Remote real-time monitoring of tunnelling-induced settlement using image analysis

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ABSTRACT: A new image-based deformation measurement technique has been developed for real-time monitoring of construction settlements. This development combines the technologies of remote digital photography, automated file transfer, the image processing technique of Particle Image Velocimetry (PIV), and a web-based reporting system. This paper describes the technology behind this new development and presents key observations from its application to the monitoring of tunnelling-induced settlements of a retaining wall in real-time as construction progressed. Additional data is presented from a validation exercise in which the performance of the technique is shown to be comparable to conventional surveying techniques.

1 INTRODUCTION

The Channel Tunnel Rail Link (CTRL) is the first new section of major mainline railway to be constructed in England in over one hundred years and will reduce the travel time between London and Paris to 2 h 15 m. This target will be achieved by routing 36 km of the high-speed railway under one of the densest urban areas in Europe.

Contract 220 of the CTRL comprises two 7.15 m inside diameter tunnels between Stratford, in east London, and St Pancras station in central London. To minimize interference with existing above- and below-ground infrastructure, much of the route is aligned below the North London Line (NLL) railway. Here, the NLL mainly runs within deep cuttings supported on both sides by Victorian masonry retaining walls with buildings founded immediately behind the walls. Excessive settlement or distortion of these masonry walls during tunnel construction activities could lead to settlement and building damage. Further, even minor spalling or other damage to the masonry retaining walls could pose a hazard to trains travelling on the NLL running corridor which carried traffic 24 h a day during the tunnelling programme.

In response to the risks associated with volume loss during tunnelling activities, an extensive ground, rail-line, and building movement monitoring programme was conducted by multiple teams of surveyors equipped with precise levels and total stations. To further ensure the safety of rolling stock travelling on the NLL running corridor, observers were stationed at trackside at critical locations to provide a 24 h visual inspection.

Along the tunnelling route, one particular section of Victorian masonry retaining wall was identified as being particularly at risk as it exhibited the characteristic signs of a long history of deformation – existing cracking, significant out-of-plane mid-span deflection and evidence of recent and historical repairs. To provide additional monitoring of this structure, a new digital image-based remote monitoring system was trialled to complement the conventional survey monitoring programme in which the tunnelling-induced movements of the retaining wall were remotely monitored in real-time.

This paper describes the technology behind the remote measurement, automated file transfer, image analysis, and web-based reporting systems which were combined in this field monitoring technique, and presents salient observations of the monitored wall displacements. Additional data from a validation exercise is presented, to assess the precision of the system and to demonstrate the potential for wider application of this method. It is shown that this new technique offers performance that is comparable to conventional surveying.

2 BACKGROUND

Conventional monitoring of tunnelling-induced building and ground surface movements uses precise levelling or a total station. A modern digital level has a typical quoted precision of 0.3 mm over a sight of up to 60 m which corresponds to 1 arc second. A modern total station has a typical quoted precision of 2 arc seconds. A typical monitoring exercise might require a survey transit of 100 metres from the stationary datum point to the monitoring point. The resulting precision of conventional surveying methods can therefore be up to 0.5–1 mm. However, the actual precision of settlement monitoring on a site such as this – with access constraints, frequent trains, an electrified railway – will be lower than the quoted value. Thus, it is not surprising that on Contract 220 typical random scatter on the order of 2 mm was observed between settlement measurements taken at intervals of a few hours by a mobile team of surveyors.

3 IMAGE-BASED MONITORING SYSTEM

The use of digital cameras to make precise deformation measurements in small-scale geotechnical modelling is described by White et al. (2001, 2003a). The resulting measurements are of comparable precision to that achievable using conventional displacement transducers (e.g. LVDTs, proximity sensors), and have significantly improved the utility of geotechnical physical modelling in recent years.

This paper describes the further development of this technology into an alternative technique for the measurement of tunnelling-induced settlements. The analysis is performed in real-time, and reported via the world-wide web. The system is shown schematically in Figure 1.

