Combination of Total Station and GNSS for the Monitoring of Civil Infrastructures in Dense Urban Areas

Gauthier Magnaval(✉), Thibault Colette, and Mouaad Boumeshal

Socotec Monitoring, Palaiseau, France
{gauthier.magnaval,thibault.colette,mouaad.boumeshal}@socotec.com

Abstract. Large infrastructure projects can have an impact on the structural health of existing buildings. For example, the boring of tunnels can affect infrastructures located on the surface. Therefore, devices are required for the monitoring of every building in the area of interest.

Topographic surveying is one of the most popular techniques for the monitoring of buildings and civil infrastructures. Standard optical prisms are targeted with high frequencies by Robotic Total Stations (RTS). In order to estimate 3D displacements of each prism, static control points are needed. These points must be located outside the area of interest. However, it is not always possible in dense urban areas.

In this study, the use of GNSS receivers as control points for topographic surveying is proposed. In this case, control points do not need to be static because their global positions are known. The methodology is explained and the required additional processing steps are outlined. The approach is implemented for the monitoring of a conveyor belt in the Grand Paris Express (GPE) project in Paris, France. Feedback is provided on implementation, data collection and processing. Finally, performance of the system is analyzed and compared to traditional monitoring techniques.

Keywords: Structural health monitoring · GNSS · Robotic total station · Topographic survey · Grand paris express

1 Introduction

Risks related to potential failures of civil infrastructures (e.g. bridges, dams, tunnels) are very high. Security, economic, social and environmental issues are at stake. Because of this, civil infrastructures must be monitored. The two most critical phases in their life cycles are during construction and near the end of their expected lifetime. During these phases, visual inspections are not sufficient. Data must be collected at higher frequency, larger scale and with better accuracy. Structural Health Monitoring (SHM) systems can provide useful data that can be used to compute structural behavior. Many SHM systems can be used depending on the required data. They can provide various types of measurands, accuracies, frequencies [5] ...

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Among them, topographic surveying is one of the most popular techniques for the monitoring of buildings and civil infrastructures. Standard optical prisms are placed at critical locations inside the area of interest (AoI). They are targeted by a theodolite. Measurements can be done manually with standard theodolites or automatically with Robotic Total Stations (RTS) [11,12]. After data processing, 3D displacements of each prism are computed. The main drawback of topographic surveying is that the station and the optical prisms cannot all be inside the AoI. If the station is inside, at least three outside static control points are needed. When monitoring a building in a dense urban area (or when the AoI is very large), it is sometimes impossible to have any static control point. To tackle this issue, RTS can be coupled with GNSS receivers. In this case, the control points can be located inside the AoI. Indeed, because the measures are satellite-based [7], the references of the GNSS system can be put far from the other critical points.

Although GNSS systems can be implemented by themselves for the monitoring of civil infrastructures [15], they have also been coupled to InSAR [10] and to total stations [2]. Coupled RTS and GNSS systems have been implemented in the case of pit mines [3], tall buildings [14] and dams [13]. Coupling can be done with two different procedures [4,9]. Such systems can be optimized by tuning the length of observation period, the number of occupations and the time between epochs [8].

In this study, the methodology is explained. It is shown how least squares topographic optimization can be tweaked in order to add GNSS data. The method is then conducted for the monitoring of a conveyor belt in the Grand Paris Express (GPE) project in Paris, France. Practical implementation is outlined, feedback is provided and results are shown. Finally, the performance of the system is analyzed and compared to standard topographic surveying.

2 Methodology

There are two ways of mixing GNSS and topographic data. On the one hand, data can be combined during the processing phase [9]. On the other hand, processed GNSS data can be used as input for topographic optimization [4]. Differences between the two procedures is shown in Fig. 1. In this study, the second method was chosen.

To better understand the procedure, let's first focus on topographic optimization. In the standard case, a total station located in the AoI targets common and control points (Fig. 2a). For every prism, three observations are made: the slope distance S_d (i.e. distance between the station and the prism), the horizontal angle H_z (i.e. horizontal orientation relative to the zero direction of the station) and the vertical angle V_t (i.e. vertical orientation relative to the horizontal plane). These observations are combined in order to compute 3D displacements x_p, y_p, z_p of the common points and 3D displacements x_s, y_s, z_s and orientation G_0 of the station.

