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Dynamic Displacement Measurement of a Long-Span Bridge Using Vision-based System

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Abstract

Displacement data under operational loads are an important aid for the estimation of structural performance, but accurate measurement of structural displacement remains as a challenging task, especially for long-span bridges. This paper describes a displacement monitoring test of a suspension bridge (Humber Bridge, UK) using vision-based system and GPS. A prefabricated planar target was attached to the mid-span of bridge to aid camera calibration. The target was tracked based on normalized grey-scale correlation (NGC) and super resolution techniques. The vertical and transverse displacement at mid-span in operation condition was recorded and the optical system was identified to be an effective way for measurement at very long range. The GPS measurement showed the accuracy of centimetre level, which was undesirable for the possible applications in structural identification. The exercises showed that better measurement of bridge displacement could be obtained by fusing GPS data with the collocated acceleration data using Kalman filter.

Keywords: vision-based system, dynamic displacement, long-span bridge, Kalman filter.

1. INTRODUCTION

Deformation information under operational and extreme loads represents structure performance and enables condition evaluation and decision-making for further management. Direct measurement of deformation is feasible using a range of technologies all of which measure the relative motion between a point on a structure and another fixed reference point. The choice of sensing technologies depends on the factors that include the measurement range and achievable accuracy, sample rate, number of directions that can be measured, installation requirement and measurement robustness. For short span bridges over accessible solid surfaces, an LVDT can be used sometimes with elevated reference positions like scaffolding, but it is not suitable for the inaccessible open space. Non-contacting options include GPS, total station, Laser vibrometers, Radar interferometry and vision-based systems. GPS sensors are the standard technology for the long-span bridge monitoring, but the measurement accuracy (centimetre level) [1] limits the application for the case with modest motion range. Robotic Total Station (RTS) is a good choice to monitor the thermal influence on bridge deflection in long term [2], but the dynamic measurement usually contaminated by clipping requires data pre-processing such as filtering [3] to make it usable. The Laser vibrometer [4], Radar interferometry [5] and vision-based system [6] have potential to provide reliable and accurate deformation information. The main focus of this paper is to discuss the potential for a vision-based system.

One of the earliest applications of vision-based structural deformation monitoring was to the Humber Bridge in 1990 [7] 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 [8] developed vision-based systems to monitor the two-dimensional displacement of a bridge based on scaling factor transformation. The systems work on the assumption that the optical sight is perpendicular to the bridge motion of interest. Chang and Xiao [9] 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 camera equipped with telephoto lens was applied in monitoring a long-span suspension bridge [10] 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.

This paper investigates the feasibility of vision-based systems in long-range displacement monitoring. The optical measurement was validated by the comparison with GPS and accelerometer measurement in time and frequency domain. The practical limitations of the vision-based system found on site are also discussed. Despite the limitations of GPS, the exercises showed the value of merging GPS data with collocated acceleration data using Kalman filtering to provide better estimate of bridge response.

2. VISION-BASED MONITORING SYSTEM

The vision-based monitoring system adopted in the test was developed by Imetrum Company in Bristol, UK. It consists of one or multiple GigE cameras, a controller containing the software package for video acquisition and real-time extraction of displacements. During the test the camera equipped with the lens is mounted on a tripod and connected to the controller via 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 [11]. 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.

To build confidence and to develop the best configuration and procedure, trial tests were conducted, 1) to track the displacement 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 show that to obtain an accurate and stable measurement, the ideal image size of the target is near 80 × 80 pixels and 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 [12].

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. NIKKOR 300mm 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.

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

The results also show that the brightness of ambient light has a direct relationship with the drift of the displacement measurement although similarity metric has been normalized during template matching. 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.

3. FIELD TEST ON HUMBER BRIDGE

The Humber Bridge, opened in 1981, has a main span of 1410m and side-spans of 280m and 530m. A single day of field test using the vision-based monitoring system was performed to measure the lateral and vertical displacement at mid-span of the bridge. The reference sensors were GPS for evaluation in time domain and accelerometers for evaluation in frequency domain.

