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The 9th International Cable Supported Bridge Operator's Conference

Halifax, Nova Scotia, Canada
June 19-22, 2016

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5B: Structural Health Monitoring

TUESDAY, JUNE 21, 2016

Evaluating a video gauge for deformation measurements of two UK long span bridges

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ABSTRACT ID

1997876

Abstract

Bridge deformation measurements provide, through time and space derivatives, a rich set of information on cable stayed bridge (CSB) performance. Direct measurements of deformation of major components of CSBs i.e. deck, pylons, cables, are difficult due to problems with access and reference points. Compared to use of GPS and accelerometers which have more fundamental limitations, optical measurements offer many advantages such as multi-target tracking with limitations on resolution and accuracy in space and time being steadily eroded through developments in software capabilities. Hence we have revisited a research technology initially developed to monitor the Humber Bridge in 1990 and which now, in the form of a robust combination of hardware and Video Gauge software, provides a robust and effective solution for field monitoring.

We evaluated the system alongside conventional instruments such as total station, accelerometer and GPS in two one-day campaigns on two rather different bridges: Humber Bridge, a 1410 m span suspension bridge and Tamar Bridge, a hybrid suspension/cable-stayed bridge with 335 m main span.

While graphically highlighting limitations of GPS, the exercises showed the value of mixing or fusing data streams using Kalman filter to provide the best 'estimate' of bridge response.

We focussed on vehicle-induced deformations which are the major driver of response on Tamar Bridge and which also contribute heavily to bearing wear and fatigue on Humber Bridge.

We conclude with recommendations on getting best results using the system.

Keywords:

Suspension bridge deformation optical target tracking

1. Introduction

Bridge performance can be characterised via a number of metrics such as internal or reaction forces, stresses, strains and accelerations but perhaps the most useful metric of all is deformation, since practically all the other metrics can be derived from it via differentiation in space (giving strain) or time (giving velocity and acceleration).

Serviceability is also reflected through deformation, since extreme values and ranges indicate problems that may limit operational use, e.g. as excessive vibrations or movement across expansion joints. Measurements of deformation also provide direct calibration of physical or numerical simulations of load/response relationships via controlled vehicle load tests and monitoring of performance in strong winds. Deformation measurements also provide a powerful diagnostic tool, for example for investigation of the truss-end link that closed the Forth Road Bridge in late 2015 [1].

Technologies for bridge deformation measurements are presented e.g. [2] and choice of technology and specific sensor type depends on the factors that include the spatial range and resolution, sample rate and frequency response, number of directions that can be measured, availability and stability of a fixed reference position and distance of sensor from locations(s) to be measured. While uniaxial movement across bearings and expansion joints can be measured using LVDTs and short range lasers, tracking deformations in bridge spans is more of a challenge. For short span road and rail bridges over accessible solid surfaces LVDTs can also be used, sometime with elevated reference positions (e.g. scaffold), leaving long spans over water and inaccessible open space. Options include total stations combining theodolite for measuring angles and laser for measuring distance [3], laser Doppler vibrometer (LDVM) [4], Radar [5], GPS antenna [6], hydraulic level sensing [7], integration of tilt or acceleration [8] and systems based on 'vision-based' image recognition and tracking. While GPS has become the standard technology, it has limitations, particularly for shorter spans where movement ranges are modest and the non-standard techniques using image tracking, acceleration integration and total stations have potential to provide more reliable information.

This paper investigates this proposition by comparing and integrating different methods for two suspension bridges in the UK, Tamar Bridge (335 m main span) and Humber Bridge (1410 m main span). The main focus is the vision-based system.

Recent developments in vision-based structural deformation monitoring

One of the earliest applications of vision-based structural deformation monitoring was to the Humber Bridge in 1990 [9] which used the ancestor of the system described in this paper. Since then a number of systems have been developed and evaluated for structural monitoring.