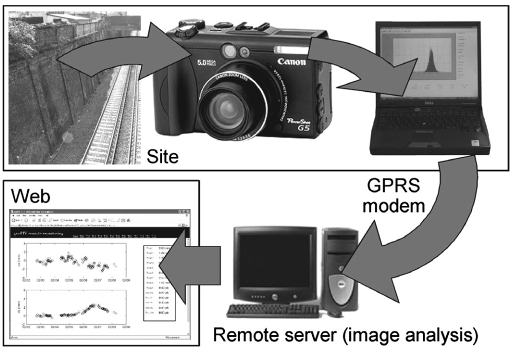

Figure 1. Schematic diagram of image-based monitoring system.

3.1 *Image capture and transfer*

Images of the structure to be monitored must be captured in digital form. Unlike video cameras, which typically operate at the resolution of TV systems, digital still cameras offer higher image resolution, allowing more precise optical measurements to be made. The digital camera is controlled directly from a stripped-down remote computer, which is also equipped with a GPRS modem that allows images to be uploaded to the remote server for subsequent analysis. The camera and PC are housed in a reinforced and camouflaged box.

3.2 *PIV image analysis*

When uncompressed, a digital image is simply a matrix which contains the intensity (brightness) recorded at each pixel on the Charge Coupled Device (CCD) of the camera. Colour images consist of three intensity matrices, one for each of the red, green and blue colour channels. By comparing the intensity matrices of a pair of images taken at slightly different times using a technique known as Particle Image Velocimetry (PIV), the settlement at any location in the image during this time period can be calculated. The measurement technique of PIV was originally developed in the field of experimental fluid mechanics to recover instantaneous velocity fields from photographs of seeded flow. The technique has been recently applied to geotechnical physical modelling (White et al 2001, 2003a).

PIV calculates the displacement of a set of points within an image that are defined by interrogation patches. A displacement vector is calculated for each interrogation patch by correlating that patch with a larger search region taken from a subsequent image (Fig. 2). The highest peak in the normalised correlation plane indicates the best match between the interrogation and search patches. This best match reveals the displaced position of the interrogation patch. The displacement vector is established to

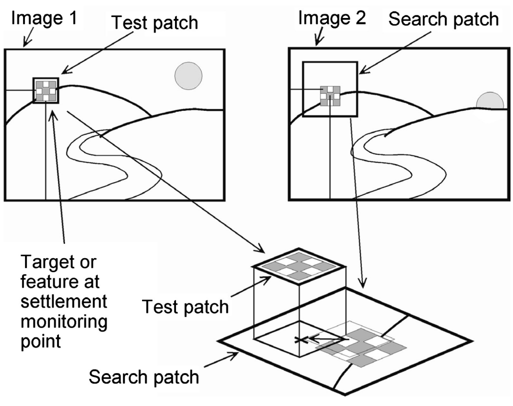

Figure 2. PIV image analysis process.

sub-pixel precision by interpolating over the correlation peak. This process can be repeated through a series of captured images to find displacement trajectories.

The precision of PIV measurements depends on the software algorithms, the image quality, and the analysis parameters. Different versions of PIV software use alternative correlation algorithms and sub-pixel interpolation methods (White et al 2004). Validation experiments show that when using artificial images, the precision of the PIV software used in this project (GeoPIV, White & Take 2002, White et al 2003a) can be better than 1/100th of a pixel. This precision exceeds values obtained in similar validation experiments using other PIV algorithms.

The bar code measurement technique used in modern digital total stations is based on the same principle as PIV. Digital total stations contain a one-dimensional CCD and a hard-coded version of the bar code. The image captured by the CCD is scaled and shifted relative to the hard coded version in order to find the best correlation. The optimal shift indicates the relative level of the bar code target and the scaling indicates the distance. The new system described in this paper is effectively a two-dimensional version of this approach. Instead of requiring bar-coded targets, any object can be monitored. A previous image of that object is substituted for the hard-coded version of the target. It is interesting that the two techniques have evolved in parallel, originally for different applications.

The early use of PIV in fluid mechanics required the fluid to be seeded to create features upon which the image processing can operate. For monitoring structural movements, the natural 'texture' (spatial variation in brightness) of these objects, such as brickwork, is often sufficient. However, it can be useful to place markers on the monitored structure to obtain a local measurement of image scale.

