THE USE OF KINEMATIC GPS AND TRIAXIAL ACCELEROMETERS TO MONITOR THE DEFLECTIONS OF LARGE BRIDGES

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Abstract

Detailed information about the characteristic deflections of large structures such as bridges and tall buildings can help to determine the "health" of such a structure as well as to evaluate whether such deflections are the same as those that the structure was designed to tolerate. Due to the ever-increasing size of some of these structures, a reliable and accurate health monitoring system could detect uncharacteristic vibrations and deflections, and help prevent disastrous consequences.

The use of kinematic GPS has been shown on many occasions to be a viable tool for monitoring the deflections of large structures through its ability to provide cm level precision, at a rate of up to 10 Hz with real time capabilities and with the rover receiver being able to be positioned at a distance of up to ~20 km away from the reference (ideal for long bridges). In addition, accelerometers have been proven useful for such monitoring, allowing precise readings at rates of up to 1,000 Hz. However, both systems have their limitations. GPS is limited partly by multipath and cycle slips as well as the need to have good satellite coverage, whilst accelerometers are limited due to the fact that their readings will drift with time. The integration of the two systems, however, results in a hybrid arrangement that eliminates the disadvantages of the two separate units.

This paper presents an integrated monitoring system, consisting of Leica CRS 1000 series and SR530 dual frequency code/carrier GPS receivers and a Kistler triaxial accelerometer. Two units are physically integrated and their data synchronised. Using spectrum analysis, main natural frequencies are established from the hybrid system. A simple data processing algorithm is presented, as well as the results from field trials to show the potential of such a system.

1. Introduction

Safety concepts form the basis of modern bridge design and assessment codes. Monitoring bridge deflection and dynamic response to the large variety of external loadings is of great importance for maintaining bridge safety [Roberts et al, 2000a; Das, 1997]. Strain gauge, accelerometer, tiltmeter, vision systems, optometer, etc. are traditional tools and methods to measure bridge displacement, acceleration, rotation, and together with temperature, wind speed and direction allow the comprehensive investigation of bridge dynamics and aeroelastic behaviours [Roberts et al, 2000b; Brown et al, 1999]. Except for the very high costs in equipment purchase, data processing and integration, these sensors must be installed, maintained, and frequently re-calibrated to produce reliable results. However, the monitoring costs are small compared to the cost of the structure. Furthermore, the collected data need to be interpreted to obtain direct geometric results, which in many cases is a very complicated procedure and out of the control of the general bridge engineers.

Duff and Hyzak [1997] presented two system architectures for structural monitoring with GPS. One of these is based on a fixed network of GPS sensors placed upon the strategic sites; this can depict the long-term movements such as foundation settlement, creep, stress relaxation, and short-term movements such as wind and traffic induced vibrations. The other implementation presented was a periodic kinematic GPS based structure surface profile survey system augmented with analogue sensors that provide an alternative method to evaluate long-term deformations through periodic visits to a specific bridge. Loves et al [1995] illustrated an earlier example for how GPS can be used to monitor the dynamic deformation of Calgary Tower in Albert, Canada. Identified vibration frequency of this 160 meter high tower under wind loading is about 0.3Hz. Efforts have been made by the Applied Research Laboratory at the University of Texas, Austin (ARL:UT), USA, to investigate GPS based structural deformation monitoring system since the beginning of 1990s [Duff, et al 1998]. The research focus of ARL:UT is mainly on practicality and the potential cost savings through the use of such systems with millimetre level accuracy.

Research has also been underway at the IESSG at The University of Nottingham to monitor structural deflection and dynamics using state of the art GPS technology since the mid 1990s [Ashkenazi, et al 1996; Ashkenazi, et al 1997]. The biggest GPS based bridge deflection monitoring trial to date at the IESSG was carried out on Humber Bridge in February 1998 [Roberts et al 1999; Brown, et al 1999]. The highest data rate obtained from these previous trials is 5Hz. According to Nyquist theorem, this data rate is not enough to detect a frequency higher than 2.5Hz, and hence it has limited application. The latest RTK GPS technology development makes it possible to monitor bridge vibration frequencies higher than 5Hz with 10Hz and soon 20Hz GPS receivers.

