

DEVELOPMENT AND TESTING OF A METHOD FOR TUNNEL MONITORING VIA VISION METROLOGY

M. Alba, L. Barazzetti, A. Giussani, F. Roncoroni, M. Scaioni

Politecnico di Milano, Dept. of Building Engineering Science and Technology, Lecco, via M. d'Oggiono 18/a, Italy
(mario.alba, luigi.barazzetti, alberto.giussani, fabio.roncoroni, marco.scaioni)@polimi.it

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ABSTRACT:

Tunnel monitoring is an important task in civil engineering that aims at determining the stability and safety of a structure by using information about its deformations. In this paper we present the development and the results of a fast method for displacement measurement based on digital images, which allows a deformation analysis along the cross-sections of a tunnel. This technique was created to overcome some drawbacks of most traditional sensors, especially in the case of underground lines, when time becomes an issue of primary importance and limits the number of cross-sections that it is possible to check.

The method was tested inside a laboratory and inside a real gallery, by using several digital cameras and different target configurations in order to determine the best compromise in terms of precision and survey time. The accuracy was checked by giving some displacements with a micrometric sledge capable of moving a reference target along prefixed directions. In addition, a control over a period of some months was carried out to test the stability of the method under different conditions in terms of temperature, humidity and illumination.

The experimental results demonstrated an accuracy better than ± 1 mm for a tunnel wider than 12 meters, notwithstanding the shorter data acquisition time and the low cost of the cameras used.

1. INTRODUCTION

1.1 Overview

Structural health monitoring is a growing field of research that is attracting increasing interest from government agencies in order to maintain the safety of buildings, dams, tunnels and civil infrastructures. For each of these structures there are different monitoring approaches and technologies. Some real applications are presented in Brownjohn (2007).

In several real surveys only a combination of different instruments can provide sufficient information to monitor the deformations and predict the behaviour of the structures. Thus, several sensors are today used, featuring different characteristics in terms of accuracy, cost, time needed for their set up and so on. However, in the case of complex structures only a monitoring system based on combined sensors allows a complete and detailed analysis of the object and its surroundings, with different accuracies according to the requests of civil engineers. In addition, multiple measurements taken with different sensors can be used to check the consistency between dissimilar technologies. The state of the art about systems that combine multiple sensors can be found in Hill and Sippel (2002). A real application is presented in Alba et al. (2010).

Nowadays, deformation monitoring with conventional terrestrial surveying instruments can be achieved via intensive manual observations or with automatic sensors, which are permanently fixed on the structure. This choice depends on many factors: the period of the monitoring, the level of risk for people or infrastructures potentially involved, the shape of the object, the measurement accuracy, the installation costs, the number of investigated points and their distribution and so on. For these

reasons there are many applications where manual measurements are steadily used, for example when operational infrastructures are subject to temporary works that actively or passively have an effect on the stability of the structure (e.g. the excavation of an underground line).

In this paper we focus on monitoring of tunnels, where structural safety is an important field of research in civil engineering. Generally speaking, it comprehends the analysis of several factors and the creation of ad-hoc solutions which guarantee rapid measurements with sufficient accuracies. We present the development and the results of a fast method for displacement measurement based on digital images, which allows the analysis of deformations along the cross-sections of a tunnel. For our applications, an accuracy of 1:20,000 is more than sufficient and seems achievable with standard photogrammetric techniques reported in the literature.

In fact, photogrammetric methods have been used in several applications which involve the determination of the shape of a body and its changes, with satisfactory results in terms of precision and cost (Fraser et al., 2003; Fraser and Riedel, 2000; Whiteman et al., 2002; Hattori et al., 2002). Commercial low-cost cameras (or photogrammetric ones), tripods, light sources and targets are the components used to obtain high precision 3D measurements for a large number of points distributed on the object.

