PHOTOGRAMMETRIC LEVELING

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ABSTRACT:

This paper presents an innovative procedure for the analysis of vertical movements of a structure. Here, the focus is on tunnel monitoring and especially on underground lines, where all measurements need to be rapidly carried out during the night, when traffic is stopped. The main concept is the substitution of optical geometric leveling, based on levels and rods, with an image-based solution coined "photogrammetric leveling". The proposed method is notably quicker and more economical. A calibrated digital camera is adopted to capture an image of two special rods placed (or hung) on a pair of height benchmarks. Some targets on the rods are used to determine the vanishing line, that is then used to rectify the image. The knowledge of the distances between opposite targets is used to remove a final scale ambiguity. This allows the estimation of the height differences between the benchmarks by using just one image. Several tests with synthetic and real data were performed to check the accuracy of the method. In addition, some theoretical, practical and numerical results, along with the advantages, limitations, and failure cases of the photogrammetric leveling approach are addressed.

1. INTRODUCTION

Nowadays structure monitoring by geometric leveling can be assumed as a standard technique due to the high accuracy that can be usually achieved. From a practical point of view, it seems very simple to accomplish a measurement campaign, especially if digital levels are employed. On the other hand, optical levels still have a primary role in high precision applications thanks to their inner accuracy, in most cases superior to that of digital levels.

The estimation of heights (and height changes) can be performed with different techniques. These encompass geometric, trigonometric, barometric, mechanical, and hydrostatic leveling, 3D traversing as well as GNSS systems and gravity data. However, geometric leveling is still undoubtedly the most used method for structure monitoring due to its limited cost (level, rods, tripod and a set of benchmarks are the only equipment needed) and its sub-millimetric accuracy.

Geometric leveling is based on the creation of a horizontal line of sight by means of a level equipped with a pendulum or a compensator. Leveling rods must have a regular graduation to obtain the scale of the leveled differences in height. According to the basic principle of leveling, the difference between two readings is the height difference: $\Delta_{i+1,i} = L_i - L_{i+1}$ (Fig. 1). The process is repeated to obtain the height difference between *backsight* and *foresight* ($\Delta_{i+2,i+1} = L_{i+1} - L_{i+2}$), so that the total height difference between widely separated points can be measured by combining the height differences of all the intermediate points.

The use of optical levels with *parallel plate glass micrometers* gives the opportunity to improve reading precision, especially if 5-mm graduations are employed. The collimation of the nearest reading with an adjustment screw is directly connected to the displacement measured by a micrometer. This provides readings with a precision of ±0.1 mm for 1-cm graduations, that are then estimated to ±0.01 mm.

As a measurement campaign is based on the progressive acquisition of several height differences, errors should be reduced to a minimum avoiding a progressive accumulation. The technical literature reports several experiences and possible solutions to this problem. Therefore geometric leveling can be assumed as a proven techniques not only for land surveying, but also for structure monitoring (see Pelzer and Niemeier, 1983; Craymer, 1984; Augath, 1985; Ihde and Steinberg, 1985; among others).

It is also noteworthy that most errors can be reduced by taking a series of ad hoc readings (backwards-forwards-forwards-backwards) from the center, e.g. (i) to correct the error due to symmetric atmospheric refraction, (ii) to compensate for the Earth curvature, (iii) and to remove the collimation errors when the line of sight is not horizontal. Other sources of errors, whose effects were extremely significant in the past, were eliminated with the introduction of more sophisticated instruments. For instance, since the end of 1982 the optical levels Zeiss Ni1 have been equipped with special compensators that are insensitive to the geomagnetic field (Weber and Schellein, 1986), except for alternating magnetic fields of high intensities.

