
Combination of GPS and RTS measurements for the monitoring of semi-static and dynamic motion of pedestrian bridge

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Abstract. GPS and accelerometers have been broadly used the last decade for the monitoring of flexible structures and bridges, while Robotic Total Station (RTS) has been successfully assessed for the monitoring of slow and dynamic motions. Further experimental studies have revealed specific drawbacks of the GPS (multipath, etc.) and RTS (clipping, etc.) monitoring techniques and how these can be surpassed by their combined use. In the current study, we assess the performance of the complementary use of GPS and RTS for the monitoring of the semi-static and dynamic displacement of a relatively rigid pedestrian bridge, with main modal frequency more than 1Hz.

Two RTS and GPS receivers were synchronised monitoring the deflection of the two sides of the mid-span of the bridge, while pedestrians excited the bridge. Several excitations (walking, marching, jumping, etc.) were examined, causing semi-static and/or dynamic displacement of the bridge, and rotation of the deck, of different amplitude and frequencies. The analysis of the RTS and GPS time-series, which was based on spectral analysis and band-pass filtering of the time-series, resulted to low- and high-frequency component expressing the semi-static and dynamic displacement. Finally, the combination of the GPS and RTS time-series made possible the estimation of 1-4mm semi-static displacement, the 5-10mm dynamic displacement and the estimation of the main modal frequencies.

Keywords. GPS, RTS, pedestrian bridge, semi-static, dynamic, filtering, modal frequency

1 Introduction

There has been a great interest in the recent years for the monitoring of the structure response, as the latter is being used for the design of structures (Bardakis and Fardis, 2011) and the estimation of

the structural health, leading to the maintenance of the structure (Knecht and Manetti, 2001; Psimoulis and Stiros, 2011; Moschas and Stiros, 2014). Until the last decade, the structure monitoring was based mainly on accelerometers, strain gauges, etc., providing mainly the frequencies of the structure motion and the corresponding strain. However, the introduction of the geodetic sensors and mainly GPS contributed significantly to the estimation of the displacement of the structure in a Cartesian coordinate system, independent of the structure.

Apart from the GPS, and recently GNSS systems, which is mainly used for the bridge monitoring (Meng et al., 2007; Roberts and Brown, 2010), other geodetic techniques, such as Robotic Total Station (Stiros and Psimoulis, 2012; Psimoulis and Stiros, 2013), interferometric radar (Dei et al., 2009; Gentile, 2010) and combination of Total Station with camera (Charalambous et al., 2015) have been recently introduced for more accurate estimation of the structure displacement. The geodetic techniques have different advantages and limitations for monitoring long- and short-period deflection of structures, resulting many times in their combined use in order to overcome their drawbacks and estimate reliably the structure response (Moschas et al., 2013). The GPS can record high frequency oscillations, but the signal-to-noise ratio reduces for small amplitude oscillation, below cm-level (Psimoulis and Stiros, 2012). On the other hand, RTS seem to be more suitable for small amplitude oscillations (a few mm), of low frequency (<2-3Hz), with high signal-to-noise ratio, having problems though such as the clipping, jittering etc (Psimoulis and Stiros, 2007; Stiros et al., 2008).

In the current study, we assess the use of GPS and RTS for the monitoring of long- and short-period response of a pedestrian bridge and the estimation of the corresponding characteristics (amplitude and frequency). The bridge was excited in many different ways, varying in load type and load



weight, aiming to examine the accuracy and the performance of the GPS and RTS for the different responses of the bridge. This study tests the limitations of the two techniques and shows that by using the appropriate analysis methods, is possible to estimate reliably the response of the bridge by reducing the noise of the two instruments.

2 Monitoring of Wilford Bridge

The Wilford suspension bridge is a pedestrian bridge (Fig. 1), consisted of two masonry anchorages and two main cables supporting the deck. Many studies have been made in the past from the University of Nottingham aiming to assess the GPS for bridge monitoring and to develop techniques improving its accuracy (Meo et al., 2006; Meng et al., 2007; Roberts et al., 2010). The bridge is characterised by displacement of up to few cm level and modal frequencies more than 1Hz (Meo et al., 2006), making it an ideal structure for monitoring testing. The bridge is constructed in 1904 with a span of 3.65m wide and 68.58m long, and it is composed of a steel deck covered by a floor of wooden slats. In 2010, the bridge was reopened after a 2-year renovation period, leading to possible modification of the main modal frequencies (Yu et al., 2014).