Basically, the precision achievable with photogrammetric techniques depends on the size of the investigated element (Maas and Hampel, 2006). For experiments in a controlled environment a standard deviation of object coordinates in the order of 1:100,000 of the largest object dimension is expected, but during analysis in repeatable system configuration (e.g. a multi-epoch test with fixed cameras) a precision of 1:250,000 was achieved (Maas and Niederöst, 1997; Maas et al., 2002). In

Fraser et al. (2005) the hyper redundancy network concept is used for the study of surface deformations of a radio telescope, with an accuracy in the range of 1:580,000 to 1:670,000 through the use of more images than those strictly necessary. For instance, two images per station enhance the effective angular measurement resolution of a factor 1.4, while four images per station lead to a factor 2. In film-based photogrammetric measurements of big antennas this concept led to an accuracy approaching 1:1,000,000 (Fraser, 1992). The method here presented was developed to overcome some drawbacks of most traditional sensors, especially in the case of underground lines, when time becomes an issue of primary importance and limits the number of cross-sections that it is possible to check. In this case, the survey is generally performed during the night, when there is an absence of traffic.

Today, the survey is carried out by using special tape extensometers which must be connected to particular stable hooks. This method allows the measuring of the reciprocal distance between all hook combinations with a high precision (± 0.01 mm). Another system is based on the use of a theodolite placed on stable supports along the wall of the tunnel. The position of several reflective targets mounted along the cross-section is estimated with a precision superior to ± 1 mm.

Both these methods (theodolite and tape) provide target movements with an accuracy which is more than sufficient to fulfil structural engineer requirements. However, the survey of a single cross-section takes several minutes (approximately 15'), because of the time needed to set up the instruments and take the measurements. This means that only few parts of the tunnel can be analysed during the hours when the trains are not running, especially in the case of very long tunnels.

To overcome this drawback a photogrammetric method was developed. The basic idea is based on the use of targets, which can be photographed by using a professional digital camera. Images will contain all the useful information to determine target positions with a scale ambiguity, which can be defined by measuring the distance between two targets with an external wire. For the sake of convenience, we measure the distance between two opposite targets close to the floor, in order to avoid complicated connections that may require a ladder or extendible tubes. For each cross-section four images are taken by moving the camera from the left to the right side of the wall, by using a tripod to obtain clear images. This method allows one to increase the productivity of the survey, because the time necessary to acquire the images is less than 2 minutes and the elaboration of the images can be carried out in office. Moreover, it is possible to analyse a larger number of targets to obtain a better description of the arch deformation.

2. TEST SITE SETUP

The goal of this work is the development of a fast method for tunnel monitoring. The techniques presented in the previous section, like theodolites or tapes, are proven approaches and are today widely used. However, they are time consuming and their usage should be carefully planned in some situations. In particular, in the case of underground lines it is possible to check only a limited number of tunnel cross-sections and all measurements must be carried out during the night, when trains are standing.

From this point of view, photogrammetry can be a convenient choice: images contain all the useful information to derive accurate measurements with a significant advantage in terms of time. In addition, the elaboration of the data can be carried out after the acquisition of the images.

2.1 Preparation of the test site

The developed method has been tested in a real tunnel in Parè di Valmadrera, located between the towns of Lecco and Bellagio (Italy). Today this tunnel is not used and the provincial administration of Lecco made the tunnel available for research experiments.

Figure 1 shows the cross section of the tunnel, which is roughly 12 m wide. Each number indicates the position of the photogrammetric targets used to monitor the deformation of the structure. Globally, 15 targets were applied but only 9 were used during data processing. A target is made up of a circular black mark with a white background (Figure 2). It is mounted on a metal support which is fixed to the tunnel wall with some screws. On the opposite side of each target a theodolite target is applied, in order to obtain other measurements to check the accuracy of the method.

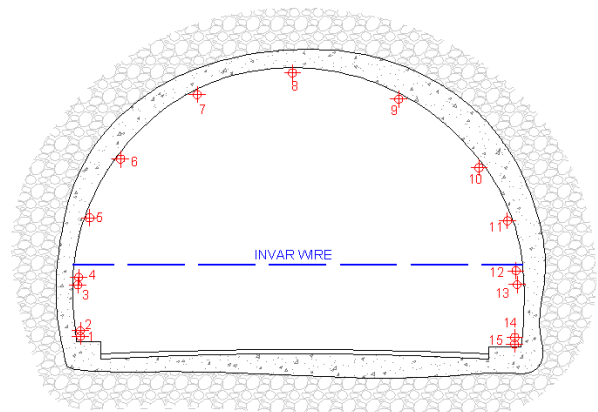


Figure 1. The cross section of the tunnel with the scheme of the targets and the wire.