In the case of structure monitoring, geometric leveling provides the vertical displacements of a series of benchmarks, i.e. points well tied to the structure. A benchmark is considered fixed if it is connected to the structure so that it follows its movement. The design of an appropriate measurement scheme coupled with precise measurements allows the determination of heights (and height changes for data taken at different epochs) with sub-millimetric precision. The design of optimal acquisition nets has a direct impact on the precision: series of closed loops with common points must be preferred to (i) improve the accuracy and (ii) to obtain an immediate check based on misclosures.

Although very accurate, geometric leveling is quite slow, with a productivity limited to a small number of points per hour. In some applications aimed at determining the safety conditions of a structure, times becomes a paramount factor and limits the number of points that can be checked. In this paper the problem of tunnel monitoring is specifically addressed. Here, measurements need to be rapidly carried out during the night, when traffic is stopped. The key concept is to replace the standard equipment by introducing an innovative image-based solution, which is notably faster and even more economical. Shown in Figure 2 is the main concept: a camera acquires just one image of a couple of photogrammetric rods and a semi-automated processing algorithm estimates the difference in elevation. The proposed method has been termed “photogrammetric leveling”.

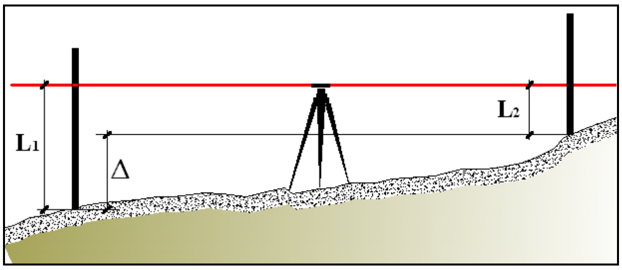

Fig. 1. Basic principle of geometric leveling: the difference in elevation can be estimated with a difference of readings.

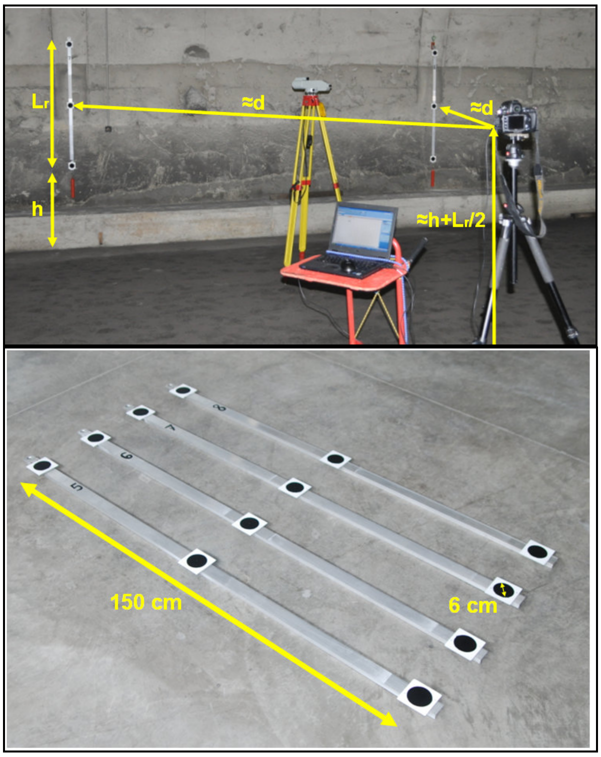

Fig. 2. An example of the basic operational scheme of photogrammetric leveling with two rods placed on benchmarks and a digital camera (top), along with some examples of the special targeted rods (bottom).