For the monitoring of the pedestrian bridge were used three GPS receivers, two RTS, an IMU and an inclinometer. The two GPS antennas were mounted with two 360° reflectors on top of the handrails at the two sides of the midspan, while the IMU and the inclinometer were installed, also, at the midspan at the deck level. The two reflectors were monitored by the two RTS (Leica TS30 and TS50) from a distance of ~70m, with capacity of sampling rate up to 10Hz (Fig. 2). Regarding the GPS stations, they



Fig. 1: Wilford pedestrian bridge

were consisted of a Leica antenna type AS10 and receiver GS10. The third GPS station was set about 100m far from the bridge, used as the reference station for the bridge monitoring. The midspan was selected, as this was the point where the maximum displacement was expected from the bridge excitation.

The bridge was excited by a group of 15 people, who produced four different types of vibrations of the bridge. More specifically, they excited the bridge by walking, jumping, swaying laterally to the bridge and marching. In total there were 12 different events of excitations, varying in type and load. All the excitations lasted from 30 to 60s. For the purpose of this study, we focused on three events (walking, jumping and marching), for the pair of the GPS and RTS records from the same side of the midspan. The IMU and the inclinometer sensors were used in this study only for the verification of the excitation starting and ending time.

3. Data analysis

3.1 GPS/RTS records preliminary processing

The GPS records were processed using the software Leica Geo Office 8.3. During the measurements there were 9 GPS and 9 GLONASS visible satellites. In order to be consistent with the GPS monitoring of the bridge from previous studies (Meng et al., 2007; Meo et al., 2006), we used only the GPS measurements. The cut-off angle was set to 15° and ambiguities were fixed to both L1/L2 frequencies. The GPS records processed in kinematic mode, resulting in coordinate time series of North, East and vertical component.



Fig. 2: The RTS with the GPS station for recording in GPS time (left) and the GPS antenna with the reflector mounted on the handrail at the midspan of the bridge (right).

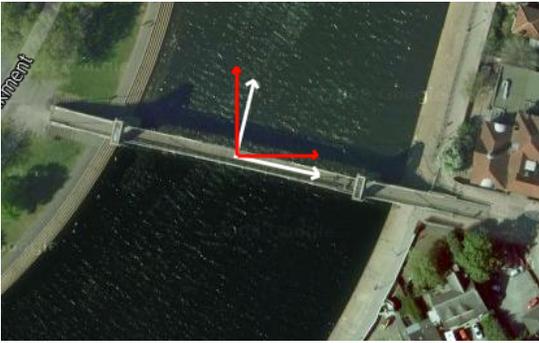


Fig. 3: The GPS coordinate system (N,E,U; red axes) and the bridge coordinate system (lateral, longitudinal, vertical; white axes), both in plan view. The vertical component is component between.

Then, the NEU coordinate system of the GPS time series was transformed by rotating clockwise, in order to coincide with the bridge coordinate system. Thus the NS and EW GPS timeseries were transformed into the lateral and the longitudinal axis of the bridge (Fig. 3).

Regarding the RTS, it was recording in GPS time, thanks to the integrated GPS station with the RTS (the Leica Viva Smartstation), and in a Cartesian coordinate system which was pre-defined according to the coordinate system of the bridge. Thus, the RTS records provide directly the kinematic coordinates in the coordinate system of the bridge (longitudinal, lateral and vertical).

Finally both GPS and RTS time series were transformed by shifting their origin point, in order the latter to correspond to the equilibrium of the monitoring station. Thus, the mean average of the first 60 seconds for each time series was subtracted and then the time series corresponding to the displacement of the lateral/longitudinal/vertical axis derived.