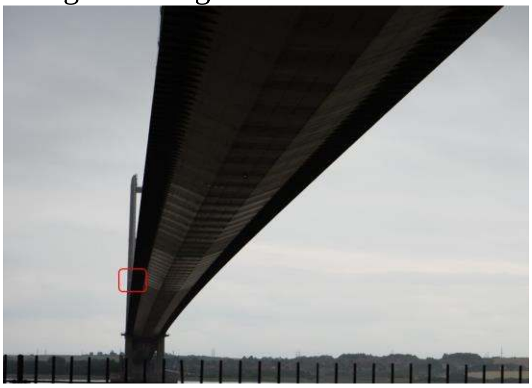
3.1 Test description

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 NIKKOR 300mm f/2.8. A custom-made steel frame with the dimension of 1m×1m 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 the 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 mid-span, 710 m from the camera lens.

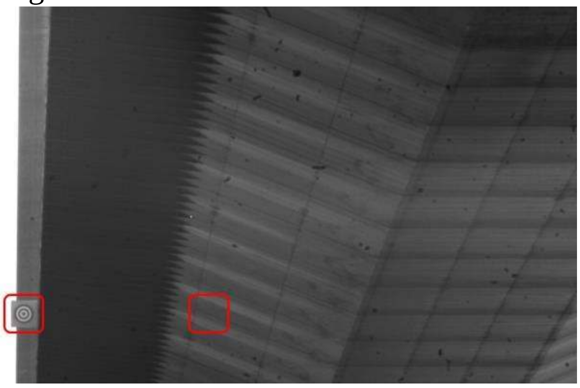
(a) Camera and controller near tower foundation (b) Custom-made target installed at mid-span

Figure 2: Camera system configuration in test of Humber Bridge

The record duration was from 11 AM to 21 PM on 22th July 2015. 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 the storage space, the image size of each frame was saved as 850×400 pixels although the default image size is 2048×1088 pixels. Both the custom-made target and the feature target at mid-span were tracked by the image processing package. Figure 3 (a) shows the view from the camera position, and (b) was 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 longitude direction of the bridge is negligible, projective transformation 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.



(a) Position of targets from the camera view



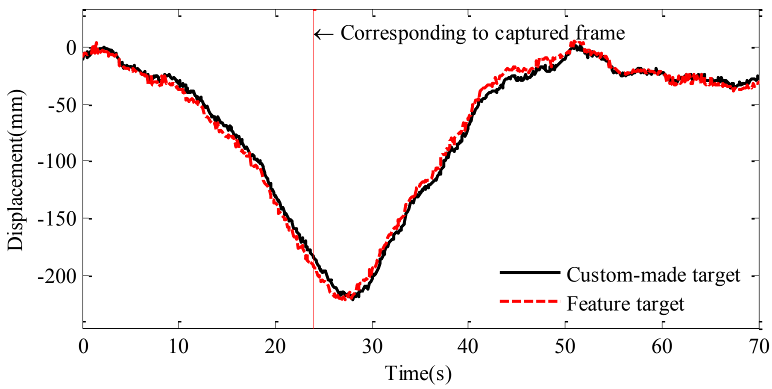
(b) Custom-made target and feature target

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

3.2 Measurement evaluation in time domain

During the test, a Nikon D800 D-SLR camera was adopted to record the video of traffic information on the bridge. Figure 4(a) was one captured frame from the recorded video when two large goods vehicles were approaching the mid-span from opposite sides. Figure 4(b) shows the corresponding measurement by vision-based system in vertical direction. The vertical deflection at mid-span caused by the two vehicles reached 221 mm. In general, the measurements by tracking two targets agree well. The vision sensor demonstrates similar performance by tracking either target.

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



(b) Vertical displacement recorded by vision-based system

Figure 4: Measurement by vision-based system when two vehicles approaching the mid-span

The long-term monitoring system of Humber Bridge, operational since 2010, includes two GPS rover receivers and three accelerometers at mid-span [13]. GPS observations were sampled at 1 Hz.

The GPS rover and custom-made target were installed in slightly different locations along the transverse direction shown in Figure 6. Before the comparison of measurement, it was necessary to compensate for deck quasi-static rotation to provide an equivalence. The cable where GPS rover was attached to is 11 m away from the centre of the box girder, while the custom-made target is located at the cantilever edge, 14m away from the centre. The tilt component in vertical direction was estimated from the variation in GPS rovers at two sides along the transverse direction.