For example, Lee and Shinozuka [10] and Feng et al. [11] developed vision-based systems to monitor the two-dimensional displacement of bridge based on scaling factor transformation. The systems work on the assumption that the optical line of sight is perpendicular to the bridge motion of interest. Chang and Xiao [12] proposed a single-camera system to extract the motion of a short-span pedestrian bridge; the three-dimensional motion could be obtained in theory but the displacement perpendicular to the target plane is not reliable. A telephoto lens was used in the long-span suspension bridge [13] where instead of fixing the camera to solid ground, four LED control points were arranged at the tower foundation and the camera was installed at the mid-span of the bridge.

Vision-based systems have occasionally been applied to in-plane motion monitoring of bridge stay cables without artificial targets [14,15]. Stay cable vibration is the rare example where LDVM –using line of sight measurement- has the advantage in facilitating rapid assessment of cable tensions [16].

2. Dynamic Monitoring Station (DMS)

The system originated from research at the University of Bristol [9,17,18] and the Video Gauge software was commercialised via university spin-out formed in 2003. The original image location and tracking algorithms were updated to provide extreme resolution up to 1/500 pixel.

The Dynamic Monitoring Station (DMS), comprises one or more GigE high performance cameras for video acquisition and real-time extraction of displacements using Video Gauge software. During the testing the camera equipped with the lens is mounted on a tripod and connected to the controller via an Ethernet cable. The camera adopted in the test has a resolution of 2048×1088 pixels and a sensor size of 11.26×5.98 mm.

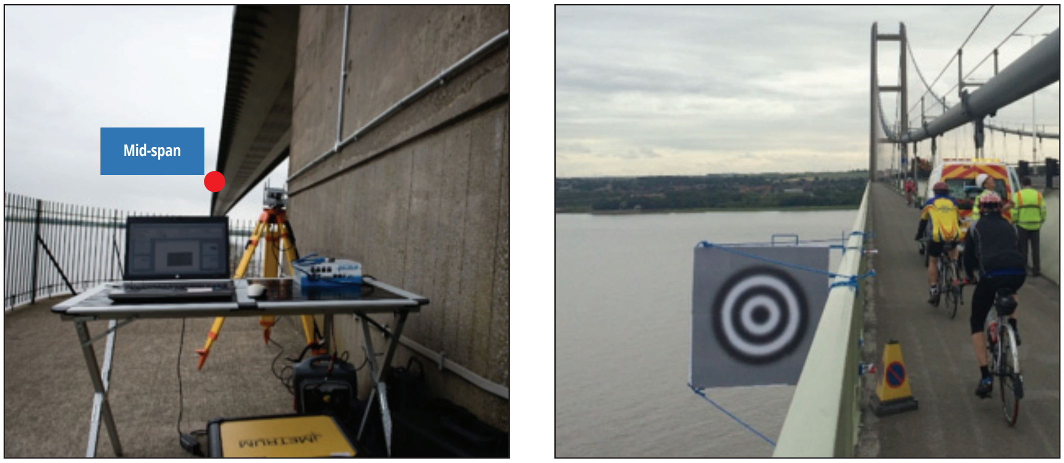
The tracking algorithms used are normalized grey-scale correlation (NGC) and super resolution techniques. The tracking objects could be either a custom-made target attached to the structure or an existing feature on the bridge surface. The system has the practical capacity to resolve better than 1/100 pixel resolution at sample rates up to and beyond 100 Hz.

Figure 1: Mounting configuration of the camera and 300 mm lens

2.1 Evaluation trials

To build confidence and to develop the best configuration and procedure, trial tests were conducted 1) to track the displacements of short-span bridges which is 'known' as obtained by other sensors, and 2) to track the 'movement' of assumed fixed objects under variable environment condition. The results showed that to obtain an accurate and stable measurement, the ideal image size of the target is near 80 × 80 pixels suggested to be not less than 40 × 40 pixels. If a custom-made target panel is required, the dimension of the panel could be estimated from the required image size and the camera-target distance using the scaling factor method [19].