The problem can be stated as (1), with L being the observation vector, X the displacement vector and V the error vector. It can be solved with a least squares optimization. First, X is initialized with value X_0. Then, (1) is linearized around X_0, with $A = f'(X_0)$, leading to (2). Besides, (1) can be transformed into (3). A and B are used to compute N (4) and C (5). The weight matrix P is equal to the inverse of the covariance matrix. Finally, the solution to the linearized problem is (6). If criterion (7) is not met, a new iteration is done with $X_0 \leftarrow \hat{X}$.

$$L = f(X) + V \tag{1}$$

$$B = L - f(X_0) = A(X - X_0) + V \tag{2}$$

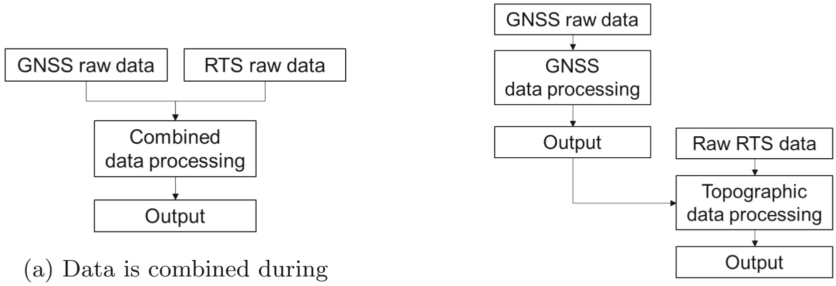
$$N(X - X_0) = C \tag{3}$$

$$N = A^T PA \tag{4}$$

$$C = A^T PB \tag{5}$$

$$\hat{X} = X_0 + N^{-1}C \tag{6}$$

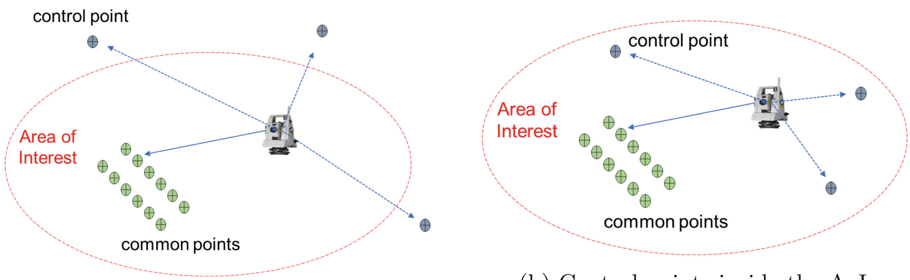
$$\hat{X} - X_0 \leq \theta \tag{7}$$



(a) Data is combined during the processing phase

(b) Processed GNSS data is used as input for topographic optimization

Fig. 1. Data fusion procedures



(a) Control points outside the AoI

(b) Control points inside the AoI

Fig. 2. RTS installation

In the equations above, observations related to control points are included in L but 3D displacements are not included in X. Indeed, these prisms are supposed to be static. However, their absolute positions are used as constants in function f linking observations and displacements. When control points are not static (Fig. 2b), their absolute positions can be known thanks to the GNSS receivers. In this case, L and X do not vary but f does. The absolute positions are not constants anymore. It is equal to the processed GNSS data.

3 Use Case: Monitoring of a Conveyor Belt in the Grand Paris Express Project

Methodology is implemented for the monitoring of a conveyor belt in the Grand Paris Express (GPE) project.

3.1 Description

GPE is the new metro in the Paris area. With the construction of 68 new stations and more than 200 km of tracks, it is currently the largest infrastructure project in Europe [1]. Most of the new tunnels are dug with Tunnel Boring Machines (TBM). Excavated materials are moved out of the tunnels using conveyor belts. Because they are strategic pieces of equipment, conveyor belts must be monitored. The one chosen for our study is instrumented by Socotec Monitoring with a Robotic Total Station and 33 optical prisms (Fig. 3). Among these, 29 are common points and 4 are control points. Since the 4 control points are inside the Area of Interest, they were coupled with GNSS receivers (Fig. 4). Another GNSS sensor is located outside the AoI. It is the reference for the GNSS system.

3.2 Practical Implementation

The methodology described in previous chapter is implemented. First, topographic and GNSS data are collected. Frequencies are 1 measure every 8 h and

Fig. 3. Conveyor belt & Robotic Total Station

Fig. 4. Optical prism & GNSS receiver

1 measure every 10 min respectively. Then GNSS data is processed and synchronized with raw RTS data. Several methods are tested for synchronization, including saving the last data point, taking the median value or computing the mean value. Then, coordinates are transformed in the local RTS referential. X, Y and Z axis are respectively east-west axis, north-south axis and vertical axis. Finally, coordinates of control points are adjusted using processed GNSS data. Topographic optimization is performed with CoMeT, a software developed by L2G-CNAM (Laboratoire de géodésie et géomatique - Conservatoire national des arts et métiers) in France [6].

3.3 Results

Data was collected for 3 days. Processing and visualization were performed live as part of the proof of concept. Results of the tweaked topographic optimization with GNSS processed data can be seen in Fig. 5. It can be compared to standard topographic optimization displayed in Fig. 6.