3.2 GPS/RTS time series analysis

In Figure 4 are presented the vertical GPS and RTS time series for the entire duration of the measurements. It is clear that the RTS time series express mainly the vertical displacement of the bridge due to the excitations, which varies depending on the type of the excitation. The GPS time series are clearly affected by long-period noise, expressing probably obstruction error (e.g. by the cables), multipath error, etc. (Moschas et al., 2013), making difficult the detection of the displacement due to the excitation. However,

further analysis can be applied for the estimation of the deflection displacement from the GPS time series.

The current study focused on the 3rd, 4th and 10th excitation, which corresponds to walking, jumping and marching. Each excitation period was analysed separately by following the same methodology.

The main aim of the methodology was to analyse the initial time series and separate it to two time series of long-period and short-period component expressing potentially the semi-static and the dynamic displacement of the bridge. Afterwards, the amplitude of the semi-static and the dynamic displacement will be estimated according to the amplitude of the long- and short-period component during the excitation period. The separation of the initial time series to the short- and long-period

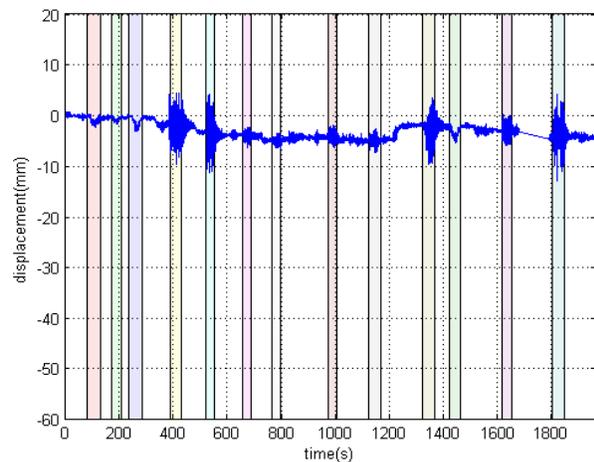
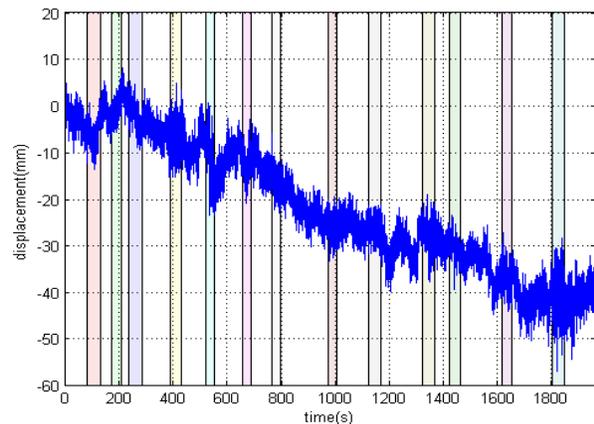


Fig. 4: The GPS (top) and RTS (bottom) vertical time series for the entire duration of the measurements. The different colour zones define the period of each excitation.

component was made by applying high- and low-pass Chebyshev filter of 8th order, with the cut-off frequency defined according to the sensor and its data characteristics.

More specifically, the cut-off frequency for the RTS was 0.1Hz in order to detect the semi-static long-period component, while for the GPS the cut-off frequency was 0.5 Hz, in order to remove the long-period noise from the dynamic component. Furthermore, the sampling rate of the filters was different between the GPS and RTS, as for GPS it was 10Hz, while for RTS was varying depending on the mean sampling rate corresponding to each excitation.

Finally, the last step of the analysis was the spectral analysis of the short-period components of the GPS and RTS time series, aiming to the estimation of the main frequencies of the motion and the detection of the main modal frequencies of the bridge. For the spectral analysis, the use of Lomb-periodogram was selected due to the unevenly-spaced data of the RTS (Pytharouli et al., 2008; Psimoulis and Stiros, 2008). However, due to the strong dynamic signal of the displacement, technique such as DFT would lead in similar results.

The above methodology was used for the GPS and RTS time series using the same techniques and parameters. However, the semi-static displacement was estimated only based on the RTS long-period component, due to the significant noise level of the GPS long-period component, which cannot make possible the detection of semi-static displacement.

