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Validation of a Data-fusion Based Solution in view of the Real-Time Monitoring of Cable-Stayed Bridges

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Abstract

A precise assessment of the displacements induced by external actions on cables-stayed bridges may be currently challenging and costly when conventional structural health monitoring (SHM) solutions are applied. In order to bypass the drawbacks of wired solutions and the use of expensive equipment, a novel approach is proposed. A Kalman filter-based data fusion of multiple responses is adopted. A GPS receiver and a three-axial accelerometer are used as sensors. The GPS accuracy is enhanced exploiting the satellite corrections provided by a single reference station. The proposed system is validated in situ on the "Tesa" timber footbridge.

Keywords: real-time; monitoring; displacement estimation; GPS; wireless solution.

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1. Introduction

The realization of real-time Structural Health Monitoring (SHM) is currently a research priority. Accelerations and displacements are the physical variables generally measured in SHM. The latter ones can be directly recorded by different technologies [1]. In particular, by a high precision GNSS (Global Navigation Satellite System) whose accuracy is enhanced exploiting the satellite corrections provided by a single reference station [2-3]. But, displacements are often pursued by indirect estimation approaches, which convert other structural responses (i.e., acceleration and strain) to displacements on the basis of their physical relationships.

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Thought equipments able for direct measures exist, the need to adopt a data fusion method based on the Kalman filtering comes from the achieved results that, as widely proven in literature, do not reach the accuracy required by a reliable SHM system due to sampling frequency issues (i.e., GPS device) or numerical errors and imperfect physical relationships. Indeed, the conversion from acceleration to displacement involves large low-frequency drift errors caused by the numerical integration in the discrete time domain [4].

Accuracy enhancements are achieved by employing multiple responses, based on a data fusion model, to reduce the drawbacks of each single acquisition [5-7]. Indeed, the conversion of the acceleration can be improved by coupling the acceleration signal and the displacement measured by any suitable device in the Kalman filtering. This method has been actively studied in the GPS (Global Positioning System) navigation field, but it needs to make a post-data fusion between accelerations and displacements as well [8-14].

The negative aspect of a device implementing such procedures is that the software assumptions consequences on the estimate add to standard lack of accuracy and noise of a conventional sensor.

The aim is to investigate the differences during the SHM of cables-stayed bridges and, especially for the case under study of a footbridge, when the measurements are carried out by: (i) devices that directly measure the displacements, (ii) accelerometers whose data has to be integrated, and (iii) data fusion approaches based on Kalman filters. This paper presents a bridge application with the purpose of outlining some subtle implications of the described methods.

2. Reference structural system and experimental devices

2.1. A bridge application

The case study investigated in this paper is the “Tesa” cable-stayed pedestrian bridge, which is located in Farra d’Alpago, not far from Belluno (Italy), as shown in Figure 1. The deck relies on two timber beams transversally linked by U shape steel elements. The design implements a cable-stayed bridge scheme.

The aim of the experimental campaign carried out was to measure the displacements of the footbridge cables.

Fig. 1. Lateral view of the Tesa footbridge.

2.2. Experimental devices

A three-axial accelerometer (147A) and a GPS receiver (R10) [15], are mounted on the same base rigidly connected to one of the 4 longest central cables (Figure 2a).

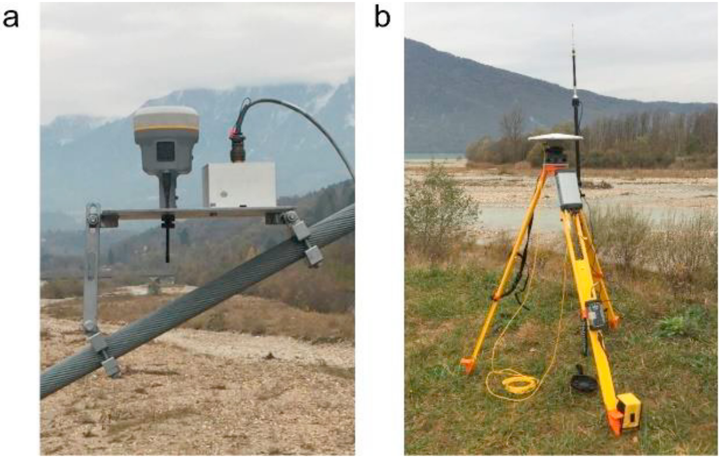

Fig. 2. (a) Systems configuration on the footbridge cable; (b) Base Station.

Nearby, a Base Station is installed. It consists of a NET R9 [15], with its geodetic antenna. The differential corrections are sent to the Rover (i.e., the Trimble R10) by a RF transmitter supplied by an external battery, as shown in Figure 2 b). The R10 relies on its own battery and save the data inside the device memory. The maximum sampling rate is 20 points per second and this value was used during the experimental campaign.

By contrast, the 147A was equipped with a data logger, which needs to be powered at 12-24V (Figure 3). The authors used the maximum available sampling rate of 1000 point per second in order to minimize the synchronization error. Both the devices provide records with the GPS time in the first column.

