Enhancement of 3D monitoring networks' sensitivity by low cost innovative implementation

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Abstract. Usually 3D monitoring networks are used for long time due to the need for several campaigns of measurements' acquisition, in concrete time intervals. Thus, the repeated instrumentation (total stations, targets or GNSS receivers) setting on specific networks' points causes centering errors, which influences the points' coordinates calculation and their uncertainty.
In order to obtain precise - forced centering, permanent, heavy and expensive pillar construction is needed. Although these pillars are appropriate cause not-reverse intervention to the construction's site. For these reasons in many cases the establishment of pillars is not allowed or preferred. This work presents a flexible solution to the above mentioned problem. A prototype way for marking network's points is being implied which assures forced unique instrument's centering less than 0.1mm. A special Portable Metallic Pillar (PMP) was used for marking accessible points. This assists the enhancement of network's sensitivity. It is light enough to carry, it accelerates and facilitates the centering and levelling of the instrumentation as well as it eliminates the time needed for the measurements. Additionally PMP is environment – friendly as it is invisible but for ever permanent.
Further a procedure for the accurate instrumentation's height measurement is analyzed.
PMPs were already used for the installation of the points of two 3D monitoring networks.
The first one was established at the streets around a modern football stadium, where 3 measurement campaigns were carried out within four years.
The second one was established at the site around a post-Byzantine Church, where 4 measurement campaigns were carried out in one year, as large displacements were observed.

The measurements analysis proved a satisfied networks' sensitivity and points out the contribution, the convenience and the usefulness of the PMPs in such applications.

Keywords. Portable Metallic Pillars (PMP); precise - forced centering; implementation of accessible points; 3D monitoring networks; Deformation

1 Introduction

Monitoring is the fastest growing discipline in the survey market. Surveyors undertake the difficult task to answer: What is moving? How fast? In what direction? Is it accelerating? The answers come from reliable, precise measurements from this modern instrumentation (Brooks O. (2011).

Also structural health monitoring is one of the important components in the maintenance technology for civil infrastructures (Hongwei L., Jinping O. (2006)).

For these reasons monitoring sensors' networks were established all around of bridges, tunnels, dams, railways, nuclear power stations, high buildings and cultural heritage monuments in order to collect any spatial and qualitative information concerning the specific construction (Nicaise Q., Cranenbroeck J. (2015)).

All these constructions benefit from implementing monitoring systems. Such systems are expected to provide multi-dimensional alarms, visualization of results in near-real time, and millimeter accuracies. (Danisch, L. et al (2008)), (Wilkins R. et al (2003)).

Thus the data are acquired continuously and are sent to central servers to be elaborate, to be adjusted and to extract the results (Singer J. et al (2009)).

3D geodetic monitoring networks and instrumentation as total station, GNSS receivers, retroreflectors ect., consist part of these sensors collecting spatial data information for the construction safety.

The main parameter is the monitoring network's sensitivity, which was defined as the minimum displacement that could be detected by a network for a concrete confidence level (usually 95%). To be more specific if it is needed to detect displacements of ±5mm for confidence level 95%, generally the points coordinates ought to have rms about ±2mm.

In most cases, accuracy of the order of ±1mm is required (Delikaraoglou D. et al, 2010), (Lambrou E. et al (2011)), (Pantazis G. (2015)), (Chounta I., Ioannidis Ch. (2012)), (Huang T., et al (2010)).

Today the technology's evolution provides the possibility of accurate geodetic measurements. The modern total stations adjust automatically and electronically in real-time the line of sight error, the tilting axis error, the compensator z and Hz error, the V-index error and the ATR collimation error if it is available (Uren J., Price B. (2010)).

Thus the displayed measurements are free of them and considerable accuracy is provided for angle and distance measurements reaching the ±0.5″ and ±0.2mm correspondingly. Also the embedded compensator ensures their accurate levelling. (Lemmon T., Jung R. (2005)) (Zogg H., et al (2009))

Nevertheless the measurement errors that still remain are:

- the centering error of both the instrument and targets
- The error in the measurement of both heights of instrument and targets.

These errors are significant and surcharge the measurements and the calculated coordinates with remarkable errors (Lambrou E. (2013)), (Doukas J. (1984)), (Lambrou E. et al, (2011)), (Nikolitsas K., Lambrou E. (2015)).