3.3 Walking excitation

In Figure 5 and 6 are presented the GPS and RTS initial time series and the corresponding short- and long-period component (the latter only for RTS). The long-period component of the RTS time series is clear that, it expresses the semi-static displacement, reaching the amplitude of 2.4mm. Regarding the short-period component of the GPS, the signal during the excitation period is of similar amplitude as before or after the excitation. More specifically the amplitude during the excitation is about ± 4 mm, while the noise level before or after the excitation is about ± 3 mm. Thus, the estimation of the dynamic component is not reliable.

Likewise, the RTS short-period component exceeds slightly the noise level (± 0.4 mm), reaching the amplitude of 1mm, making unclear whether this expresses dynamic displacement. However, the spectral analysis reveals three main frequencies of

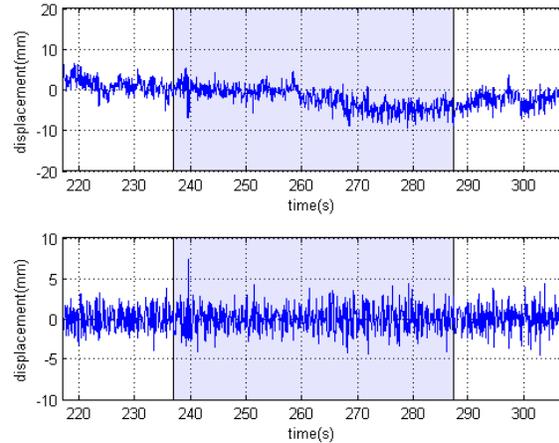


Figure 5: The initial (top) and the short-period time series (bottom) of the GPS for the walking excitation.

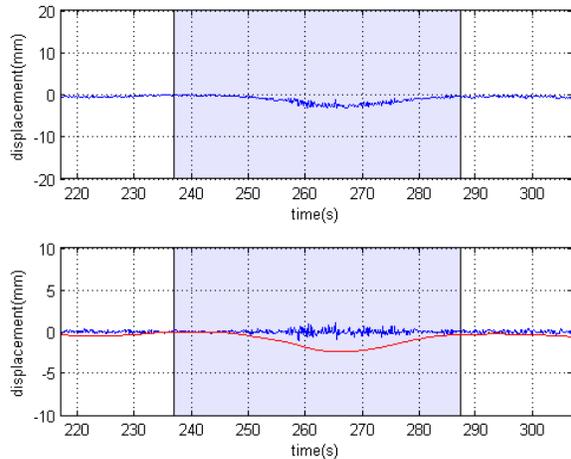


Figure 6: The initial (top) and the short-period time series (bottom) of the RTS for the walking excitation. The red line indicates the long-period component.

1.7Hz, 1.89Hz and 2.03Hz (Fig. 7), which are statistically significant, corresponding to potential modal frequencies of the bridge.

3.4 Jumping excitation

The filtering of the initial GPS time series for the jumping excitation reveals the short-period component, which is a signal combination of noise and dynamic displacement (Fig. 8); the maximum estimated dynamic amplitude is about 8mm. From the RTS time series analysis, it is observed that no

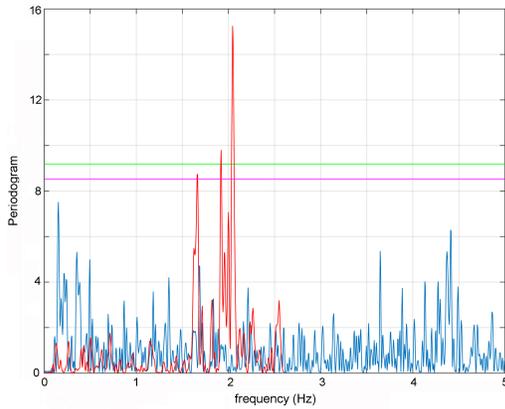


Figure 7: The spectrum of the short-period component of GPS (blue line) and RTS (red line) for the walking excitation, with the purple and green corresponding to the 95% confidence level.

significant semi-static displacement derives from the long-period component, while the short-period component is characterised by clear signal of dynamic displacement, exceeding the noise level, reaching up to $\pm 8\text{mm}$ (Fig. 9). Furthermore the spectral analysis of the short-period component of GPS and RTS revealed the main frequencies of 1.6 Hz (Fig. 10), while there are other neighboring frequencies both for GPS and RTS, corresponding probably to the same modal frequency and is the result of signal leakage. The RTS detect also a frequency of 2.2Hz, which is not though statistically significant.