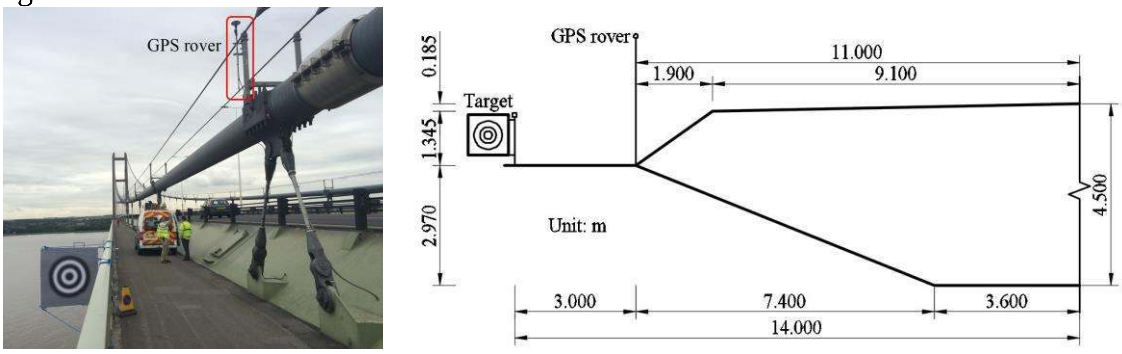
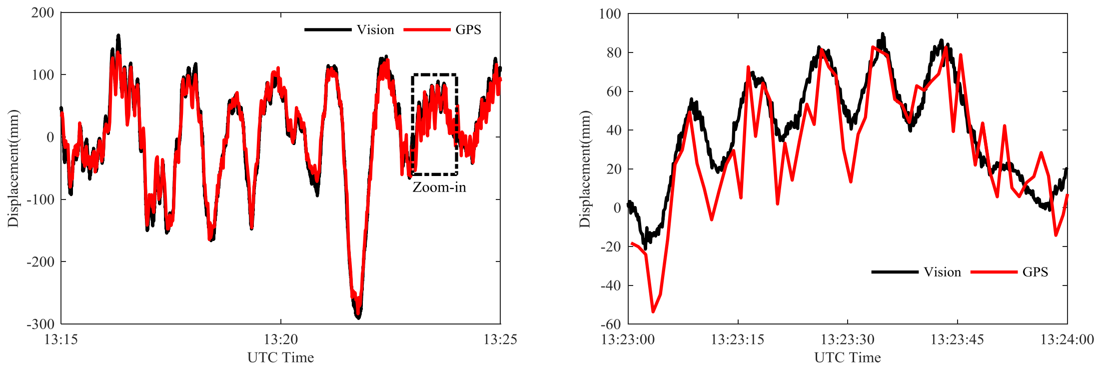


Figure 5: Position of sensors installed at mid-span

Figure 6(a) shows the vertical displacement measurement by vision-based system and the GPS receiver at mid-span. Figure 6(b) showed a zoom-in view of one-minute signals. The vision system had better performance in recording the low-frequency components, and the accuracy of GPS observation was in the centimetre-level.



(a) Ten-min signals of vertical displacement (b) Zoom of the area marked by rectangle in (a)
Figure 6: Comparison of vertical displacement by vision-based system and GPS

3.3 Measurement evaluation in frequency domain

Three single-axis accelerometers (Q-Flex QA-750), part of long-term monitoring system, are located inside the deck at mid-span. They are sampled at 20 Hz and the measurement is regarded as the reference to validate the displacement measurement in frequency domain.
The power spectrum density (PSD) computed from the measured displacement is shown in Figure 7. The GPS observations captured the first symmetric mode of vertical vibration and the measurement by the vision-based system captured the first to the fourth symmetric mode in vertical direction.