Figure 2. The “double face” target for photogrammetric and theodolite measurements.



Figure 3. The wire and the gauge used to remove the scale ambiguity from the photogrammetric project.

In addition, two opposite targets (4 and 12 in Figure 1) were fixed on the supports for the wire. They allow the measuring of the distance variation between these points (Figure 3). This is useful for a multi-epoch control: photogrammetric projects have a scale ambiguity that must be removed with an external constraint. The wire used (made of invar steel), coupled with a mechanical gauge, is a cheap and fast solution for determining the variation of distance between these points. Moreover, this method has a high accuracy (± 0.01 mm), more than sufficient if compared to the expected accuracy of the photogrammetric method (± 0.5 mm). During the measurement with the gauge it is also useful to read the temperature inside the tunnel, in order to correct systematic errors due to thermal variations.

2.2 Photogrammetric equipment

In our tests we used two digital cameras: a Nikon D80 with a 20 mm Sigma lens and a Nikon D700 with a 35 mm Nikkor lens. Photogrammetric cameras were not taken into account because of their high costs. Although a photogrammetric cameras would allow the acquisition of high quality images with a significant improvement in terms of sensor stability (quite important for a multi-epoch analysis), the advantage of this method consists in the possibility of analysing a large number of cross-sections. This means that people with several cameras could photograph different cross-sections at the same time. Obviously, this can be carried out by using low-cost sensors only.

In all our elaborations we calibrated the cameras in the tunnel after the acquisition of the images. Calibration plays a fundamental role for this application: SLR digital cameras are not stable but a good calibration can remove systematic errors during a multi-epoch analysis. In our tests we used iWitness targets (Photometrix) because they provide a comfortable calibration polygon, easy to use in certain place at the best of times. Then, for each epoch the camera calibration process was carried out in order to determine interior orientation parameters and distortion coefficients. Further analysis on the covariance matrix of the bundle solution showed a theoretical precision of about ± 2 microns for the principal distance and principal point coordinates, while distortion coefficients were determined with a precision in an order of magnitude less than the estimated value. We verified that this precision is sufficient to remove systematic errors larger than 0.2 mm in terms of object coordinates. This value can be accepted for a tunnel wider than 10 m and does not cause a significant worsening of the detected displacements (an accuracy of 0.5 mm is the goal of this project).

2.3 Preparation of theodolite reference data

To validate the photogrammetric results during each measurement epoch all targets were measured by a theodolite Leica TCA 2003 (Leica Geosystems). To achieve an accuracy less than ± 1 mm in the determination of the target coordinates, a method based on two stations (intersection) was adopted. The instrument was placed on 2 stable shelves on the opposite sides of the wall of the tunnel. The distance between the shelves and the analysed cross-section is less than 20 m. For each station a plate was rigidly fixed to the wall of the gallery. Thus, each shelf can be mounted on the plate at different epochs while the correct positioning is guaranteed by the fixed plate (Figure 4). The general scheme used to determine the target coordinates with this instrument is shown in Figure 5. The main difference between theodolite and photogrammetric coordinates is related to the possibility to fix a vertical reference system. In fact, the bubble of the theodolite allows us to define the vertical

direction (Z), while an ambiguity in the horizontal plane remains. To partially remove this effect we set the Y axis from the right shelf towards the left one. However, this reference system can be considered as stable only if there are no shifts between the shelves. As the photogrammetric method does not guarantee any stable direction and provides only convergence measurements, the data collected with the proposed theodolite scheme are more than sufficient for a further check.



Figure 4. The theodolite used in this experiment with its supports.

The measurements were adjusted via Least Squares and theoretical precisions of about ± 0.5 mm in X (the depth), ± 0.2 mm in Y and ± 0.2 mm in Z were achieved. This method is widely used in a lot of real cases and can be assumed as a proven technique, useful to validate the photogrammetric measurements.