Fig. 3. Equipment configuration during the in-situ tests.

2.3. Experimental campaign

On November 11, 2016, a set of tests were carried out to acquire the cables dynamic response (i.e., the accelerations and the GPS positions of a reference point along them) under different loading conditions. The records elaborated in this paper were collected when shaking the cable by hands.

Figure 4a provides the acceleration vertical component after signal processing. The vertical shifts with respect to the rest position is drawn in Figure 4b, together with the displacement time history obtained by double integration from the acceleration signal (see also Figure 4c).

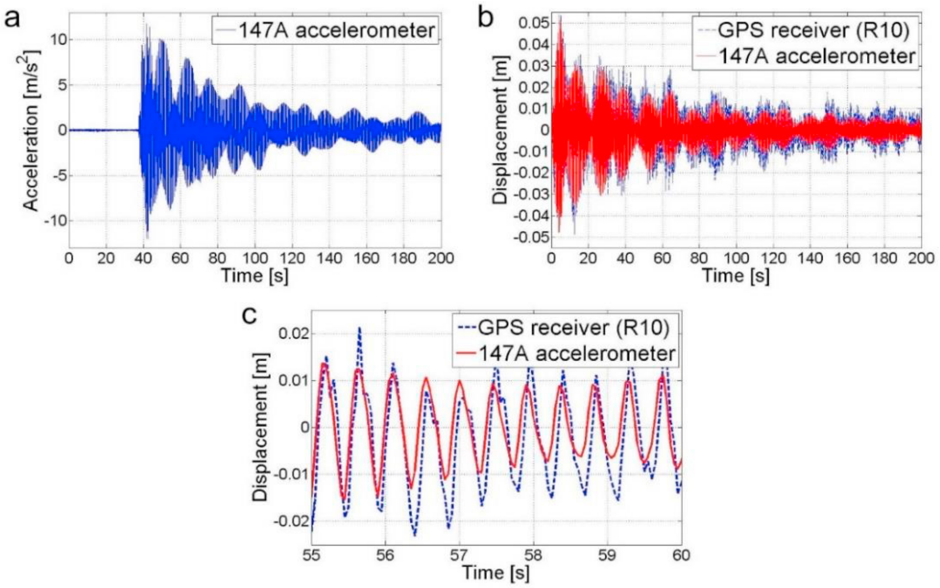

Fig. 4. (a) 147A acceleration along the vertical axis; (b) displacement time histories as integrated from the accelerometer, together with the GPS signal; (c) focus on the crucial area.

Figure 4 shows the displacements achieved by the difference of two consecutive positions (R10) and the time history obtained after double integration of the accelerations (Figure 4a) recorded in the direction of interest. In Figure 4b, the origin of two time axes is translated to the instant when the excitation starts and the signal obtained by the double integration was decimated to have the same time-step of the signal collected by the GPS receiver. In addition, the signals delay, coupled with the poor accuracy, can be observed in Figure 4c.

3. Data fusion

The theory on the back of data fusion by Kalman filter is all in the book by Lewis [16]. The paper [17] was re-proposing it to the attention of the scientific community. Recently the authors published the steps required by a software implementing it in a credit card size computer board [18].

In synthesis one can write:

$$u_{up}(t) \;=\; \Phi\;(u_m(t)\;,\ddot{u}_m(t)\;|\;r,q,\bar{\boldsymbol{y}}_0,\boldsymbol{p}_0) \tag{1}$$

where the displacement u appears by its update value u_{up}, i.e., after the data fusion, and its measured value, as denoted by the subscript m. The double dot denotes the second time derivative, i.e., the acceleration, as measured.

In Eq. (1), one assumes that the two measured quantities are affected by a noise, which is modelled as white noise Gaussian processes $(i.e., \boldsymbol{w} \sim [0,\boldsymbol{Q}];\ v \sim [0,R])$ with covariance q and r, for acceleration and displacement, respectively $\left(i.e., \boldsymbol{Q} = \begin{bmatrix} 0 & 0 \\ 0 & q \end{bmatrix};\ R = r\right)$. By the term $\boldsymbol{y}$, one denotes a two entries vector, made of velocity and acceleration. The initial state is assumed to be normally distributed, i.e., $\boldsymbol{y}(0) \sim (\bar{\boldsymbol{y}}_0, \boldsymbol{p}_{\boldsymbol{0}})$.

The time t is usually discretized in finite time steps. It is the largest between the two-sampling rate (0.05 s in this case study). It is well known in the literature that this approach can result unstable for some sets of the input variables q and r. Nevertheless, the investigation of this paper is on the effects of $\boldsymbol{p}_{\boldsymbol{0}}$, $\bar{\boldsymbol{y}}_0$ being $\begin{bmatrix} 0 \\ 0 \end{bmatrix}$.

Without any attempt to optimize them, the values of q and r were selected to be 1 and 2.5 10^{-5}. The choice depends on the peaks achieved in the plots of Figure 4: 10 units for the acceleration and 0.05 for the displacement. Since the error is assumed to be 10% of these peaks, the covariance will be equivalent to 1 and 0.005, and the adopted values will be corresponding to their squares. Figure 5 shows the result achieved by the data fusion when $\boldsymbol{p_0}$ is assumed to be a 2 by 2 matrix of zeros. The consequences of this choice on the resulting time history is here outlined.