2. DETERMINING DIFFERENCES IN ELEVATION WITH A SINGLE IMAGE

The estimation of the difference in elevation between two points can be carried with a calibrated camera and a couple of special photogrammetric rods. The camera must be calibrated beforehand in order to determine its interior orientation and additional parameters (Remondino and Fraser, 2006), which are needed to remove the effect of image distortion and determine a precise height difference. The employed rods have a length of 150 cm and the typical graduation is substituted with 3 circular targets. These can be recognized and measured in the image with sub-pixel precision. The camera is placed in front of the rods (with a similar distance to acquire data from the center). The attitude of the camera does not require particular care. On the other hand, rods are placed on benchmarks and are quasi vertical thanks to a heavy mass that is connected at the bottom end. This is the fundamental difference between the standard geometric leveling approach (where the level gives a horizontal line of sight) and the photogrammetric one (where two rods provide the vertical direction and the attitude of the camera can be variable). The camera should be placed in the center in order to remove some systematic errors, and not only considering the horizontal distance between both rods (equidistant), but also the vertical setup (see Figure 2). The central target on the rod allows the rapid positioning of the camera with a correct instrumental height. If the benchmarks have not a comparable height a compromise during the camera setup must be found using the reticle.

A couple of parallel rods forms a parallelogram in space. This configuration is sufficient to determine a transformation that recovers affine properties, such as ratios of lengths on collinear or parallel lines, ratios of areas, and parallelism. However, this is not sufficient to estimate the difference in elevation as a direct measurement of metric distances remains impossible.

Metric properties can be recovered with the estimation of a homography, i.e. a projective transformation with 8 degrees of freedom. A planar homography is represented by a 3×3 non-singular matrix:

$$\mathrm{x} = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 \\ h_7 & h_8 & h_9 \end{bmatrix} \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = \mathbf{H}\mathrm{X} \tag{1}$$

where points are expressed in homogenous coordinates by adding an extra value to the pair $[x\ y]^{\mathbf{T}}$. This new last coordinate gives a new triplet $\mathrm{x}=[\lambda x\ \lambda y\ \lambda]^{\mathbf{T}}$ for any non-zero value λ. Therefore an arbitrary homogeneous image vector $\mathrm{x}=[x_1\ x_2\ x_3]^{\mathbf{T}}$ represents the same point $\mathrm{x}=[x_1/x_3\ x_2/x_3]^{\mathbf{T}}$ in $\mathbf{R}^2$.

Homographic transformations are often used for different applications, e.g. metric rectification (Liebowitz and Zisserman, 1998) image mosaicing (Szeliski, 1994), panoramic photography (Brown and Lowe, 2007), and architectural reconstructions (Liebowitz et al., 1999). A common method for the estimation of $\mathbf{H}$ is based on a set of point to point $\mathrm{x} \leftrightarrow \mathrm{X}$ correspondences (at least four), which however cannot be employed to substitute the traditional leveling approach, as the needed coordinates are unknown values.

The photogrammetric leveling approach uses the vanishing line coupled with the constraints available from camera calibration: this information is sufficient to recover metric properties without acquiring metric data (e.g. known ratios of distances and angles), except for an overall scale ambiguity that requires knowledge of a distance in the object plane. This missing data can be derived from the distance between opposite targets on the rod.

Most digital camera equipped with CCD or CMOS sensors follow the *pinhole camera* model, which expresses a mathematical relationship between image (x) and object (X) points through a 3×4 projection matrix $\mathbf{P}$ (Hartley and Zisserman, 2004):

$$\mathrm{x} = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \mathbf{P} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \mathbf{P}\mathrm{X} \tag{2}$$

P can be decomposed into the matrix product:

$$\mathbf{P} = \mathbf{K}[\mathbf{R}\ \mathrm{t}] \tag{3}$$

where:

$$\mathbf{K} = \begin{bmatrix} c & 0 & x_0 \\ 0 & c & y_0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

is called *calibration matrix* and encapsulates the interior orientation parameters of the camera used (principal distance c and principal point coordinates x_0, y_0), **R** is a *rotation matrix* and the vector t contains the coordinates of the perspective center.

Collins and Beveridge (1993) demonstrated that the orientation of the object plane with respect to the camera can be estimated if both *vanishing line* l* and calibration matrix **K** are known.

The image coordinates x and x′ of rod targets (Figure 3a) allow the estimation of a line as l=x×x′. A vanishing point v can be estimated by using the intersection of a couple of parallel lines l and l′: v=l×l′.

