled to millimetres as shown in Figure 3(a). The results from a test where the beam was deflected 3mm at the mid span are shown in Figure 3(b). It can be seen in Figure 3(b) that the optical flow method matched quite well with the LVDT measurement. The displacement from the cross correlation also broadly tracked the LVDT displacement but there seem to be some resolution issues as the calculated displacement appears 'stepped'.



(a) (b)  
Figure 3: (a) Test set-up (b) Measured and calculated deflections

Ultimately the purpose of this research is to assess the potential for camera based monitoring of structures using deflection as a damage indicator. A final test was carried out to determine the suitability of deflection as a metric for damage detection. As with the previous test, the timber beam was set up under the testing rig. However, for this test the load was applied using stroke control, a maximum load of 0.5kN was applied to the midspan of the timber beam at a rate of 0.1kN /s. A 5mm deep saw cut was then made on the underside of the midspan of the beam and the test was repeated. The results in Figure 4 show the deflections calculated using the optical flow algorithm. The damage was equivalent to a 23% reduction in section at the midspan of the beam this resulted in a 25% increase in deflection, confirming that for this case deflection could be used as a damage indicator.

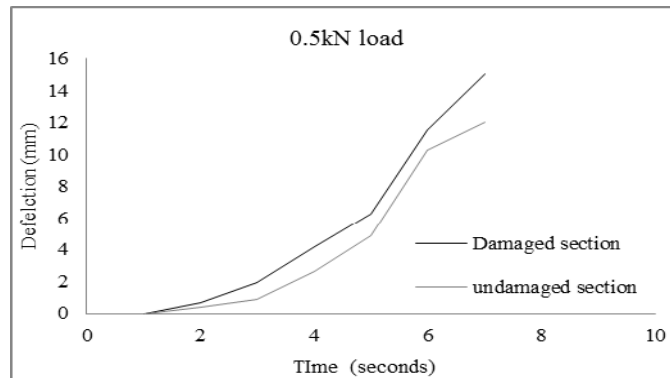


Figure 4: Optical flow calculated deflection to detect damage

## Drive by monitoring systems

In recent years, alternative low-cost indirect vibration-based SHM approaches have been proposed by a number of researchers which utilise the dynamic response of a vehicle to carry out “drive-by” monitoring of bridges [7,8] and/or pavements [9]. Typically the vehicle is fitted with sensors, such as accelerometers, on its axles to monitor vibration thus reducing the need for (a) on-site SHM installations on the bridge which can be expensive and (b) expensive laser-based technology and sensors currently used in inertial road profilometers. However, these methods, summarised by Malekjafarian et al. [8], lack comprehensive experimental verification, with very few field trials reported in the literature.

A low-cost drive-by system is proposed by this research group, utilising smartphone technology and sensors. Due to the current prevalence of such technology [10], drive-by vehicle monitoring systems could potentially move beyond the limitation to unique instrumented vehicles, or localised instrumented public vehicle fleets [11]. Therefore, this section presents an investigation of the practical implementation of such drive-by monitoring systems via field trials. For this purpose, a two-axle vehicle is instrumented with accelerometers to measure vibration and global navigation satellite system (GNSS) receivers to record the vehicle position in the road network; it is then driven along predetermined routes in the Belfast road network.

### Field trial setup

For this field investigation, the instrumented vehicle was a Ford Transit van (Figure 5). A digital camera was also used to record video footage of each vehicle test run while the average vehicle speed during testing was 30 mph (48 km/h). The accelerometer setup in the vehicle is illustrated in Figure 5, consisting of 3 accelerometers. The two wired accelerometers were model 4610A-002 ( $\pm 2g$ ) and 4610A-005 ( $\pm 5g$ ) units by Measurement

Specialties™, while the smartphone accelerometer tested was the LG Nexus 5 triaxial MPU6515 sensor. Smartphone accelerations were sampled at 200 Hz via the Android application “Vibration Alarm”, while the wired accelerometer measurements were sampled at 1000 Hz via a National Instruments multifunction USB-6353 X-Series data acquisition (DAQ) device logged to a Panasonic Toughbook running NI Signal Express.