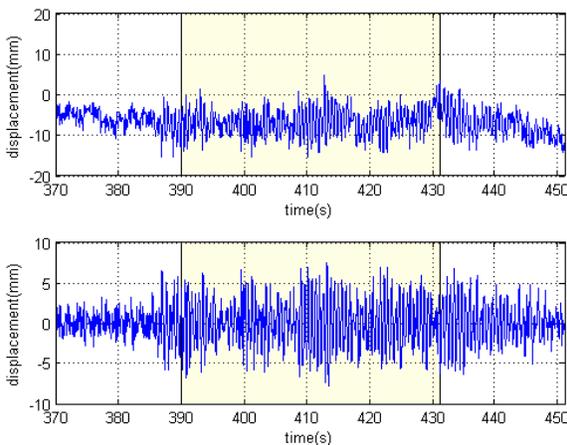


Figure 8: The same plot as Figure 4 for the GPS for the jumping excitation.

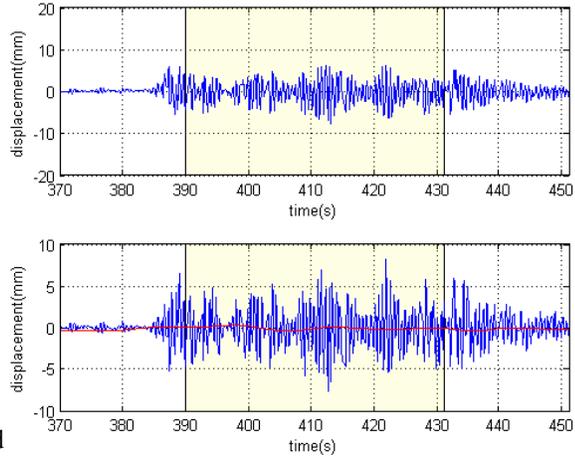


Figure 9: The same plot as Figure 5 for the RTS for the jumping excitation.

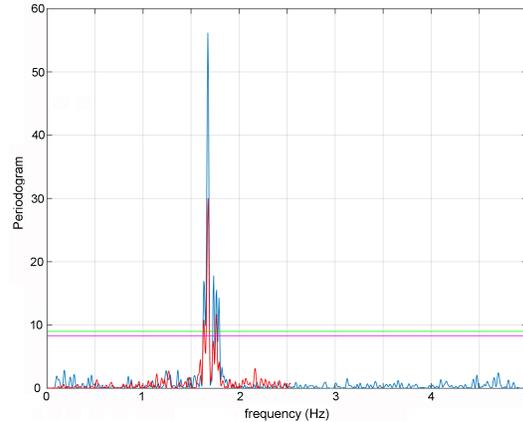


Figure 10: The same plot as Figure 6 of the spectrum GPS and RTS for the jumping excitation.

3.5 Marching excitation

Regarding the marching excitation the GPS short-period component expresses clearly the displacement, with a stronger and more consistent signal than in case of jumping and amplitude reaching $\pm 8\text{mm}$ (Fig. 11). The RTS time series consists of the short-period component, expressing dynamic displacement of amplitude similar of that of GPS ($\pm 7\text{mm}$), and the long-period component, expressing clearly a semi-static displacement as it is increasing during the marching period, with amplitude reaching up to 2.4mm (Fig. 12). The spectral analysis of the GPS and RTS short-period components (Fig. 13) revealed the frequencies of 1.6 Hz, with the RTS spectrum appearing again the frequency of 2.2 Hz.