Finally, the identification of the vanishing line can be carried out by using two vanishing points: l*=v×v′.

The estimation of the rectifying transformation is performed through a homography $\mathbf{H}=\mathbf{KRK}^{-1}$, where **R** is made up of a set of vectors that form an orthonormal set: $\mathbf{R}=[\mathrm{u}_r\ \mathrm{u}_s\ \mathrm{u}_n]^{\mathbf{T}}$.

The unary vector u_n is derived from the normal n to the plane as $\mathrm{u}_n=\mathrm{n}/\|\mathrm{n}\|$, where $\mathrm{n}=\mathrm{K}^{\mathbf{T}}\mathrm{l}^*$.

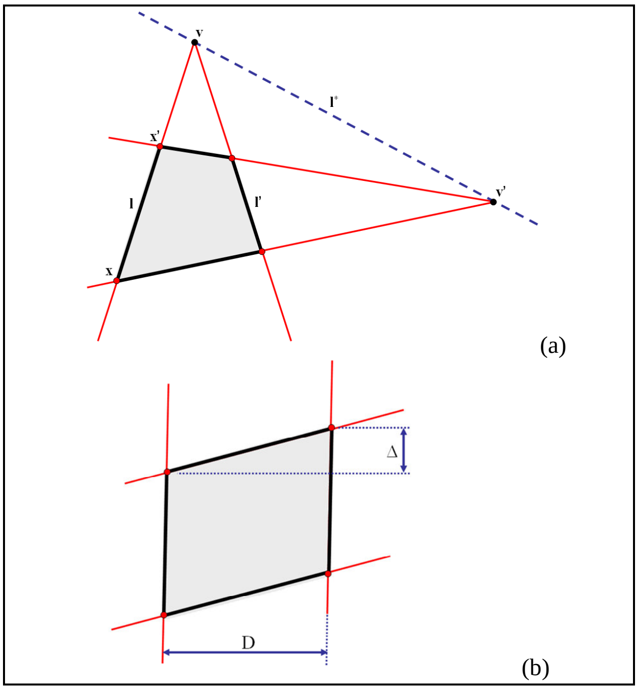

Fig. 3. Geometric quantities used to rectify the original image (a) and the estimated values (b).

The new frontal image has an ambiguity due to the rotation around the normal n. In a few words, in three dimensions there is an infinite number of vectors perpendicular to n. This leads to an under-determined system of equations. The triad of orthonormal vectors u_r, u_s and u_n is estimated with some constraints applied to the second vector r in order to take into consideration all degenerate configurations. The last vector s can be estimated with a simple cross product.

The last step consists in the estimation of a similarity transformation $\mathbf{H}_s$ in order to align the rod along the vertical direction and scale the rectified coordinates X by using the distance between the targets:

$$\mathrm{X}' = \begin{bmatrix} X' \\ Y' \\ 1 \end{bmatrix} = \begin{bmatrix} \lambda\cos\alpha & \lambda\sin\alpha & t_X \\ -\lambda\sin\alpha & \lambda\cos\alpha & t_Y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = \mathbf{H}_S\mathrm{X} \tag{5}$$

where the numerical values t_x and t_y are not mandatory for the estimation of height differences (constant values can be employed), λ is given by the rod length and α depends on the transformed image coordinates. Figure 4 shows original (without lens distortion) and rectified images, which however are just a visualization to understand the procedure as the rectification algorithm is usually applied to the measured numerical values of pixel coordinates.

The final step is the estimation of the height difference with a simple difference ($\Delta=Y'_3-Y'_1=Y'_4-Y'_2$) and, optionally, the horizontal distance ($D=X'_3-X'_1=X'_4-X'_2$) between the rods. This last value cannot be measured with a standard leveling procedure but requires a repositioning system of the rod with a stable connection at different epochs.