A stable mounting condition for the camera and lens is proven to be important. If the mounting condition is not satisfactory, the displacement measurement could be easily influenced by wind buffeting, especially when the lens is cantilevered from a single mounting point and has mass of 2.9 kg (e.g. 300 mm f/2.8 lens) or larger. Therefore a translation stage, shown in Figure 1, was designed to provide a stable restraint to the lens and the camera.



(a) DMS near tower foundation

(b) Custom-made target installed at mid-span

Figure 2: Camera system configuration in the Humber Bridge test

The results also showed that the brightness of ambient light has a direct relationship with the drift of the displacement measurement. For this reason, it is suggested to provide a steady exposure for the camera through automatically adjusting the exposure time according to the environmental conditions.

Following the evaluation and optimisation trials, the system was applied to study the operational movements of two long span bridges.

3. Application on Humber Bridge

The Humber Bridge [2], opened in 1981, has a main span of 1410 m and side-spans of 280 m and 530 m. A single day of field testing using the DMS was performed to measure the lateral and vertical displacement at mid-span of the bridge. The DMS performance is evaluated by comparing with a GPS 'reference sensor' in time domain.

3.1 test description

In the field test of the Humber Bridge, the camera and controller along with battery power supply, were located near the foundation of north (Hessle) tower shown in Figure 2(a). The lens used was the 300 mm f/2.8. A custom-made steel frame with the dimension of 1 m×1 m was mounted on the parapet at the mid-span shown in Figure 2(b). The pattern of the target is a set of concentric rings with a gradual blend from black to white at the edges. To ensure a reliable mounting condition, two C channels welded to the target frame were fixed to the top and the vertical railing of the parapet. Four ropes were tightened between the target and the railing to prevent out-of-plane rotation. The target was close to midspan, 710 m from the camera lens.

The frequency range of interest was less than 1 Hz, thus the sampling rate was chosen as 10 Hz, fast enough to obtain the structural vibrations. In order to save storage space, the image size of each frame was saved as 850×400 pixels although the default image size is 2048×1088 pixels.

(a) Position of targets from the camera view

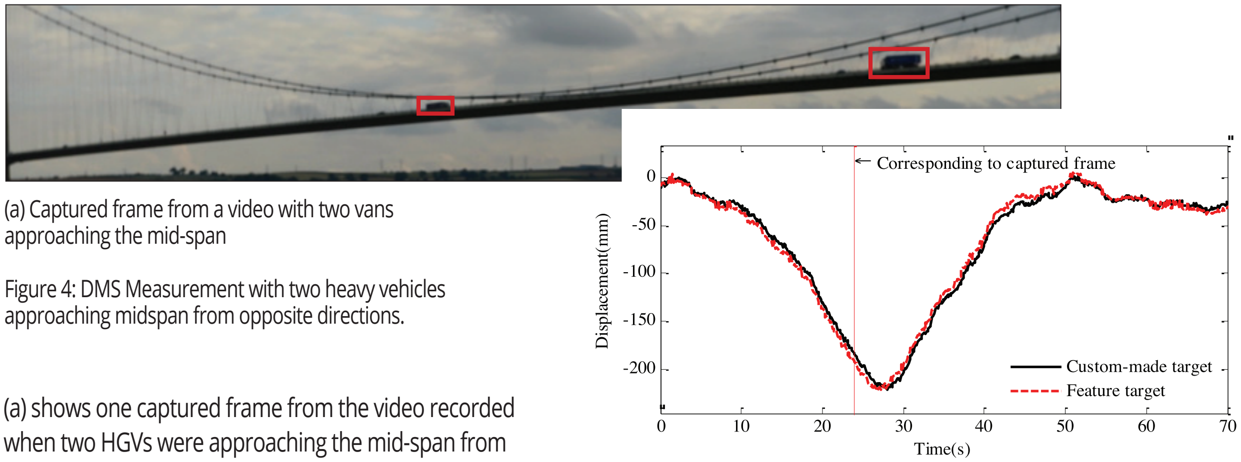
(b) Custom-made target and feature target