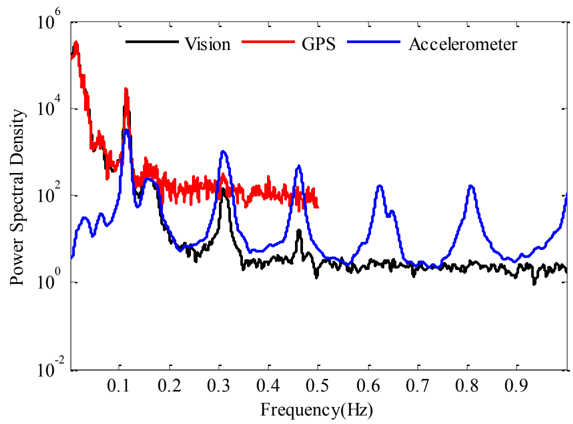


Figure 7: Power spectrum density plot of measurements by three sensors

4. DISCUSSION

4.1 Stability of vision-based system

Figure 8 showed a brief summary of the process components of a vision-based system [14]. In data acquisition part, the image sequences of region of interest were recorded in the storage devices. If more than one camera is used, time synchronization of the connected cameras is important.

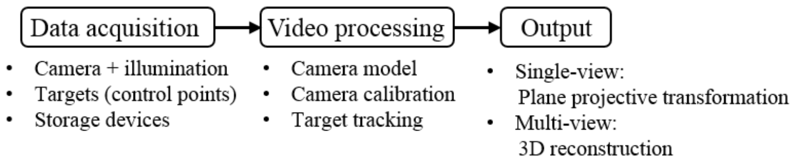
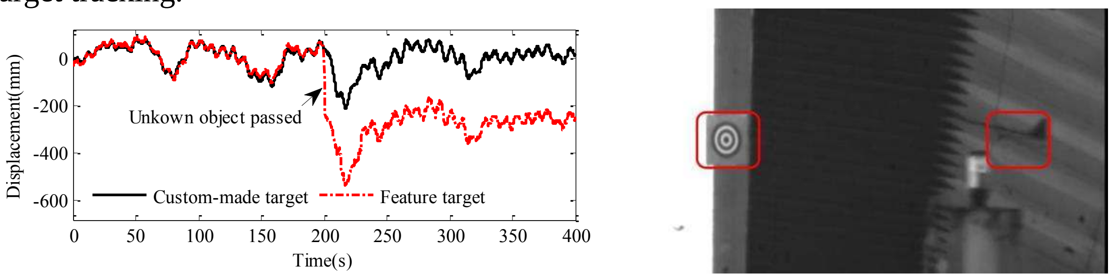


Figure 8: process components of a vision-based system [14]

The vision-based system requires a clear view 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 9 is one example during the test of Humber Bridge, and the jump of 242.38mm occurred suddenly due to a ship passing below the bridge. The displacement did not move back after the ship passing because the template image is constantly updated during target tracking.



(a) Time history of vertical displacement (b) Captured frame from recorded video

Figure 9: An object passing through the line of the sight

The system is easily affected by the environmental conditions such as illumination or weather changes. Measurement by vision-based system is easily influenced by shading and lighting. In the test, about one hour before the sunset period, the target panel on the east side was located in the shadow of the bridge railings shown in Figure 10. The video frame flickered when tall vehicles passed through and obstructed the sunlight from the west, casting the shadows. This flickering situation was observed by eye as well and was 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. No active illumination was provided for the targets in this test. As night fell, the steady exposure was reached at the expense of gradually decline of sampling rate. The recording was stopped at 9 PM 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.

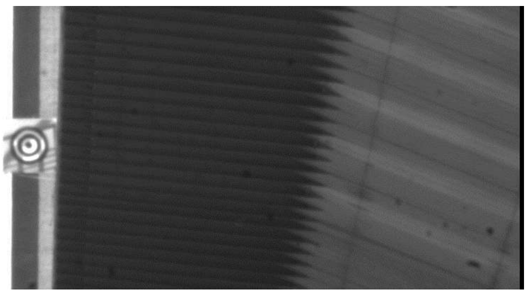


Figure 10: Target panel in the shadow of railings

For the single-camera system, the projective transformation between the target plane and image plane relies on the coplanar point or line correspondences. During the test, the known dimensions of the custom-made target were used for the calibration. If the region of interest in the bridge already has at least four coplanar points with known coordinates or three coplanar lines with known dimensions, the artificial target could be avoided. Scaling factor method is the special case of projective transformation. It is only suitable when the optical axis of the camera is exactly perpendicular to the target plane.