3.3 *Real-time web-based reporting*

To provide real-time monitoring, the displacement data is automatically calculated by the PIV software running on the remote PC as soon as a new image is captured and uploaded from site. These results are added to a database that automatically generates a series of web pages which provide plots of settlement against time for each monitoring point, and show the current image and net displacement vectors for each camera view (Fig. 3).

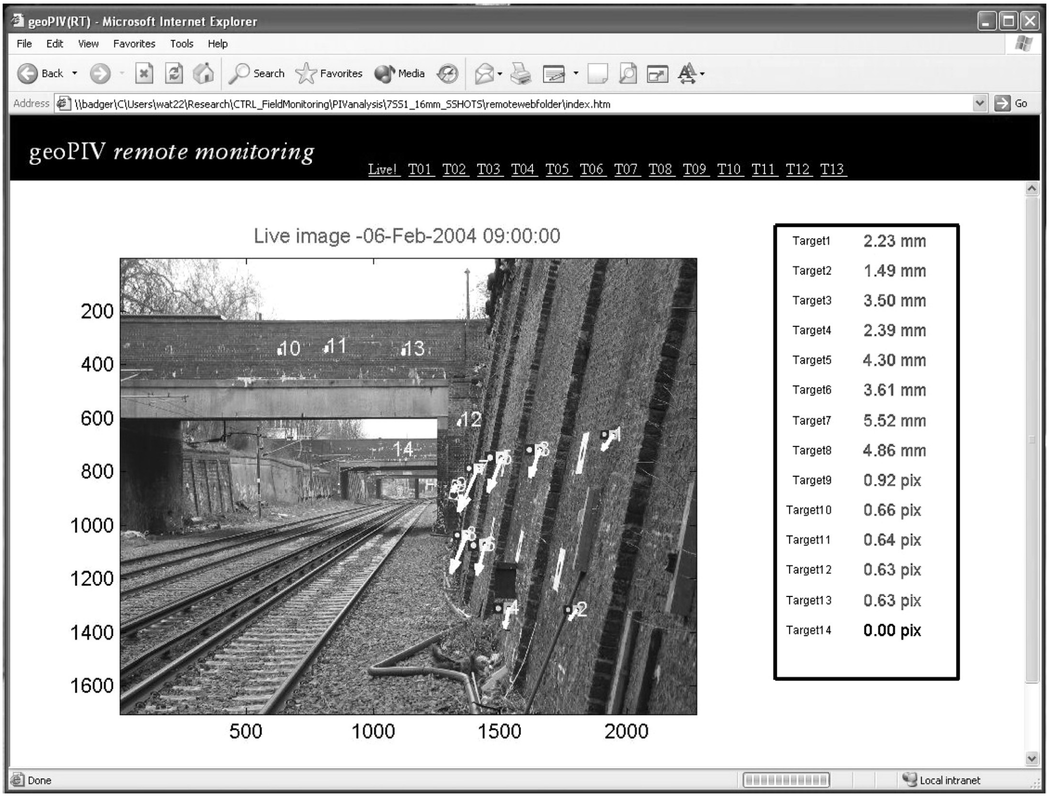

Figure 3. Real-time settlement data reported via a web page (view from camera S1 at 0900 on February 6th 2004).