Figure 3: Custom-made target and feature target from the camera view

Both the custom-made target and the feature target at mid-span were tracked by the Video Gauge software. Figure 4(a) shows the view from the camera position, and (b) a single captured video frame. The red dashed boxes in the figure include the custom-made target and a natural target on the bridge soffit. The establishment of the transformation from physical coordinates to camera sensor coordinates is required. Assuming that the out-of-plane motion along the longitudinal direction of the bridge is negligible, projective reconstruction was conducted using three or more coplanar line correspondences. The lines with known dimensions came from the edge and diagonal of the installed artificial target frame.

3.2 measurement evaluation in time domain

During the test, a D-SLR camera was adopted to record the video of traffic information on the bridge. Figure 4 (a) shows one captured frame from the video recorded when two HGVs were approaching the mid-span from opposite directions. Figure 4 (b) shows the corresponding measurement by DMS in vertical direction, with vertical deflection at mid-span caused by the two vehicles reaching 221 mm. In general, the measurements by tracking two targets agree well; the Video Gauge demonstrates similar performance for tracking either target.



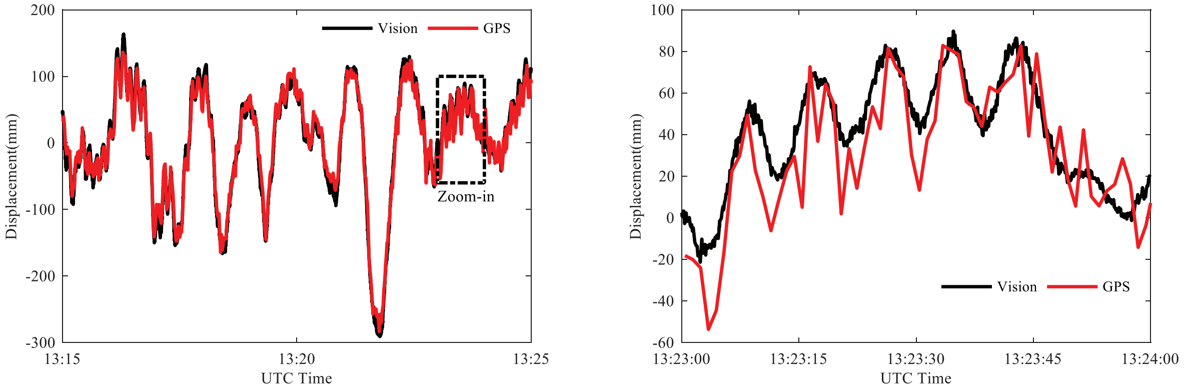
(a) Captured frame from a video with two vans approaching the mid-span

(b) Vertical displacement recorded by vision-based system

Figure 4: DMS Measurement with two heavy vehicles approaching midspan from opposite directions.

The long-term monitoring system of Humber Bridge, operational since 2010, includes two GPS rover receivers at two sides of mid-span [2]. GPS observations are sampled at 1Hz. Figure 5 (a) shows the vertical displacement measurement by DMS and the GPS receiver at mid-span.

Figure 5 (b) shows a zoom-in view of one-minute signals. The DMS had better performance in recording the low-frequency components, and the accuracy of GPS observation was in the centimetre-level.



(a) Ten-minute signals of vertical displacement

(b) Zoom of the area marked by rectangle in (a)

Figure 5: Comparison of vertical displacement by Video Gauge and GPS

4. Application at Tamar Bridge

Tamar Bridge spans the River Tamar between the City of Plymouth on the east bank and the town of Saltash on the west bank. A single day of field testing using the DMS was performed to measure the lateral and vertical displacement at mid-span of the bridge. The system performance is evaluated by comparing with measurements by GPS and robotic total station (RTS).