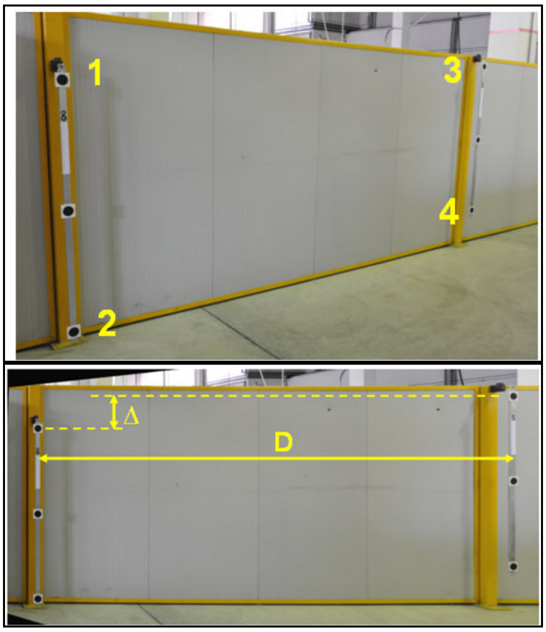

Fig. 4. A distortion-free image (top) and its corresponding rectified image (bottom).

3. DATA ACQUISITION

As demonstrated in the previous section, a difference in elevation can be estimated using a single image acquired with a calibrated camera. As previously mentioned, the camera must be

setup between the rods with an instrumental height close to that of the central target. Then, the target centers are measured in order to estimate the rectifying homography based on camera parameters. On the other hand, an important consideration deserves to be mentioned: the precision during the measurement of image coordinates affects the precision of object coordinates, requiring not only a sub-pixel method, but also a mathematical model for distortion removal.
This section illustrates the methodology adopted to calibrate the camera in order to obtain the matrix **K** and distortion-free image coordinates. Then, the method employed to measure target centers is described.

3.1 Camera calibration

A camera is assumed as calibrated if its interior orientation parameters (principal distance and principal point position) and distortion coefficients (also called additional parameters) are known. Image distortion generates a misalignment between the perspective centre, image and object points. It is quite simple to understand that the collinearity principle (Kraus, 2008), which is the basis for image orientation, is no longer respected.
The importance of camera calibration is confirmed by the vast number of papers dealing with this topic. Accuracy aspects, use of both low-cost and professional cameras, applications, methods, stability of parameters, variations with different color channels, algorithmic issues, etc., were reported in Fraser (1997), Peipe and Stephani (2003), Läbe and Förstner (2004), and Remondino and Fraser (2006), among others.
Image distortion can be represented with an 8-term mathematical model. This is made up of 3 interior orientation parameters (c, x_0, y_0), 3 coefficients of radial distortion (k_1, k_2, k_3), and 2 coefficients of decentering distortion (p_1, p_2).
Radial distortion is modeled with an odd-ordered polynomial:

$$\delta r = k_1 r^3 + k_2 r^5 + k_3 r^7 \tag{6}$$

where r is the radial distance from the principal point:

$$r = \sqrt{(x - x_0)^2 + (y - y_0)^2} \tag{7}$$

The components along x and y of δ may be estimated as follows:

$$\delta x = (x - x_0)\frac{\delta r}{r}, \qquad \delta y = (y - y_0)\frac{\delta r}{r} \tag{8}$$

A misalignment of lens elements along the optical axis instead generates decentering distortion. The corrections of the image coordinates are given by:

$$\begin{aligned} \Delta x &= p_1\left[r^2 + 2(x - x_0)^2\right] + 2p_2(x - x_0)(y - y_0) \\ \Delta y &= p_2\left[r^2 + 2(y - y_0)^2\right] + 2p_1(x - x_0)(y - y_0) \end{aligned} \tag{9}$$

These coefficients can be estimated with a calibration project, where a set of *coded targets* are photographed using a block of images with a good distribution in space. These conditions are needed to minimize the effect of the correlation between lens distortion coefficients. A block must include convergent and rolled images, and variable camera-object distances. Lastly, a *free-network bundle adjustment* (Granshaw, 1980) provides all calibration parameters.
As our method was developed for tunnel monitoring, the camera was directly calibrated in the tunnel using the portable targets of the iWitness software (Fraser et al., 2005). This package allows one to complete the calibration phase within 5 minutes, without requiring any manual measurements.