Despite many developments in GPS hardware and algorithms, multipath is still one of unsolved limiting factors, especially in the context of a bridge monitoring scenario. Since GPS positioning accuracy depends on a strong geometric distribution of satellites in view, it could be very hard to have an ideal GPS constellation to result in high quality output all the time, depending upon location. When conducting real-time bridge monitoring, there are few redundant observations to be used to monitor the integrity of the GPS itself. Loss of lock is another drawback of GPS technology, which introduces new ambiguities to be solved.

To address the problems encountered when using GPS alone in a bridge deflection monitoring system, this paper presents a hybrid GPS and triaxial accelerometer configuration that can be easily installed on the deck of a bridge. A specially designed device, which houses the GPS antenna and accelerometer together, and the accelerometer alignment procedure, are introduced in the first section of this paper. The coordinate transformation algorithm and instant attitude determination via three GPS sites are explained in the second section. A real structural monitoring trial on a Nottingham suspension footbridge over the River Trent is presented in the third section. Some data processing techniques are also introduced in this section. The paper ends with some results, analysis and preliminary conclusions.

2. GPS and Triaxial Accelerometer Integration

To avoid relative movement of the sensors in order to simplify the GPS and triaxial accelerometer data integration and to reduce the complexity of the data processing algorithm, the two kinds of sensors should be seamlessly fixed together. At the same time one axis of the triaxial accelerometer should be aligned with a known direction, usually the bridge’s main axis (normally in the longitudinal axis direction). All the measurements are then transformed into a uniform coordinate system. A Software package developed at the IESSG can be used to synchronise the time series from the sensors. To meet the above requirements, a specially designed device is used to mount the GPS antenna and triaxial accelerometer (Figure 1a, 1b). This device consists of two rotatable plates connected with three bolts. The GPS antenna is mounted on the upper plate which can be orientated to north. The triaxial accelerometer is fixed on the second plate with four screws. Its physical centre B coincides with the plate centre and one axis locates on the straight line marked by A and C. The whole device can be installed onto any standard tribrach. When the tribrach is properly levelled, the centre of the GPS antenna, the physical centre of the accelerometer and the centre of the tribrach's base are situated into the same vertical axis. Through levelling and rotation, the body frame of the triaxial accelerometer can be aligned with the bridge's axis. In practical use, a U-shaped clamp with centring bolt on top is used to fix the device on the bridge's handrail (Figure 1c). Figure 2 shows the accelerometer alignment procedure. A theodolite is placed upon the handrail of the bridge, and used to define the bridge's longitudinal axis through targeting the centre bolt of the middle span tribrach. The first plate of the housing device is rotated until markers A and C (Figure 1a) are oriented along the bridge's axis. The antenna is orientated to north at the same time.

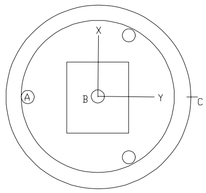

Figure 1 a Horizontal view of the device.

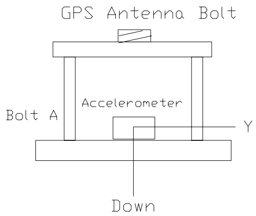

Figure 1b Vertical view of the device.

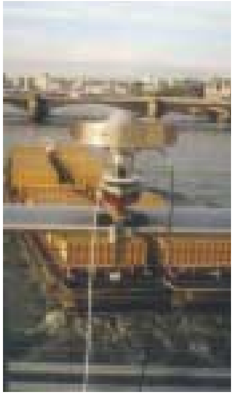

Figure 1c Device on the bridge handrail.

3. Coordinate Transformation and Attitude Determination for the Bridge Deck

For integrating the time series from two separate systems, GPS coordinates (WGS84) are first transformed into local coordinate system OSGB36 in this project, then projected onto OSGB national grid using Codawin, a software package for coordinate transformation developed at the IESSG. The transformed coordinates in the local coordinate system are then projected to the bridge axis system using rotation matrix [Eq. 1].