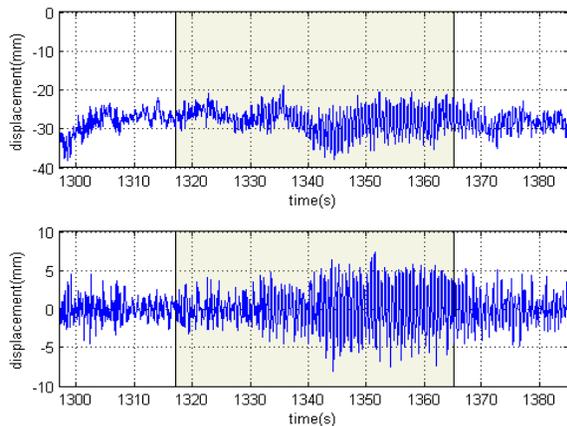


Figure 11: The same plot as Figure 4 for the GPS for the marching excitation.

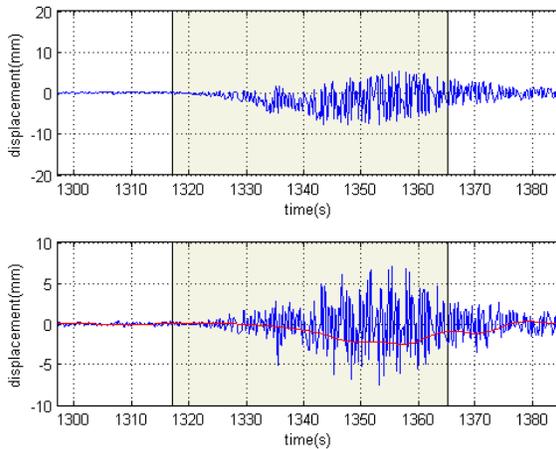


Figure 12: The same plot as Figure 5 for the RTS for the marching excitation.

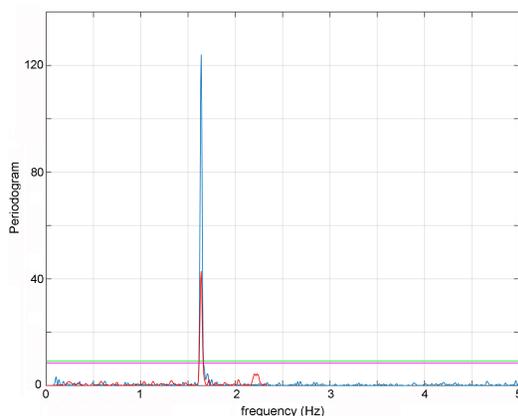


Figure 13: The same plot as Figure 6 of the spectrum GPS and RTS for the marching excitation.

4. Conclusions

The Wilford pedestrian bridge is a well-monitored bridge, being the experimental field for many studies in the past. In the current study, we focused on the comparison of the analysis of GPS and RTS data for different types of excitations. The main outcome of the current study is that RTS proved to be reliable and accurate in detecting and estimating small semi-static displacement even of 2.4mm amplitude, which was caused by a small group of people (7 people). The accuracy of RTS in detection of dynamic displacement is higher, however there is the problem of not describing precisely the oscillation cycles due to the ranging sampling rate (Psimoulis and Stiros, 2008).

Regarding GPS, its weakness in monitoring semi-static displacement of small amplitude was confirmed, due to the long-period noise in structures with structural elements, such as cables. However, by using the appropriate filtering technique was possible to remove the long-period noise and estimate reliably the dynamic displacement. The latter was possible for strong vibrations of the bridge, caused by jumping or marching. Finally, with both instruments, it was possible to detect the main modal frequencies, with GPS being more precise as the RTS is characterised by more noise in its spectrum due to the jitter effect.

Finally, regarding the characteristics of the bridge it is clear that the estimated modal frequencies are similar with those estimated for the same bridge in previous studies (Meo et al., 2006; Meng et al., 2007). However, small deviations, such that of 2.2Hz, detected by RTS might be due to modification of the bridge dynamic characteristics, after the maintenance work of 2011 (Yu et al., 2014).