Single-camera system could only export two-dimensional displacement based on the assumption that the motion in optical axis direction is negligible. In the Humber Bridge test, the optical axis of camera was nearly perpendicular to the target plane and the out-of-plane motion (longitude displacement of the bridge) was relatively small in short term. However if the two-dimensional reconstruction process is highly sensitive to the out-of-plane motion, the in-plane displacement result might include significant errors [15]. Three-dimensional measurement could be reached by using two cameras in stereoscopic configuration, depending on the application requirements.

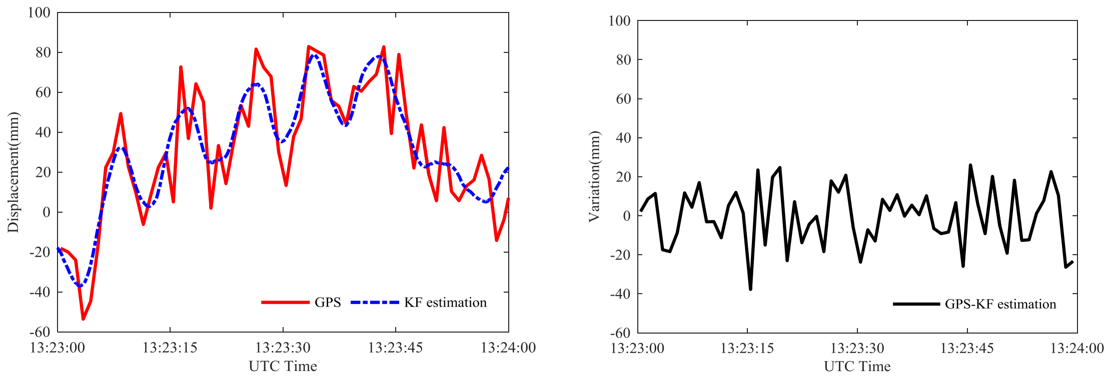
The vision-based system requires fixed position and orientation of cameras, but they are often changed slightly because of wind, oscillations and the lack of stability of ground in the field test. The effect of camera movement is included in the measured displacement and the error is more obvious in long-range measurement. Camera movement correction [16] is necessary to build a robust vision-based system.

In summary, vision-based system is a good option for short-term displacement measurement under operational conditions since it has satisfactory performance in accuracy level and frequency range. However, with the limitations considered, currently it could not replace the standard sensor GPS in long-term monitoring.

4.2 Data fusion to improve measurement accuracy

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 the system identification such as direct identification of influence lines and weights for vehicles with varying speed, tying into model validation, calibration and updating, etc..

The accuracy of GPS measurement is in centimetre level, which is not satisfactory for applications in structural identification. Other than finding high-accuracy sensors, an alternative way is to improve GPS measurement by fusing additional observations. 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 multi-rate Kalman filtering algorithm with backward smoothing was applied to merge the GPS observations with the collocated acceleration signals [17]. The expectation–maximization (EM) algorithm was applied to tune the noise parameters before the fusion. Figure 11(a) shows the estimation result of vertical displacement in the Humber test. The estimated displacement can lower the GPS noise at high-frequency range and broaden its frequency bandwidth. Figure 11(b) is the predicted noise in GPS observations with the root mean square of 14.806 mm.



(a) Vertical displacement time histories (b) Variation between two signals

Figure 11: Comparison of vertical displacement by GPS measurement and Kalman filter estimation

4.3 Next steps

The vision-based system allows for distributed sensing by tracking multiple targets simultaneously. 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 robustness of the vision-based system is weakened due to the sensitivity to the environment conditions such as heat haze, illumination and camera vibration, etc.. Future work should be carried out toward robustness improvement.

Data fusion is an effective way to improve the accuracy level of GPS observations. Kalman filtering is an on-line prediction tool. When the smoothing and EM algorithms were used to improve the estimation, the method lost the feature of on-line estimation, thus not suitable for the case requiring real-time signals. The feasibility and accuracy of real-time estimation needs further investigation.

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