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} E \\ N \\ H \end{bmatrix} \quad (1)$$

Where, $\alpha = \arctan \dfrac{E_{mean2} - E_{mean1}}{N_{mean2} - N_{mean1}}$ is the azimuth of the bridge main axis in the local coordinate system, which can be calculated from the mean coordinates from two adjacent GPS sites on the same bridge handrail. The left part of the above equation is the coordinate vector in the bridge axis system.

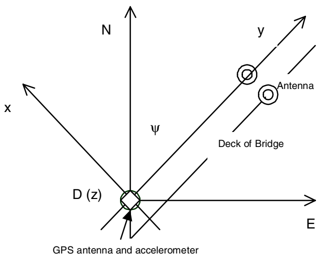

Figure 2a Schematic for coordinate transformation.

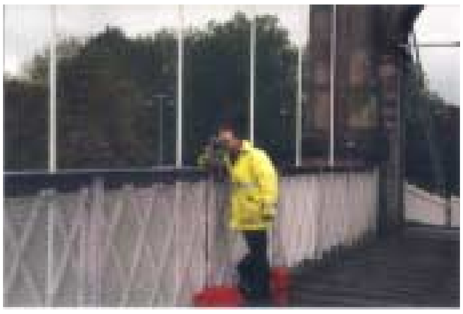

Figure 2b Theodolite for aligning accelerometer (Courtesy of Andy Nesbitt).

The GPS/accelerometer configuration is a gyro-free INS aided GPS structural deflection monitoring system. To associate the accelerometer data into the body frame of the converted GPS coordinates in the bridge axis system, an alternative approach is developed to calculate instant pitch, roll and yaw, and their changes over time. Measurements from three GPS sites can be used to determine pitch, roll and yaw with GPS sampling data rate. In practice, two adjacent GPS sites along the same bridge handrail, simultaneously gathering data, are used for calculating pitch and yaw [Eq. 2, 3] and two GPS sites simultaneously gathering data on opposite sides of bridge deck are used to calculate roll [Eq. 4].

$$pitch = \theta = \frac{\Delta H}{\Delta Y} = \frac{H_{site2} - H_{site1}}{Y_{site2} - Y_{site1}} \tag{2}$$

$$yaw = \psi = \frac{\Delta X}{\Delta Y} = \frac{X_{site2} - X_{site1}}{Y_{site2} - Y_{site1}} \tag{3}$$

$$roll = \phi = \frac{H_{site3} - H_{site1/2}}{\sqrt{(\Delta X^2)_{site1/2,3} + (\Delta Y^2)_{site1/2,3} + (\Delta H^2)_{site1/2,3}}} = \frac{\Delta H}{d} \tag{4}$$

In Eq. 4 d stands for the spatial distance between two GPS antennas located on opposite sides of bridge deck.

These calculated parameters are then used to convert instant accelerations into the three directions of the bridge axis system using Eq. 5.

$$\begin{bmatrix} a_{brx} \\ a_{bry} \\ a_{brc} \end{bmatrix} = R_{bd2br} \begin{bmatrix} a_{bdx} \\ a_{bdy} \\ a_{bdz} \end{bmatrix} \tag{5}$$

Where,

$$R_{bd2br} = \begin{bmatrix} 1 & \psi & -\theta \\ -\psi & 1 & \phi \\ \theta & -\phi & 1 \end{bmatrix}^{-1} \tag{6}$$

Through double integral and with the initial velocities and positions from GPS, these converted accelerations in the bridge axis system are used to integrate GPS data to output more reliable and accurate positioning solution.

Figures 3, 4 and 5 are calculated pitch, roll and yaw changes with a 10Hz update rate obtained from the Leica GPS receivers. The smallest change is seen in yaw and the biggest one in roll which stands for relatively larger lateral wind blowing the bridge deck and cables. After completing alignment and coordinate transformation, the data processing is described in section 5.