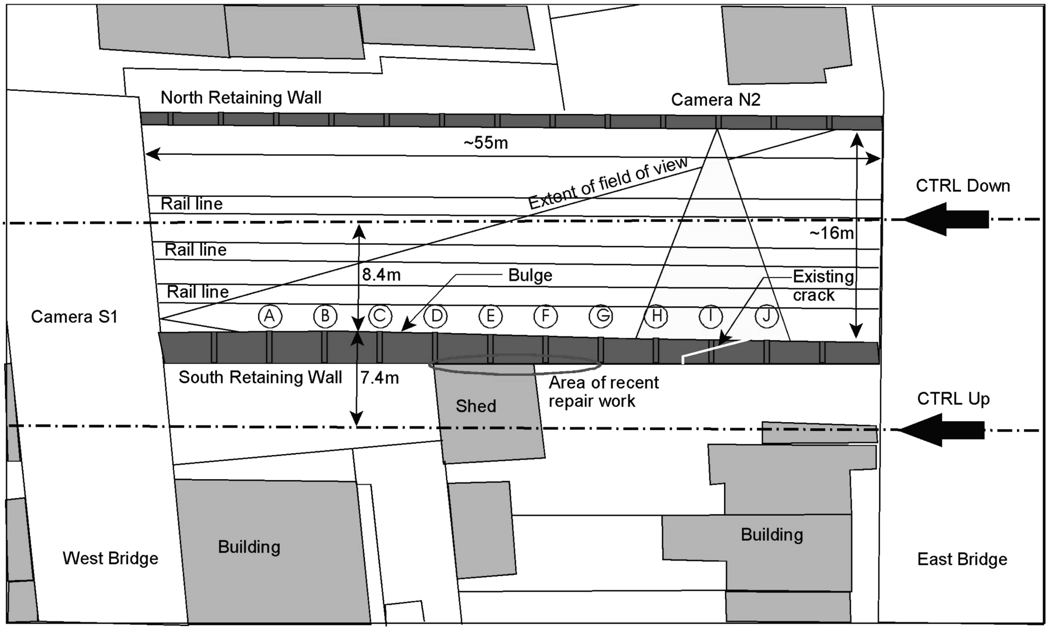

Figure 4. Site plan of monitoring trial.

4 SETTLEMENT MONITORING TRIAL

4.1 *Test site*

The new system was used to monitor the movement of a Victorian masonry retaining wall in a cutting on the North London Line. At this location, the masonry retaining wall is approximately 55 m long, 5 m high, and is bounded to the west and east by bridges. The south wall is divided into 13 bays separated by 12 ribs, labelled A to J in the field of view (Fig. 4). The retaining wall on the south side of the cutting was considered particularly vulnerable to tunnelling-induced ground movements. Repairs to the brick work are evident, and the top section of wall bounded by ribs D-G had recently been reconstructed. Unlike the neighbouring sections of the cutting, the masonry wall at the test site is not anchored. Possibly as a result, the wall is bowed outwards at the midspan, and had a significant shear crack between ribs H and J prior to tunnelling (Fig. 4). The CTRL upline bore passes parallel to the south wall at an offset of 7.4 m and was constructed first. The downline bore was also aligned parallel to the retaining walls and passed under the approximate centre of the footprint of the cutting at an offset of 8.4m from the wall. Monitoring of the south retaining wall was performed using the new image-based system during the passage of this downline TBM.

4.2 *Camera arrangement*

Two Canon G3 digital cameras were used to observe the wall. The first camera, denoted S1 in Figure 4, was fixed on the west bridge, viewing parallel to the south wall, to capture vertical settlement and out-of-plane wall movement. A second camera, denoted N2 on Figure 4, was located on the north side of the cutting, facing directly towards the eastern end of the south wall. This position was selected to allow monitoring of the existing shear crack between ribs H and J.

4.3 *Targets*

High contrast targets comprising two black and white circles painted on a metal plate were fitted on ribs B-E to provide discrete monitoring points. The targets are visible and numbered on Figure 3 and their locations in plan are shown on Figure 4a. These targets allowed the image scale (mm/pixel) to be found at each rib, since the actual separation of the circles (in mm) was known, and the separation in image-space (in pixels) could be measured. By placing two rows of targets at low and high level, any rotation of the wall could be identified.