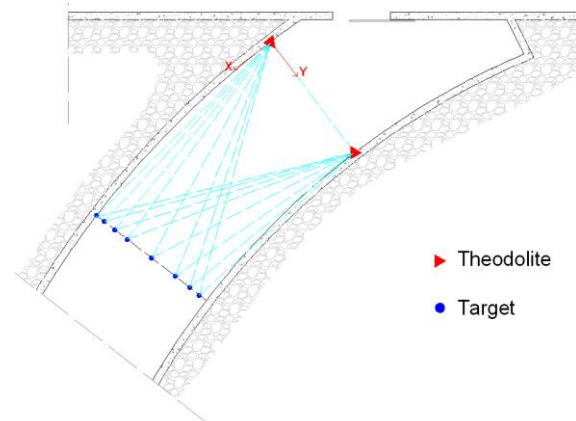


Figure 5. The adopted scheme for theodolite measurements.

3. EXPERIMENTS

To determine a good compromise in terms of images and precision several test with different network geometries were carried out. A simple solution based on a single strip composed of four images gave satisfactory results. With this configuration, images are taken by moving the camera from the left to the right side of the wall (or vice versa), by using a tripod to obtain clear images.

Targets are measured with the *Least Squares Template Matching* (LSTM) algorithm (Gruen, 1985) in order to obtain sub-pixel accuracy, then 3D coordinates are estimated with a free-net bundle adjustment (Granshaw, 1980). Finally, the scale ambiguity is removed with the wire readings.

Figure 6 shows a 3D view with the computed 3D points and camera poses. A picture of the gallery is also shown. As can be seen, there are some points on the road, which were used to

increase the redundancy of the system and to improve the tie points distribution in the images. After the acquisition of the images they can be removed.

The light of the illumination plant of the tunnel was used for the analysis reported in this paper. However, we verified how the use of external light sources (e.g. lamps) does not modify the results.

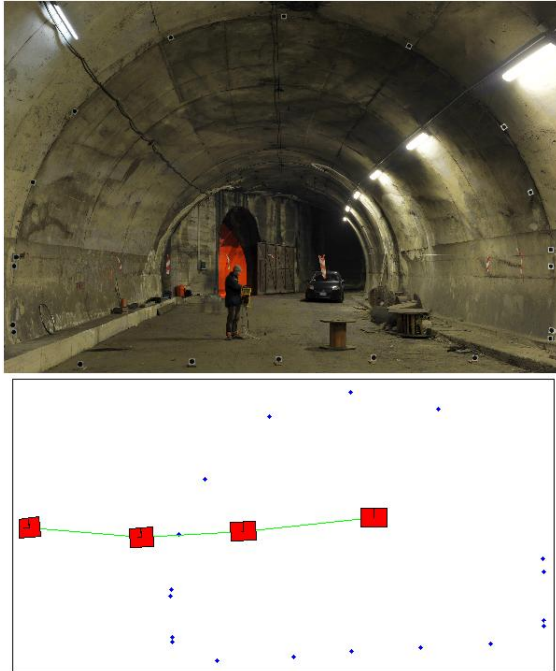


Figure 6. The used tunnel and a 3D view with camera poses and 3D target positions.

3.1 Single epoch deformation measurement

The first test that was performed to determine the accuracy of the method was a single epoch check. Here, some movements for a target were given with a micrometric sledge (Figure 7) and their magnitude was measured with two mechanical tools with an accuracy of ± 0.01 mm. The sledge allows the simulation of planar movements by using some micrometric screws. However, only 1D movements were simulated in order to be detected with the photogrammetric method, which is capable of determining only the variations of the distances between all targets.



Figure 7. The micrometric sledge used in these tests.

This check is based on the simulation of a displacement in the cross-section plane, which is measured with the mechanical tools but also with the images. In this last case, a strip of four images was acquired. Then, a movement was given with the micrometric screw and a new image sequence was taken. This experiment was repeated several times at the same epoch, in order to avoid systematic errors due to the stability of the camera used. Globally, the experiment took less than 15'.

Table 1 shows the results related to a typical situation: four movements were given (+1, +1, -1 and -1 mm) with the sledge and their magnitude was estimated with a Nikon D700. As can be seen, the discrepancy between the measurement is less than 0.3 mm and confirms the accuracy of the proposed method. Moreover, the closure error (+0.22 mm) is quite good and make this results satisfactory in terms of accuracy.