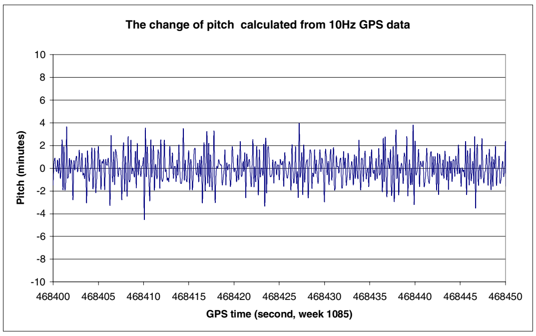

Figure 3 Schematic for pitch change.

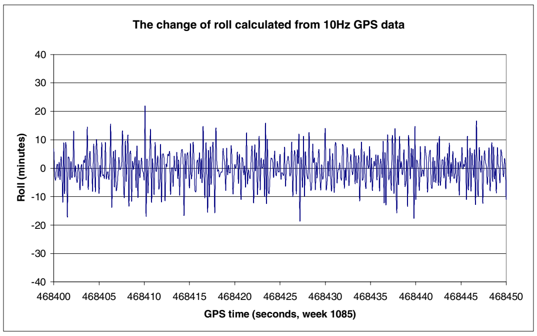

Figure 4 Schematic for roll change.

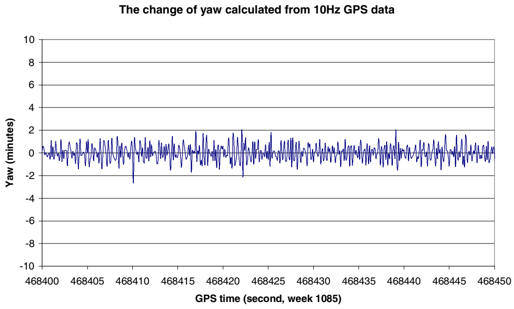

Figure 5 Schematic for yaw change

4. Nottingham Suspension Footbridge Trials

A small suspension footbridge is situated over the River Trent in Nottingham. It is a 60-meter long and 3-meter wide wooden deck suspension bridge [Figure 6]. This bridge is used to conduct drinking water from the Severn Trent Water Company to the residents in the nearby area. The water pipes are put under the deck of bridge and pedestrians access over the bridge is also possible.

The objectives of this trial were to collect real bridge deflection data using GPS and accelerometer sensors under wind and pedestrian loadings, promote conceptual development for the integrated system and algorithms, test and improve the specially designed tribrach device. The instruments used were three Leica CRS1000 series receivers, three Leica SR530 receivers, Leica AT504 choke-ring antennas and AT302 (lightweight) antennas, a Kistler triaxial accelerometer (±2*g*), a Wild T2 theodolite, and four laptops for data logging. Trials were conducted over a period of four days from 17th October to 15th November 2000. Figure 7 illustrates the instrument layout for the bridge monitoring trial on the 17th October 2000. In this trial, one Leica CRS 1000 receiver was put on the IESSG building (3.6Km away) as reference station. Another CRS 1000 reference was set up on the riverside. One CRS 1500 together with the triaxial accelerometer was installed at midspan. Two Leica SR530 were installed on both sides of bridge with another SR530 opposite the CRS 1500 at midspan. The data rate for GPS was set to 10Hz with 200Hz for the triaxial accelerometer. Four thirty-minute sessions were observed and the GPS data were post-processed with Leica SKI-Pro software.

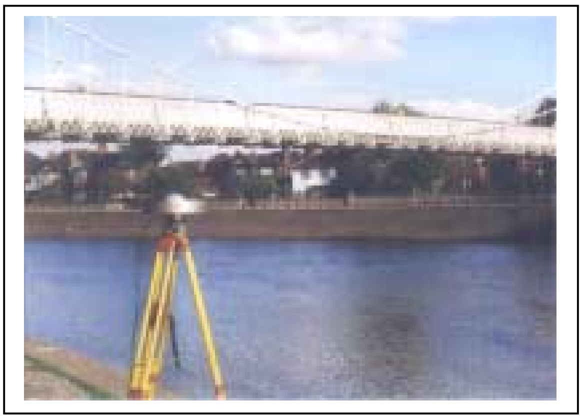

Figure 6 Nottingham suspension footbridge over River Trent.