4.4 *Monitoring results*

4.4.1 *Wall settlement: Camera S1*

All settlement measurements are relative to a datum established by image analysis on the distant bridge

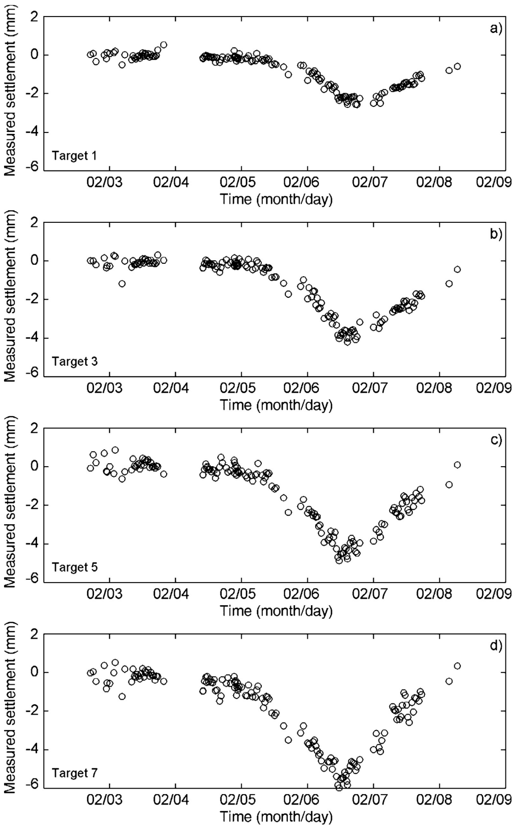

Figure 5. Vertical settlement history of targets 1,3,5, and 7.

(120 m east of the camera) shown in the captured image of the web-based reporting tool in Figure 3. This constantly updating webpage shows the latest image of the site with the displacement vectors of each target superimposed. Here, the datum is labelled as Target 14, and was assumed to be stationary during the period of monitoring due to its distance from the TBM.

The monitoring period began at 16.40 on February 2nd 2004. As shown in the settlement history of targets 1, 3, 5 and 7 in Figure 5, negligible movement was recorded during the first 22 hours of baseline readings. The average scatter recorded at targets 1 and 7 during this period was ∼0.1 and ∼0.25 mm respectively (Figure 5). The higher noise at target 7 reflects the greater camera-to-target distance. During the evening of February 5th, settlement was detected at target 7. Progressive settlement of all 4 targets is evident as the TBM advanced beneath the wall. Target 7 settled quickest at a rate of ∼0.15 mm/hour. The maximum settlements of targets 1, 3, 5 and 7 increase in sequence towards the centre of the wall, indicating sagging. As the tunnel passed under the west bridge, the

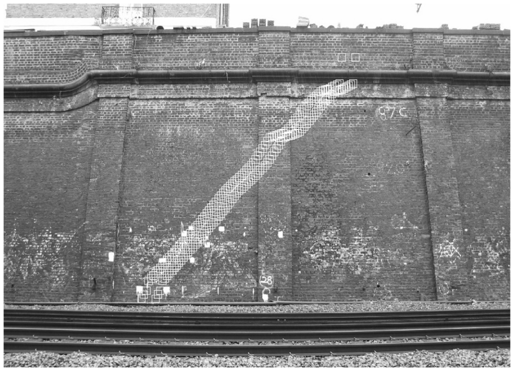

Figure 6. Camera N2: PIV patches as crack width gauges.

camera itself settled, leading to settlement measurements that were no longer absolute, but relative to the settlement of the west bridge (i.e. note change in settlement direction). This movement of the west bridge does not prevent the differential movement along the wall being calculated. Targets 1, 3, 5, and 7, which are spread along 15 m of the wall, show final movements within 1 mm of each other, indicating a differential movement of $<1/15000$. The out-of-plane wall movement, which is not presented in this paper, did not exceed 3 mm. The maximum wall settlement relative to the west bridge did not exceed 6 mm.

4.4.2 *Wall distortion: Camera N2*

Camera N2, viewing across the cutting, allowed the shear crack between ribs H and J to be monitored. The change in width of this crack was measured by analysis the relative movements of pairs of PIV patches located on either side of the crack. Figure 6 shows these measurement patches which acted as a set of 87 remotely-monitored crack width gauges. The differential movement that was recorded across the crack was at the level of noise (1/10th of a pixel). By applying an appropriate scale factor, it is calculated that the movement across the crack was less than 0.8 mm.

5 VALIDATION EXERCISE

The site trial described above shows the potential of this new monitoring system. In order to assess the performance and robustness of the system in a more controlled manner, a validation exercise has been conducted. The influence of factors such as variations in lighting and inadvertent camera movement and rotation on the precision and accuracy of the system has been investigated.