4. EXPERIMENTAL RESULTS

The photogrammetric leveling approach can be used in real surveys only after an evaluation that makes clear the precision achievable, its advantages and limitations. The experimental phase was carried out with different images (synthetic and real) in different sites (laboratories with controlled conditions and tunnels) in order to check (i) the correctness of the implemented software and (ii) its use in practical applications.

4.1 Processing of synthetic data

A set of 20 synthetic images generated with 3D Studio Max (Figure 5) was used to check the correctness of the implemented algorithms (measurement of target center and rectifying homography). The distortion-free images were created assuming a camera similar to a Nikon D100 (sensor size 3008×2000 pixels, pixel size 7.8 μm) equipped with a 20 mm lens, that were virtually acquired from different stations. The imaged scene is quite simple, as only two vertical rods are visible. During the acquisition of the images, both rods were moved along both horizontal and vertical directions to simulate different displacements. The magnitude of displacements is therefore known and can be used to validate the results of photogrammetric leveling. In a few words, the simulated horizontal D_i^s and vertical distances Δ_i^s were compared with those estimated using the image-based procedure (D_i^{pl}, Δ_i^{pl}), with a simple difference and a statistical evaluation.

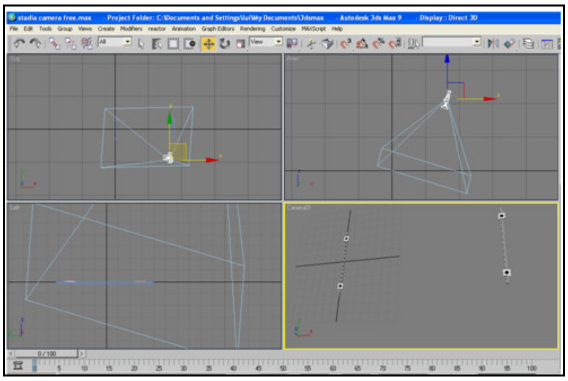

Fig. 5. Generation of synthetic data (images with known calibration parameters and object geometry) with 3D Studio Max.

The length of the simulated rod, i.e. the distance between the targets, is 150 cm. The horizontal distance varied from 4 to 6 m and images were taken not only from the center, but also from "inappropriate" positions in order to obtain narrow angles of view. The direct comparison between simulated and estimated values ($d_i = D_i^s - D_i^{pl}$, $\delta_i = \Delta_i^s - \Delta_i^{pl}$) was performed by using the average μ and standard deviation σ of both (d_i, δ_i) and provided the following results:

$\mu(d_i)$ = -0.08 mm $\sigma(d_i)$ = ± 0.08 mm
$\mu(\delta_i)$ = 0.04 mm $\sigma(\delta_i)$ = ± 0.07 mm

They confirms a relative accuracy of 1:40,000, although a systematic error is evident from the mean values. In any case, the geometry used during these tests was quite complicated as in real applications images will be always taken from the center.

4.2 Moving the camera

During a monitoring campaign, if images are acquired at different epochs it is normal to setup the camera approximately in the same position. This test aimed at determining the same difference in elevation (rods are fixed) from different standpoints, in order to simulate a multi-temporal data acquisition, where the measured Δ_i^{pl} should be constant. The main difference with respect to the previous check is the use of real images acquired with a calibrated Nikon D80 equipped with a 20 mm lens. In all, 16 differences in elevation were measured and the results are shown in Figure 6. The standard deviation of the measured values is ±0.1 mm, that is quite similar to the precision of a good optical level.