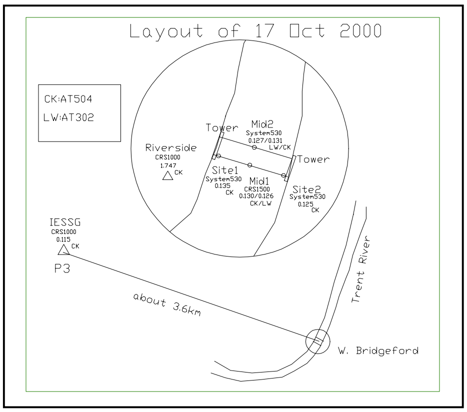

Figure 7 Instrument layout for bridge trial.

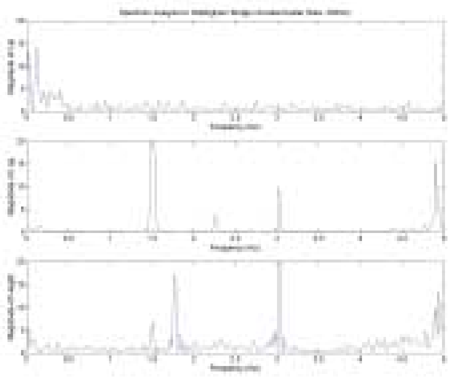

Figure 8 Spectrum analysis for extracting vibration frequencies.

5. Data Analysis and Results

Through selecting suitable parameters such as FFT length, window, amount of overlap, and data rate, spectrum analysis can be used for isolating and detecting the dominant structural vibration frequencies from GPS and accelerometer data which are buried in the wide-band noise [Figure 8]. The vibration frequencies can be easily identified for three axes. Spectrum method can be used to clean or suppress higher frequency noise according to the structure type, material etc. Analysis of both the GPS and the accelerometer data can supply mutual checks before further data processing is applied. If the wrong cutoff frequency is selected, the actual signal might be filtered out in the inverse FFT process. Due to the nature of bridge deflections (i.e. the lower bridge natural frequencies maybe at the same level as those of instrument and multipath) and observation conditions, GPS data may be largely contaminated by the noise and spectrum approach sometime can not be applied for extracting the frequencies in these bands. Eliminating the influences from the various noises is a tough task in GPS signal processing. Further research is required in this area and is a topic of research at the IESSG. Without the support from a triaxial accelerometer, it is impossible to select suitable cutoff frequencies for the different directions, except by supplying more redundant measurements, hence the advantage of the hybrid system.

Figure 9 shows the detailed procedure for the data processing algorithm. A software package has been developed with Microsoft Visual C++ to implement this algorithm. A sample data set of about 500 GPS points and 10, 000 accelerometer points from the Nottingham bridge trial was processed using this package. Figures 10, 11 and 12 show the output of both GPS alone and integrated solutions for lateral, longitudinal, and vertical movements respectively. In all three figures a 2cm offset has been applied to the integrated solutions, i.e. for ease of comparison. Figure 13 illustrates that with 200Hz acceleration sampling rate more position solutions can be obtained through integral between the GPS fixes. This supplies a way to detect abnormal measurements from GPS when loss of lock to the satellites occur. About 1.0cm maximum lateral, 1.4cm longitudinal and 2cm vertical displacements in this period of time are evident. When the tests were made, the external forces acting on the deck were from casual pedestrians and continuous lateral wind. It can be concluded that with the above physical configuration and algorithm, millimetre precision can be reached through the use of the hybrid system.