The vehicle location was tracked during testing by the LG Nexus 5 using a freely available Android smartphone application ‘*GPSEssentials*’, which utilises smartphone’s GPS receiver, incorporating assisted GPS. To serve as a reference for the vehicle position recorded by the Nexus 5 during testing, a Leica Viva GS14 GNSS smart rover antenna was mounted magnetically on the roof of the van and used to manually log the vehicle location coordinates to a removable SD card throughout testing, incorporating Network Real-Time Kinematic (RTK) corrections obtained via mobile network. This system can achieve horizontal and vertical accuracies of 8 mm and 15 mm respectively for static measurements, although this was expected to vary during testing, particularly in urban or wooded areas where satellite visibility or signal strength can be restricted, and due to the movement of the vehicle.



Figure 5: (a) Instrumented vehicle and (b) data acquisition system

### Field trial results

Figure 6 shows an example of the full time history of acceleration measurements obtained from the 2g uniaxial and smartphone accelerometers in the instrumented vehicle for test route 1. It can be seen that despite the differences in sampling frequency, the smartphone acceleration time history compares relatively well to the corresponding measurements from the wired 2g accelerometer. Sharp peaks at the beginning and end of the signals were used to confirm accurate synchronisation while the vehicle was motionless. During movement i.e. from 140 – 860 seconds, only four peaks exceeded +2g, marked in Figure 6 by black circles. However, the maximum peak magnitudes measured by the wired accelerometers were not obtained by the smartphone due to its range limit. The times corresponding to peaks in the acceleration signals were used to inspect synchronised video footage. Figure 7(a) and (b) shows screenshots of the road surface corresponding to the two largest peaks, P1 and P3. Fig 7(c) shows vehicle location coordinates logged during testing indicated by white markers. Coordinates identified as the approximate location of the van when peaks P1-P4 occurred are marked with black dots. This highlights that unique features, such as speed ramps and manholes are present at these locations and can be identified.



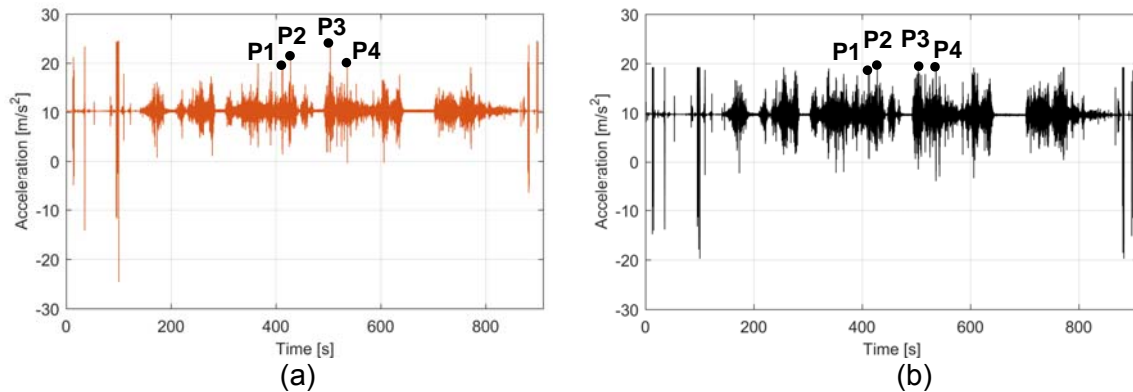


Figure 6: Acceleration measurements for test route 1 (a) 2g uniaxial (b) Nexus 5 MPU-6515



Figure 7: Video screenshots of peak locations (a) at P2 (b) at P3 and (c) Vehicle position coordinates identified (black dots) at peak locations using smartphone and Leica GNSS.

## Conclusions

This paper has presented an overview of some work carried out by the Intelligent Infrastructure group at QUB, namely Bridge Weigh in Motion, contactless deflection monitoring and drive by monitoring systems. It has been shown that fibre optic sensors can be used successfully for B-WIM and axle detection. Results from experimental trials of a camera-based deflection monitoring system show significant promise for practical applications but further work is required to establish the robustness of the approach in the field. The practical implementation of a drive-by monitoring system incorporating smartphone sensors and a GNSS tracking device has been investigated via field trials, illustrating its feasibility. However, further analysis of smartphone acceleration responses is required to evaluate their level of accuracy and precision for drive-by monitoring methods and damage detection algorithms.

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