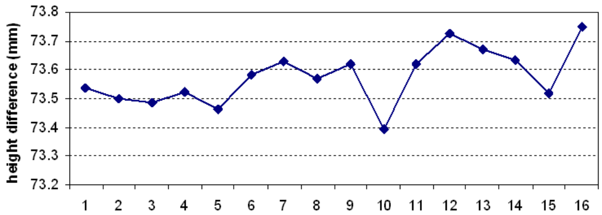

Fig. 6. The same difference in elevation measured by placing the camera at different stations. The standard deviation of the values shows a discrepancy between the measurements of ±0.1 mm.

4.3 Comparison with an optical level

Another test was carried out with real data by using several images taken with a calibrated Nikon D700 with a 35 mm and two metal rods placed on benchmarks (Figure 7). A ruler was also applied to each photogrammetric rod in order to measure the difference of height with a first order automatic level Zeiss Ni1 (standard deviation/km leveling ±0.2 mm).

As the level provides the height difference $\Delta H_{12}=L_2\text{-}L_1$ the comparison was performed by using variations of height differences, and therefore measurements taken at different epochs $d^{\Delta H,i}=\Delta H^{i+1}\text{-}\Delta H^{i}$ were needed after simulating a displacement with a movable benchmark (Figure 7b). The statistic on the differences $d^{\Delta H,i}$ showed a mean value $\mu(d^{\Delta H,i})$=0.05 mm and a standard deviation $\sigma(d^{\Delta H,i})$=±0.09 mm.

4.4 An experiment in a real tunnel

A test similar to that carried out in a laboratory was performed in a tunnel (Figure 8). A series of benchmarks was installed along the wall. The photogrammetric rods have a ruler to obtain also the measurements with the Zeiss Ni1. A benchmark was equipped with the adjustable screw to simulate some vertical movements. In addition, there is also a mechanical gauge able to measure the displacements.

Data were collected following a closed path with 4 benchmarks (first in one direction, then in the opposite one) in order to check the loop vertical misclosure. The photogrammetric method provided satisfactory results, as the final misclosure was less than 0.2 mm.

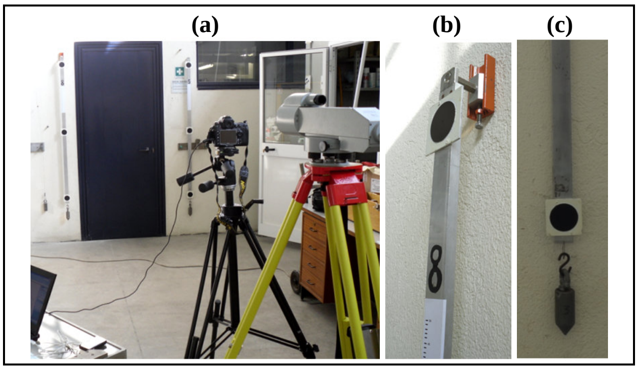

Fig. 7. The test with an optical level: (a) the rod with a graduated card mounted on a movable benchmark (b) and a heavy weight to make each rod more stable (c).

However, a direct comparison between the simulated displacements based on level and gauge measurements provided discrepancy superior to 0.4 mm. The cause of this unexpected effect is still not clear and might depend on several factors. Probably, the method is sensitive to the distance between the rods, and a rod of 150 cm is not sufficient to cope with distances larger than 5 m. This is an evident limit but its investigation needs more exhaustive analysis.

Another problem was found when the rod is not stable, especially when it swings like a pendulum. This is not a serious problem for measurement carried out with a level, which gives a horizontal line of sight. However, the photogrammetric method is highly sensitive to this effect as the rod gives the vertical direction.

Fig. 8. The experiment in a real tunnel with a sequence of rods on fixed and movable benchmarks.

The installation of a heavy weight (5 kg) allows one to strongly reduce this effect, although bubbles should be installed on the rods to obtain a certain check of their stability.