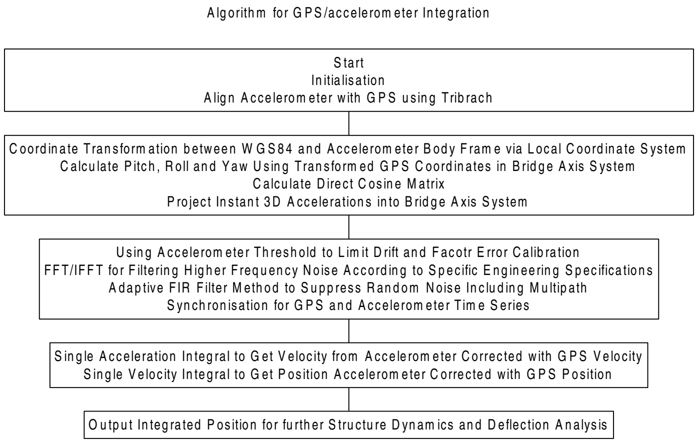

Figure 9 Data processing flow chart

6. Conclusions

In this paper, a GPS and triaxial accelerometer based bridge deflection monitoring system is introduced together with some considerations of the accelerometer axis alignment, coordinate transformation, data processing and integration. With such a device and developed algorithm, it is possible to measure small bridge displacements and frequency responses even when the external force agitation to the bridge is low. Millimetre GPS position accuracy is reached through the comparison to the integrated solution. Further trials on the Nottingham footbridge and other suspension bridges are arranged with more Leica SR530 GPS receivers and larger external loading applied on the decks of the bridges. Multipath mitigation is still a very important research topic whenever high precision is required.

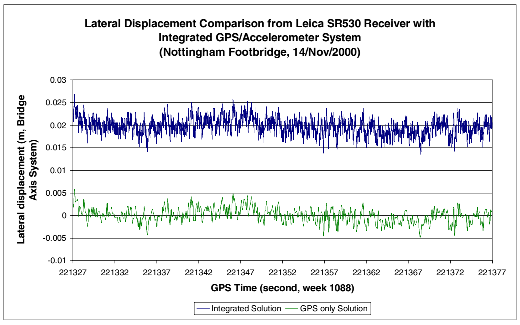

Figure 10 Lateral displacement.

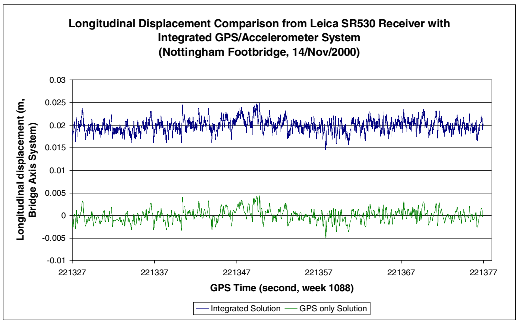

Figure 11 Longitudinal displacement.

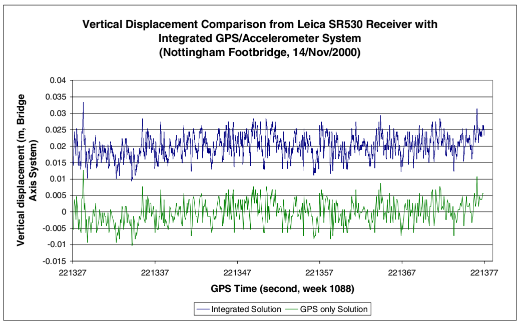

Figure 12 Vertical displacement.

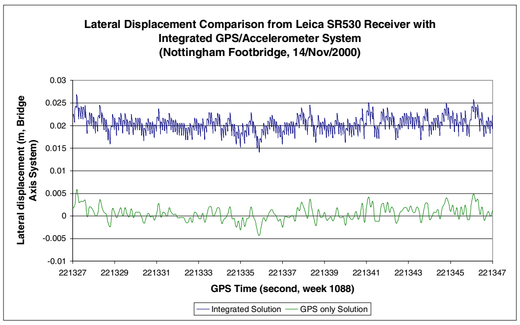

Figure 13 Enlarged lateral displacement.

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