This paper aims to propose techniques in order to clear or eliminate these errors.

Usually monitoring networks are implemented by permanent instrumentation which is established at permanent positions namely cement pillars, metallic arms or other permanent constructions. In these cases the centering and levelling error of the instrumentation are totally removed as all the measurement phases are referred to the initial point where the instrument was set and levelled.

This instrumentation consists of tens or hundreds of Total Stations (TS), or GNSS receivers and thousands of retroreflectors and other sensors. (http://www.ipcmonitoring.com/portfolio/the-London-crossrail-project)

It is obvious that a permanent 3D network is of high cost which isn't always feasible to afford. Additionally cement pillars, metallic arms or other permanent constructions which are appropriate for the instrumentation set up aren't allowed to be established at every site such as the archaeological ones. (Telioni E., Georgopoulos G. (2006)), Georgopoulos G., Telioni E. ((2008)).

So there are cases where the permanent establishment of this instrumentation is banned for cost reasons or for environmental circumstances or for another special status quo.

Thus the main goal is to devise an innovate fabrication for the 3D networks definition of high precision, not permanent, with low cost and without any visible interference to the environment. Additionally this implementation should ensure the force centering and the proper levelling of the instrumentation in order to erase the above mentioned fundamental errors. The successful results of the use of the Portable Metallic Pillars (PMP), in two sensitive 3D monitoring networks, support the above statement. The PMP permits the establishment of high sensitivity networks with minimum cost. Additionally PMP allows the quick instrumentation set up, so it eliminates the time for the network measurement.

2 Outline of Portable Metallic Pillar (PMP)

The special PMP (picture 1) is composed by two separate parts: The pole and the ground - base.

The pole is a cylinder made by nickel-plated heavy duty steel, protected of the corrosion. It has length 118cm, diameter 5cm and it weights about 8Kgr. The length of the pole should be such as to not oscillate during the measurements, a medium height observer to be able to use it and finally the line of sight of the instrument must overcome common obstacles as cars, motorcycles, etc.

The top of the pole is a flat circular disk of 12cm diameter and 7mm width. It has a projected screw at the center in order to put on the tribraches at a unique position. The center of the screw of the pole's top defines the network's point.

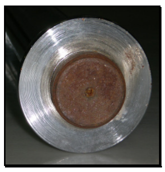
The bottom of the pole has also a flat circular disc and the projected part of its body is formed so as to be a screw (picture 1) in order to screw in the ground - base accurately at a unique position.

The poles' manufacture should satisfy the following requirements in order to be used at every network's point:

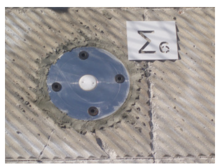
- All the poles must have the same length (The distance between the top and the bottom circular disks).

- The center of the screw at the pole's top and the center of the screw at the pole's bottom must belong to the axis of the pole (cylinder). Also the axis of the pole must be perpendicular to both circular disks (bases of the cylinder). (Lambrou E. et al (2011)).
- Each pole must be screw exactly by the same way on every ground - base.

The ground - base is circular with 20 cm diameter and 2 cm thickness; it has a hole with turns of screw in the center of 5cm diameter where the pole screws (picture 2). Also it has four holes at the circumference where special porps are put to firm it in the ground. The base was made by inox in order to protect it from rusting. A pole's turning costs about 250 euros as 300 euros are enough for the ground – base.



Pict. 1 The Portable Metallic Pillar



Pict. 2 The ground – base

3 Implementation of Portable Metallic Pillar (PMP)

The ground base is incorporated in the ground at the selected position. It is stabilized by concrete. Special attention must be paid for the proper levelling of the ground-base. It should be horizontal in order to force the pole to stand at vertical position when it is screwed on it. This could be realized by using a digital level during the establishment procedure.

When a pole is screw on a ground base, a tribrach is also screw and leveled on the top of the pole so as a TS or a GNSS receiver or a retroreflector could be put accurately at the same point at every measurement campaign. Thus the centering error is totally removed. When a measurement campaign finish, the poles are put off. Nothing remains at the site except the embedded bases in the ground.

It is obvious that the base will permanently remains at the ground position as it is almost impossible to be removed. Thus they are needed as many ground bases as the network's points are. On the contrary, the poles are mobile. So any pole can be put on every ground base as they are exactly suchlike each other. Also the same poles can be used in several of such networks. In order to eliminate the total cost isn't need to manufacture as many poles as ground–bases.