5. CONCLUSION

This paper presented a new approach for tunnel monitoring where geometric leveling is replaced by an image-based approach. The method was specifically designed for this application as the benchmarks can be easily installed along a straight line and can be photographed by translating the camera. For other categories of objects (e.g. historical buildings, bridges, …) this method cannot substitute the standard level-based approach because of the geometry of the structure and also some illumination problems. Indeed, illumination conditions must be very stable to achieve accurate results, while we found some limits when a target is partially illuminated. Obviously, in a tunnel external light sources are often needed and this drawback can be easily overcome.

The adjustment model of a leveling network does not change with the photogrammetric approach as the observation equations are exactly the same of standard optical level-based data. It is also recommended to acquire multiple photographs for a generic difference in elevations. The camera position should be slightly varied in order to obtain independent measurements.

The precision in experiments carried out under controlled conditions was satisfactory (±0.1-0.2 mm), although in real experiments in tunnels some unexpected results were discovered. This still limits the use of the photogrammetric leveling approach in real cases and makes new analysis necessary to understand better the behavior of the method and possible sources of error.

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References

Augath, W., 1985. Höhennetze. Geodätische Netze in Landes- und Ingenieurvermessung II, Edi. Pelzer and Wittwer, Stuttgart.

Brown, M. and Lowe, D.G., Automatic panoramic image stitching using invariant features, International Journal of Computer Vision, 74(1), pp. 59-73 (2007).

Craymer, M.R., 1984. Data series analysis and systematic effects in levelling. Technical report n.6, University of Toronto.

Collins, R. T. and Beveridge, J. R., Matching perspective views of coplanar structures using projective unwarping and similarity matching. Proceedings of CVPR (1993).

Fraser, C.S., 1997. Digital camera self-calibration. *ISPRS Journal of Photogrammetry and Remote Sensing*, (52): 149-159.

Fraser, C.S., Hanley, H. and Cronk, S., 2005. Close-range photogrammetry for accident reconstruction. *Optical 3D Measurements VII*, (2): 115-123.

Granshaw, S.I., 1980. Bundle adjustment methods in engineering photogrammetry. *Photogrammetric Record*, 10(56): 181-207.

Grün, A., 1985. Adaptative least squares correlation: a powerful image matching technique. *South African Journal of Photogrammetry, Remote Sensing and Cartography*, 14(3): 175-187.

Hartley, R.I. and Zisserman A., 2004. *Multiple View Geometry in Computer Vision*. Second edition. Cambridge University Press, Cambridge, 672 pages.

Kraus, K., 2008. *Photogrammetry: Geometry from Images and Laser Scans*. Second edition .Walter de Gruyter. 459 pages.

Läbe, T. and Förstner, W., 2004. Geometric stability of low-cost digital consumer cameras. *Int. Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 35(5), 528-535.

Liebowitz, D., Criminisi, A. and Zisserman, A., Creating architectural models from images. Proceedings of EUROGRAPHICS (1999).

Liebowitz, D. and Zisserman, A., Metric rectification for perspective images of planes, Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition (1998).

Ihde, J. and Steinberg, J., 1985. Leistungsfähigkeit und Reserven das geometrischen Präzisionsnivellements, Part I-II, Vermessungstechnik 33.

Peipe, J. and Stephani, M., 2003. Performance evaluation of a 5 megapixel digital metric camera for use in architectural photogrammetry. Int. Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 34 (5/W12): 259-261.

Pelzer, H. and Niemeier, W., 1983. Precise Leveling. Workshop on Precise Leveling, Dümmler Verlag, Bonn.

Remondino, F. and Fraser, C., 2006. Digital camera calibration methods: considerations and comparisons. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 36(5): 266-272.

Szeliski, R., Image mosaicing for tele-reality applications, Digital Equipment Corporation, Cambridge, USA (1994).

Weber, D. and Schellein, H., 1986. The present situation of precise levelling. Symp. On Height Determination and Recent Vertical Crustal Movements in Western Europe, Hannover, Germany, 11p.