Part of this validation exercise involved the controlled movement of a target, to allow the movements measured by the image-analysis system to be compared with actual movements. White et al (2003a) report a series of similar validation experiments conducted at small scale in laboratory conditions. This new validation exercise was conducted at a scale comparable to a typical field application, using targets located up to 30 m from the camera.

Figure 7 shows an example set of results comparing the applied and measured movement of a target located 20.5 m from the camera. The target was mounted on a miniature machining table and moved a total distance of 90 mm in 23 steps of increasing size. The images were captured by a Canon G5 camera which was set in a wide angle zoom mode. The resulting field of view was 9.4 m wide at the distance of the target.

The RMS discrepancy between the applied and measured movement during the validation experiment was found to be 0.17 mm, or 1/57000th of the field of view. Part of this error may arise from the control of the machining table. Noting that the image width is 2592 pixels, this error can be expressed in image-space as 0.045 pixels. This is in agreement with a value of 0.04 pixels found in a more rudimentary large-scale validation exercise using the same PIV software reported by White et al (2003b).

It should be noted that measurement noise is best expressed as a fraction of the field of view or preferably in image-space units of pixels, rather than as absolute values (in mm). Measurement noise introduced during image processing is an image-scale effect. If the image

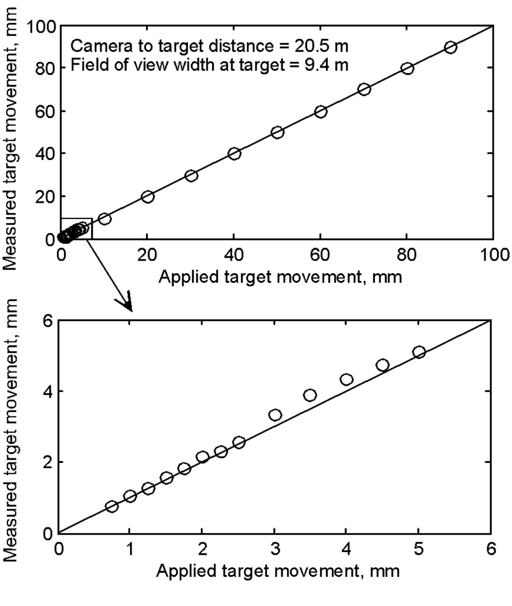

Figure 7. Example results from large-scale validation exercise.

scale (mm/pixel) is reduced by increasing the camera zoom setting or raising the CCD resolution, the measurement noise in absolute terms will decrease. If only the zoom setting is changed, the measurement error from the image processing remains the same fraction of the field of view.

The performance observed in this validation exercise is comparable to conventional surveying equipment. The RMS error of 0.17 mm at a range of 20.5 m represents an angular error of 1.7 arc seconds, which compares well with that achievable using a digital total station (typical precision 2 arc seconds). The image-based system allows an unlimited number of measurement points to be automatically analysed within each image. The wide-angle zoom setting used in this exercise corresponded to a 25° field of view. The measurement error can be reduced by using a narrow-angle zoom setting, although this also reduces the field of view.

6 CONCLUSIONS

This paper describes a new image-based system for remote monitoring of ground and building movements. The system is based on digital photography and PIV image analysis, and allows real-time settlement data to be disseminated over the internet. The system was successfully used to monitor the deformation of a Victorian masonry retaining wall adjacent to the North London Line, whilst the CTRL TBMs passed below. Measurements of wall movements displayed a measurement noise of less than 0.25 mm and indicated that the wall displaced outwards less than 3mm and settled by less than 6mm. A pre-existing shear crack running the full height of the wall was monitored throughout tunnelling. Remote measurements from 87 'virtual' crack width gauges showed that crack displacements did not exceed 0.8 mm.

Results from an additional validation exercise conducted to establish the potential of this new image-based system have been presented. These results demonstrate performance that is comparable to digital levels and total stations. The frequency of measurement, multiple measurement locations and internet-based dissemination offered by this system, plus the visual surveillance provided, represent significant benefits compared to conventional methods.

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