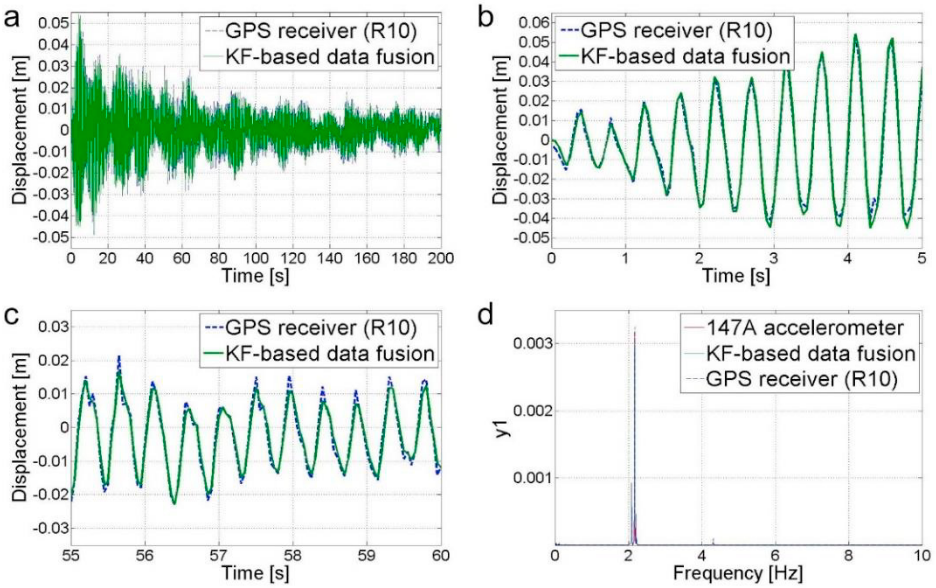

Fig. 5. Comparison between the GPS displacements before and after the data fusion: (a) global signals; (b) initial time window; (c) crucial area; (d) related periodograms with that integrated from the accelerometer 147A.

Comparing the content of Figure 4 with the time history after the data fusion based on a Kalman filter (Figure 5), the precision of measurements is enhanced (green) and the time delay of the accelerometer (red) can be reduced until to be reset. Otherwise, the periodograms related to each signal (Figure 5d) do not suffer from significant changes, while Figure 6 gives the same plots achieved with a more convenient choice of $\boldsymbol{p_0}\left(\boldsymbol{p_0} = \begin{bmatrix}0.08^2 & 0\\ 0 & 1\end{bmatrix}\right)$.

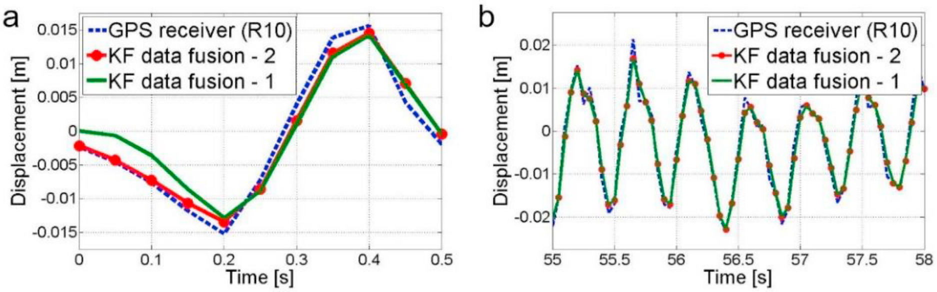

Fig. 6. Comparison between the GPS displacements before and after the data fusion as reported in Fig. 5 (KF data fusion - 1), and after the data fusion for a more convenient choice of the initial conditions covariance matrix (KF data fusion - 2): (a) initial window; (b) crucial area.

As shown by the above representations, it is seen that no significant deviations can be detected after the decay of the improvement in the initial sequence (i.e., from zero to 0.2 seconds) of Figure 6a.

4. Conclusions

In this paper, the authors pursue a refinement of the displacement estimate achieved by a GPS (Global Positioning System) receiver able to integrate the corrections from a reference station, i.e., working at a centimeter-level accuracy by the so-called RTK (Real Time Kinematics) technique. The two receivers observe the same constellation of satellites and, since the reference station position does not change in time, differential corrections may be generated in order to improve the results of the measurement point. The additional information for the pursued refinement comes from a three-axial accelerometer. For this purpose, a Kalman filter-based approach, allowing a data fusion of the measured responses (i.e., accelerations and GPS positioning data), is proposed in view of an accurate estimation of the displacement of civil structures under significant external excitations.

The Kalman filter approach requires that some parameters are assigned. The focus of this paper is on the covariance matrix by which the initial position is known. It is worth noticing that in view of a real-time implementation the data transmission from the adopted devices should rely on a real time wireless technology [19].

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