Lastly, several other experiments demonstrated similar results.

	Screw	Nikon D700	Differences
Step1 – Step0	+1 mm	0.78 mm	0.22 mm
Step2 – Step1	+1 mm	1.11 mm	-0.11 mm
Step3 – Step2	-1 mm	-0.82 mm	-0.18 mm
Step4 – Step3	-1 mm	-0.85 mm	-0.15 mm
Closure	0 mm	+0.22 mm	

Mean	-0.06 mm
Std.dev	0.19 mm

Table 1. The relative displacements detected with the photogrammetric method and their “real” values.

3.2 Multi-epoch deformation analysis

A multi-epoch monitoring is the goal of this project. To verify the potentialities of this method several dataset taken at different epochs were compared. Here, the fundamental issue is related to the stability of the cameras used. In fact, SLR digital cameras cannot be assumed as stable instruments and must be calibrated at every epoch to remove systematic errors.

Each dataset was taken in different months, in order to obtain a temporal window of 30 days among the epochs, roughly. During this period, cameras were used for other works in order to worsen their stability.

All measurements were carried out by estimating the distances d_{ij} between all target combinations. Thus, measurements of the first epoch t were compared with those of the next one $t+1$:

$$\Delta_{\text{photo}}^{t,t+1} = (d_{ij})^t - (d_{ij})^{t+1} \quad (1)$$

where $\Delta_{\text{photo}}^{t,t+1}$ are the variations. The same variations were also measured with the theodolite by using the scheme previously shown, obtaining a reference dataset to check the accuracy of the image-based methodology.

The comparison was carried out by analysing the differences of variations between the employed measurement techniques:

$$\delta^{t,t+1} = \Delta_{\text{photo}}^{t,t+1} - \Delta_{\text{theodolite}}^{t,t+1} \quad (2)$$

These tests were carried out with 2 digital cameras and the achieved results are reported and discussed in the next sections.

3.3 Results with a Nikon D80

The first camera used is a Nikon D80 equipped with a 20 mm Sigma lens. This camera has a 10 Mpix sensor (pixel size is 0.0061 mm) and allowed the acquisition of images in which any target was pictured with at least 18×18 pixels. Three epochs were used to check the quality of the photogrammetric measurement and the results are shown in table 2.

	Epoch 1	Epoch 2	Epoch 3
Mean (mm)	0.23	0.66	0.88
Std.dev (mm)	0.57	0.60	0.53
RMS (mm)	0.62	0.89	1.03

Table 2. Comparison between Nikon D80 and theodolite results based on the calculated $\delta^{h,h+1}$.

As can be seen, there is a systematic error. The magnitude of this error is larger than the expected accuracy (0.5 mm). Moreover, the mean is worse than the standard deviation of the differences.

Obviously, this systematic error cannot be removed from the data in real applications (exception made for an elaboration coupled with theodolite measurements). For these reasons we repeated the tests with a new camera (see next section), with superior characteristics.

3.4 Results with a Nikon D700

The same analysis were repeated with a Nikon D700 equipped with a 35 mm Nikkor lens. The quality of this camera is superior to that of a D80 (12 Mpix with a pixel size equal to 0.0084 mm). In addition, the metal body of the camera is naturally more robust and stable.

With this camera we paid a particular attention during the acquisition of the images employed for camera calibration. In addition, we performed a more exhaustive statistical analysis on the estimated calibration parameters.

The images, taken at different epochs, provided the results shown in table 3. As can be seen, the systematic effect was reduced and the standard deviation of the differences of variations gives a value less than 0.5 mm.

	Month 1	Month 2
Mean (mm)	0.00	-0.06
Std.dev (mm)	0.32	0.32
Max (mm)	0.78	0.65
Min (mm)	-0.37	-0.60

Table 3. Comparison between Nikon D700 and theodolite results based on the calculated $\delta^{h,h+1}$.

To complete this analysis, we report also the theoretical precision given by the covariance matrix of the bundle solution. With an object reference system in which Y and Z lie in the plane of the cross-section and X represents the depth, the estimated mean theoretical precisions were $\sigma_Y = \sigma_Z = \pm 0.1$ mm and $\sigma_X = \pm 0.2$ mm. These values are better than the estimated accuracy, but we have to take into account that the check with theodolite measurement is based on mutual distances, rather than point coordinates.