4.1 test description

The configuration of vision-based monitoring system was a little different from that for Humber Bridge. The camera was installed at the top of a rigid steel tower together with robotic total station, Figure 6. A custom-made 750 mm square target frame was mounted on the parapet at mid-span. One GPS rover and one circular prism were mounted at the target frame in Figure 7. The target was about 380 m away from the camera lens. Vision-based system and GPS sample rates were 10 Hz and 2 Hz, respectively, RTS nominally 10 Hz.

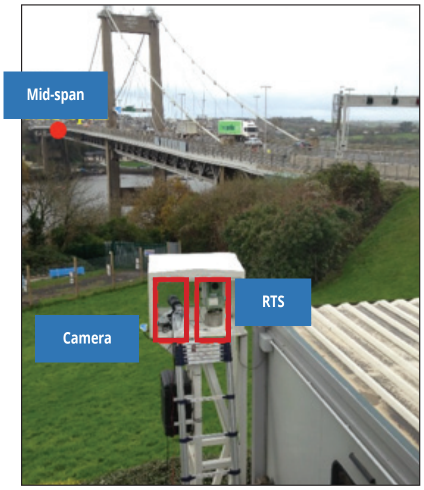
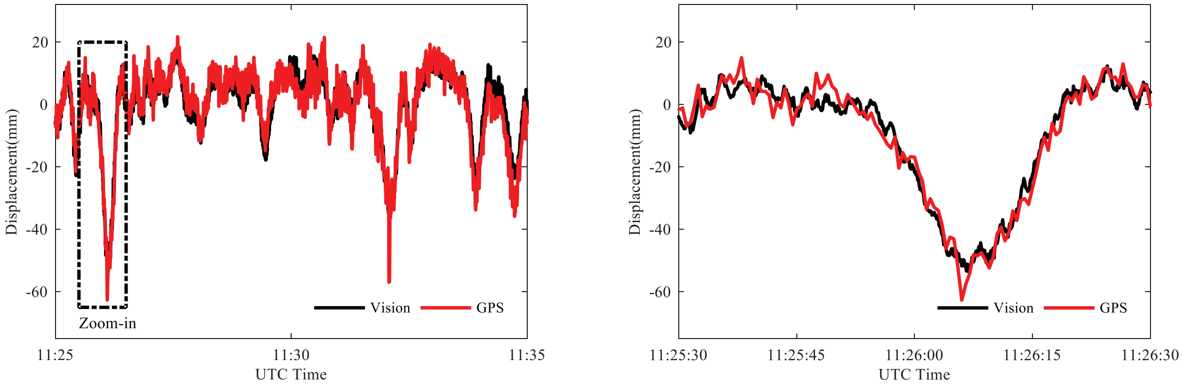


Figure 6: Configuration of vision-based system and RTS

Figure 7: Mounting configuration of target frame at mid-span

4.2 measurement evaluation in time domain

Figure 8 shows sample time histories of vertical displacement by vision system and GPS. Generally the measurements by these two sensors agree well, showing that measurement by vision-based system is stable in short-term monitoring. From the zoom-in view in Figure 8(b), the vision-based system provides higher resolution.