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References

- Bardakis, V., and Fardis, M. (2011). A displacement-based seismic design procedure for concrete bridges having deck integral with the piers. *Bull. Earthquake Eng.*, 9(2), pp. 537-560.
- Charalambous, E., Psimoulis, P., Guillaume, S., Spiridonakos, M., Klis, R., Bürki, B., Rothacher, M., Chatzi, E., Luchsinger, R., Feltrin, G. (2015), Measuring sub-mm structural displacements using QDeadalus: a

- digital clip-on measuring system developed for total stations. *Applied Geomatics*, 7(2), pp. 91-101.
- Dei, D., Pieraccini, M., Fratini, M., Atzeni, C., Bartoli, G. (2009). Detection of vertical bending and torsional movements of a bridge using a coherent radar. *NDT and E International*.; 42(8), pp. 741–747.
- Gentile, C., and Herrero, P. (2010). Application of Radar Technology to Deflection Measurement and Dynamic Testing of Bridges, *Radar Technology*, Guy Kouemou (Ed.), ISBN: 978-953-307-029-2, InTech
- Knecht, A., and Manetti, L. (2001). Using GPS in structural health monitoring. In: *Spie's 8th annual international symposium on smart structures and materials*, Newport Beach (CA), USA, March 4-8.
- Meng, X., Dodson, A.H., Roberts, G.W. (2007). Detecting bridge dynamics with GPS and triaxial accelerometers. *Engineering Structures*, 29, pp. 3178-3184.
- Meo, M., Zumpano, G., Meng, X., Cosser, E., Roberts, G., Dodson, A. (2006). Measurements of dynamic properties of a medium span suspension bridge by using the wavelet transforms. *Mechanical Systems and Signal Processing*, 20, pp. 1112-1133.
- Moschas, F., Psimoulis, P., Stiros, S. (2013). GPS/RTS data fusion to overcome signal deficiencies in certain bridge dynamic monitoring projects. *Smart Structures and Systems*, 12(3-4), pp. 251-269.
- Moschas, F., Stiros, S. (2014). Three-dimensional dynamic deflections and natural frequencies of a stiff footbridge based on measurements of collocated sensors, *Structural Control and Health Monitoring*, 21, pp. 23-42.
- Psimoulis, P., and Stiros, S. (2007). Measurement of deflections and of oscillation frequencies of engineering structures using Robotic Theodolites (RTS). *Engineering Structures*, 29(12), pp. 3312-3324.
- Psimoulis, P, Stiros, S. (2008). Experimental Assessment of the accuracy of GPS and RTS for the determination of the parameters of the oscillation of major structures. *Computer-Aided and Civil Infrastructure Engineering*, 23, 389-403
- Psimoulis, P., and Stiros, S. (2011). Using Robotic Theodolites (RTS) in Structural Health Monitoring of short-span railway bridges. In: *1st Joint International Symposium on Deformation Monitoring*, Hong Kong, China, November 2-4.
- Stiros, S., and Psimoulis, P. (2012). Response of a historical short-span railway bridge to passing trains: 3-D deflections and dominant frequencies derived from Robotic Total Station (RTS) measurements. *Engineering Structures*, 45, pp. 362-371.
- Psimoulis, P., and Stiros, S. (2012). A supervised learning computer-based algorithm to derive the amplitude of oscillations of structures using noisy GPS and Robotic Theodolites (RTS) records. *Computers and Structures*, 92-93, pp. 337-348.
- Psimoulis, P., and Stiros, S. (2013). Measuring deflections of a short-span railway bridge using a Robotic Total Station (RTS). *Bridge Engineering*, 18(2), pp. 182-185.
- Pytharouli, S., Stiros, S., (2008). Spectral analysis of unevenly spaced or discontinuous data using the "Normperiod" code. *Computer and Structures*, 86, 190-196
- Roberts, G., Brown, C. (2010). Monitoring the deflection of bridges in the UK by GPS. In: *Proc. Of the International Conference on Computing in Civil and Building Engineering (icccbe)*, Nottingham, UK, 30 June-2 July.
- Stiros, S., Psimoulis, P., Kokkinou, E. (2008). Errors introduced by fluctuations in the sampling rate of automatically recording instruments: Experimental and theoretical approach. *Surveying Engineering*, 134(3), pp. 89-93.
- Yu, J., Meng, X., Shao, X., Yan, B., Yang, L. (2014). Identification of dynamic displacements and modal frequencies of a medium-span suspension bridge using multimode GNSS processing. *Engineering Structures*, 81, pp. 432-443.