Results of standard topographic optimization show that common points inside the AoI barely move (Fig. 6). However, processed GNSS data proves that control points inside the AoI are not static, which is not consistent with the previous observation. Thus, topographic surveying needs to be adjusted using processed GNSS data. When the proposed methodology is implemented, vertical displacements of common points are not negligible anymore (Fig. 5). Besides, it can be seen that results are smoothed thanks to the least squares procedure.

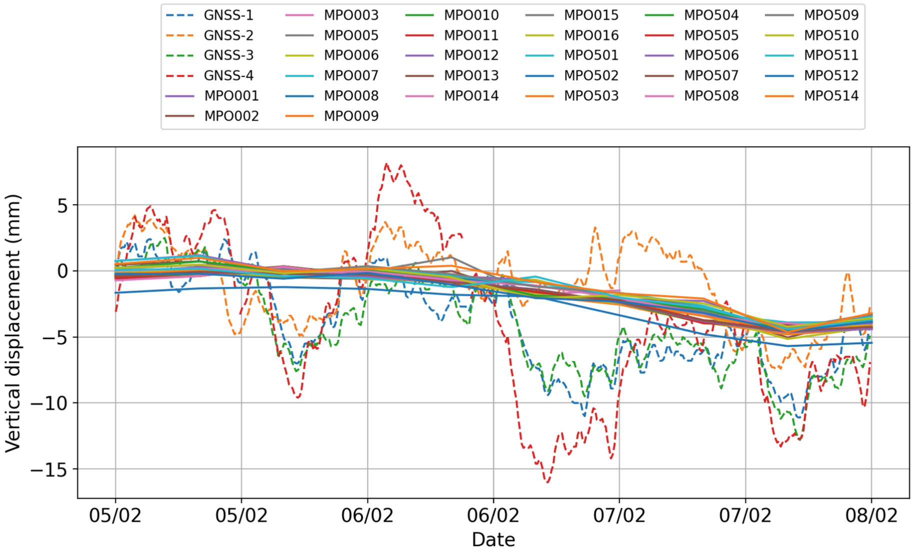


Fig. 5. Topographic optimization with GNSS data

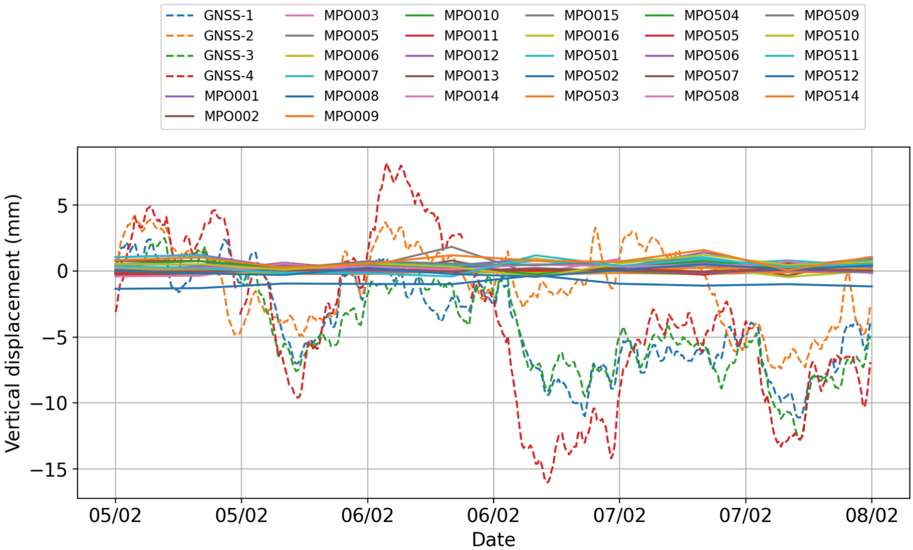


Fig. 6. Topographic optimization without GNSS data

It is important to underline that the proposed methodology improves standard topographic surveying only if the control points are not static. Indeed, GNSS data shows greater uncertainties than RTS data: half-centimetric precision versus sub-millimetric precision. Therefore, control points should always be placed outside the AoI when possible. When it is not possible (very large AoI, dense urban area), the proposed methodology proves to be a good way to limit uncertainties and have good results.

4 Conclusion

In dense urban areas, it is often difficult to put the control points of topographic surveying outside the area of interest. In this study, it is shown how to tackle this issue by coupling a Robotic Total Station with GNSS receivers. In the proposed procedure, processed GNSS data is used as input for topographic least squares optimization. The methodology is implemented for the monitoring of a conveyor belt in the Grand Paris Express project. Results are very promising, since vertical displacements could be updated thanks to the new procedure.

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