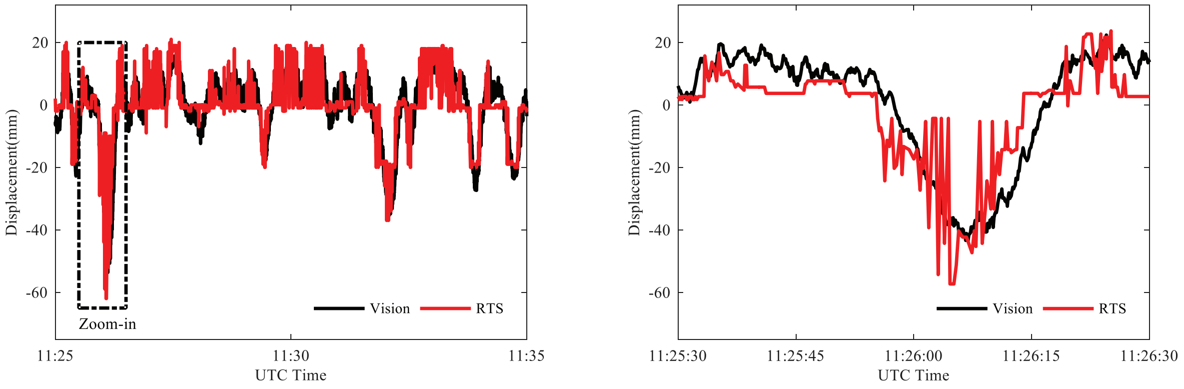


(a) Ten-min signals of vertical displacement

(b) Zoom of the area marked by rectangle in (a)

Figure 8: Comparison of vertical displacement by vision-based system and GPS

Figure 9 shows time histories of vertical displacement by vision system and RTS. The RTS observations were not stable, although the reason for this has not yet ben identified.



(a) Ten-min signals of vertical displacement

(b) Zoom of the area marked by rectangle in (a)

Figure 9: Comparison of vertical displacement by vision-based system and RTS

5. Lessons and next steps

5.1 Stability of vision-based system

The DMS is easily affected by the environmental conditions such as illumination or weather changes. It was not able to measure displacement in the case of obstructions in the line of sight. The unpredictable obstruction along the principal axis disturbs the process of target tracking and might lead to significant errors. Figure 10 is one example during the test of Humber Bridge, and the jump of 242 mm occurred suddenly due to a ship passing below the bridge.

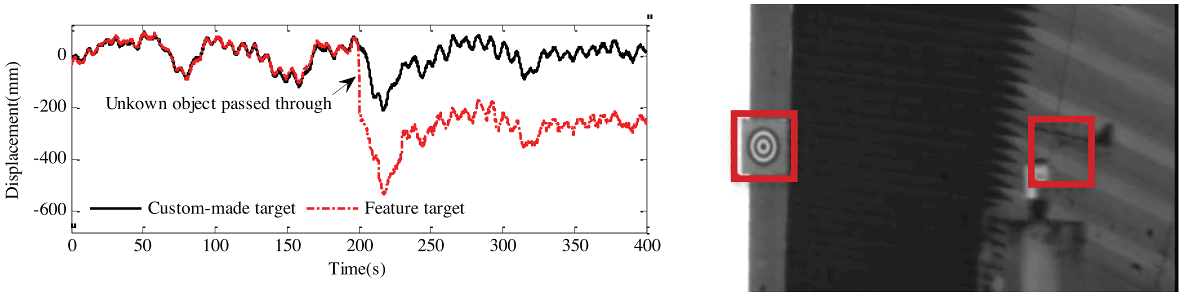


Figure 10: an object passing through the line of the sight

Measurement by DMS is easily influenced by shading and lighting. In the test, about one hour before the sunset period (in July sunset is at 9PM), the target panel, on the east side, was located in the shadow of the bridge railings shown in Figure 11. The video frame flickered when the tall vehicles passed through and obstructed the sunlight from the west casting the shadows. This flickering was observed by eye as well and unrelated to camera setting. Missing data occurred when the system failed to track the artificial target but the feature target in the soffit was not influenced. When raw video data are recorded, there are options to change the software behaviour to minimise risk of losing targets, at the expense of match quality and hence tracking capability.