These experimental results demonstrated an accuracy of about ± 0.5 mm for a tunnel wider than 12 m. As this value is quite similar to the nominal accuracy of theodolite data, they seem

sufficient for real surveys. However, a further processing will be carried out in order to validate the method.

4. SOME PRACTICAL ISSUES

The obtained statistics demonstrated how this method can provide good results with a rapid data acquisition. A good reflex camera, a tripod and a steel wire with a mechanical gauge are the instruments needed to determine the convergence of the tunnel by means of targets. A good calibration performed just after the completion of the survey provides sufficient information to remove systematic errors due to the stability of a SLR camera. However, some technical problems were found during these tests and are reported in this section.

First of all, targets are composed of a black dot with a white background. Normally, the quality of the colours of the target can be modified by the bad conditions of tunnels, which are not at the best of times a clean place to work. However, after several months the used targets did not require any cleaning. Moreover, a good cleaning can be carried out with a telescopic tube carrying a paintbrush.

Another issue is related to the use of light sources to ensure stable illumination conditions. In our test we verified that the measurements with and without external light sources do not vary significantly. Thus, if a tunnel is not completely dark the illumination plant of the gallery is more than sufficient. In fact, the exposure time can be estimated directly by the camera once the f-stop is chosen. In our test we selected F/11 and the "aperture priority" modality of the Nikon cameras estimated a time of 3 seconds roughly to take the photographs in the tunnel used for the tests. Obviously, the use of a tripod is mandatory.

An additional issue was found for targets close to light sources. In this case they result much brighter in the images and the LSTM method demonstrated bad results. The bundle solution showed higher residuals on the image coordinates for these points, thus we preferred to remove all points close to artificial light sources.



Figure 8. For narrow tunnels a 3-4 m calibrated bar (e.g. a telescopic tube) can substitute the wire and remove the scale ambiguity of the photogrammetric project.

Another problem is related to the procedure used to remove the scale ambiguity from the photogrammetric reconstruction. The solution with the steel wire is relatively cheap and fast. We studied also the possibility to use a calibrated bar with two targets. In this case the distance between them is given with a high precision and can be used as external constraint. However, this solution can be applied only in the case of very long bars, similar to the tunnel. In fact, the accuracy of the

photogrammetric projects must be taken into account. It generates a systematic error equals to the expected accuracy multiplied by the ratio between the width of the tunnel and the length of the bar. With a 2 m bar this factor is 6, and generates a systematic error equal to 3 mm. For this reason, this solution can be applied only in the case of narrow tunnels.

The calibrated bar used and the tool for its calibration are shown in figure 8.

5. CONCLUSION

The method presented in this paper was developed to overcome some drawbacks of traditional sensors today used in tunnel monitoring. It was designed to reduce the time needed to take the measuring (images and a rapid wire-based reading are the input elements) and provides the mutual distances between some targets mounted on the tunnel cross-section. The accuracy, estimated with several tests, is surely less than ± 1 mm, thus similar to that of a theodolite for monitoring applications. Moreover, the photogrammetric equipment (camera, tripod, targets, ...) is surely cheaper than a theodolite. To remove the scale ambiguity from the photogrammetric project a wire is used to determine the baseline between two targets. The advantage of this solution are its limited cost and the fast and accurate measurements.

Several single- and multi-epoch controls were carried out to test the performances of the method under different conditions in terms of temperature, humidity and illumination. The single-epoch analysis demonstrated the precision achievable with 4 images taken by moving the camera from the left to the right side of the wall of the tunnel. With this configuration, an accuracy better than ± 0.3 mm was reached for a tunnel wider than 12 m, even without a good distribution of the images around the object. The multi-epoch analysis showed some issues related to the stability of the camera and its calibration. However, a good SLR digital camera was sufficient to reach an accuracy of ± 0.5 mm roughly, which is good for our real applications.

An issue still open regards the possibility to determine 3D coordinate variations, rather than distance variations. This aspect needs further investigations (e.g. the use of a bubble) and will be considered in forthcoming improvements.

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