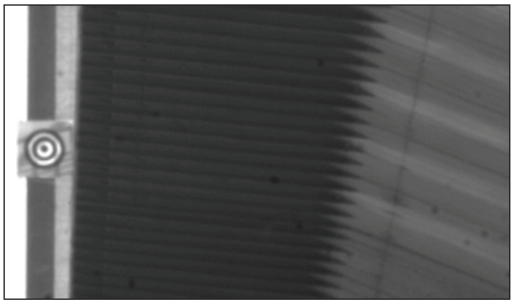


Figure 11: Target panel with shadow of railing before sunset

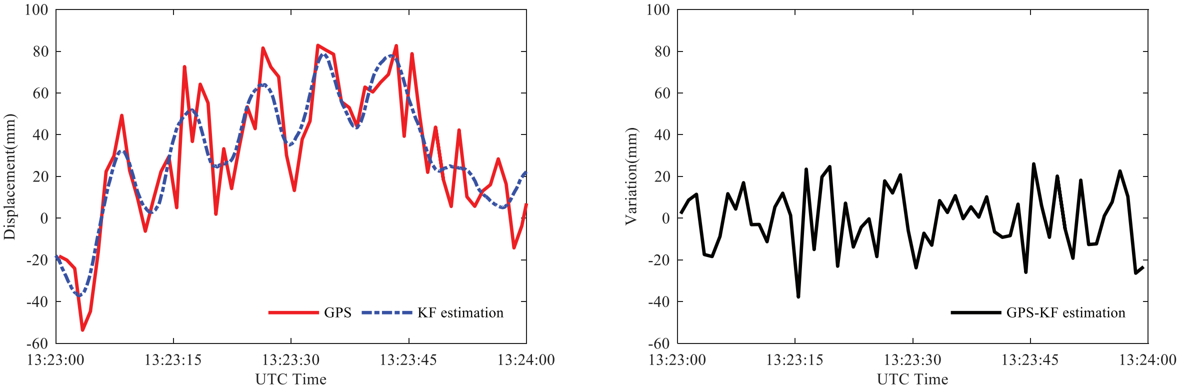
No active illumination was provided for the targets in these two tests. As night fell, the steady exposure was reached at the expense of gradually decline of sampling rate. During the test in Humber Bridge, the recording was stopped at 9PM because the displacement measurement sampling at less than 2 Hz could not record the information of interest. A solution for working at night would be artificial illumination including infra-red, as used at Humber and Severn bridges [9,17].

5.2 Sensor selection for dynamic displacement measurement

The dynamic motion of the bridge induced by traffic, wind and temperature etc. is of interest for structural monitoring. The displacement data are an important aid for system identification such as direct identification of influence lines and weights for vehicles with varying speed, tying into model validation, calibration and updating, etc.. It is noted that the measurement of displacements invariably requires a reference position. When using GPS or total stations for monitoring purposes, no specific reference position is required, but it is usually enough to determine displacements with respect to an unloaded, un-deformed state.

The accuracy of GPS measurement is in centimetre level whereas the Video Gauge is validated to have millimetre accuracy. The DMS allows for distributed sensing via multiple targets while the GPS supports only single-point measurement. However the DMS requires an unobstructed view to the target, stable exposure and good illumination condition.

Except for the chance to find high-accuracy sensors, another effective way is to merge the displacement observations with additional acceleration data. Accelerometers are often more accurate for higher frequencies and higher sampling rates are often available. This opens the possibility to exploit the inherent redundancy in the sensor information and to obtain more reliable and accurate estimation of displacement. Hence the multi-rate Kalman filtering algorithm was applied to merge the GPS observations with the co-located acceleration signals [20]. Figure 12(a) shows the estimation result of vertical displacement in the Humber Bridge test. The estimated displacement can lower the GPS noise at high-frequency range and broaden its frequency bandwidth. Figure 12 (b) is the predicted noise in GPS observations with the root mean square of 14.8 mm.



(a) Vertical displacement time histories

(b) Variation between two signals

Figure 12: Comparison of vertical displacement by GPS measurement and Kalman filter estimation

5.3 Next step

With the distributed sensing characteristics, the application of the vision system could be expanded to the measurement of displacement fields along the bridge longitude direction. Furthermore, three-dimensional measurement could be achieved by using two cameras in stereoscopic configuration, depending on the application requirements. To enhance the convenience, efforts should be made to eliminate the need for pre-installed targets on the structure. The performance of vision-based systems is easily influenced by the environment conditions such as heat haze, camera vibration, etc.. Future work should be carried out towards accuracy improvement and to improving applications for monitoring civil structures, which have already begun to be investigated [21,22].

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