4 Accurate measurement of instrument height (IH)

The second significant error emerges by the measurement of the height of TS, targets and GNSS antenna.

The following methodology ensures accuracy of ±0.1mm to ±0.2mm for instruments height measurement. A digital level and a staff are required.

On a point A, close to the TS's station B, about 5-6m, the staff is put. The reading e on the staff is taken by the TS, under the presupposition that the line of sight is horizontal (namely z=100g). Two readings are taken in 1st (e^{I}) and 2nd (e^{II}) telescope position (namely z= 300g) (Figure 1α). The mean value is calculated as

$$e = \frac{e^{I} + e^{II}}{2} \qquad (1)$$

Then the TS is removed. Next the level is put at the middle between A and B. Both readings backward O (to point B) and forward E (to point A) are taken. (Figure 1b).

The high difference between the points A and B is calculated as

$$\Delta H_{AB} = O - E \qquad (2)$$

Thus the IH comes out as the sum of e and ΔH_{AB},

$$IH = e + \Delta H_{AB} \qquad (3)$$

As the level's reading accuracy on a digital staff is ±0.1mm. The total accuracy succeeded depends on the observer's reading skill on the staff (e), that could be ± 0.2 mm.

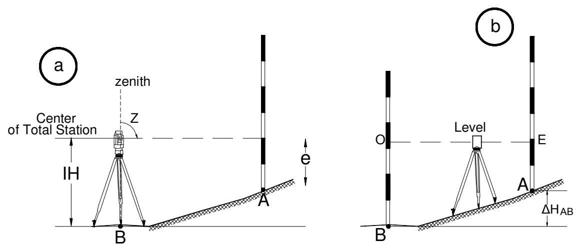


Fig. 1 Accurate measurement of instrument- target height

A simpler procedure is applied for the accurate measurement of a GNSS antenna height. The level is put close to the network point. The staff was put both on the surface where the antenna's bottom is seated where a reading e_A is taken (Figure2a), and next on the surface where the height of the point should be referred (i.e. the bottom of the pillar) where a reading e_B is taken (Figure2b).
The antenna's height comes out as

$$IH = e_B - e_A + FCH \tag{4}$$

Where FCH (Face Center Height) is the distance from the antenna's bottom to the antenna's face center (is given by the manufacturer). The total accuracy succeeded is of the order of ±0.1mm.

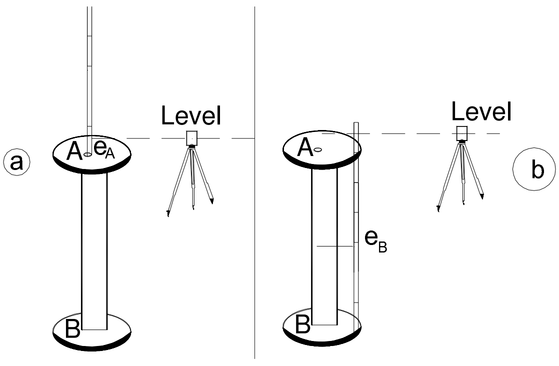


Fig. 2 : Accurate measurement of GNSS antenna height

5 Applications of PMP

5.1 ″Karaiskaki″ football stadium

The ″Karaiskaki″ football stadium, of a capacity of 32000 people, was constructed on a very unstable area close to the sea.The stadium was built on 2004, in order to support the Athens Olympic Games. For monitoring the structure's behaviour a 3D control network of twelve points was established at the surround stadium area (Fig. 3). (Bisbilis K. (2007)). The six accessible points of the network were implemented by using PMPs. The rest six inaccessible points were put on the supporting body of the stadium. These points were also marked permanently by small circular targets. The distances between the points fluctuate from 45m to 220m.
The network was measured three times, December 2006, May 2007 and March 2010. In the two campaigns (December 2007, May 2007) the total station Topcon GTS 3003 was used for the measurements, which provide accuracy $\pm 9^{cc}$ for the direction and ±2mm ±3ppm for the distance measurements. In the third campaign (March 2010) the total station Leica TCRM 1201^{+} was used for the measurements, which provide accuracy $\pm 3^{cc}$ for the direction and ±1mm±2ppm for the distance measurements.

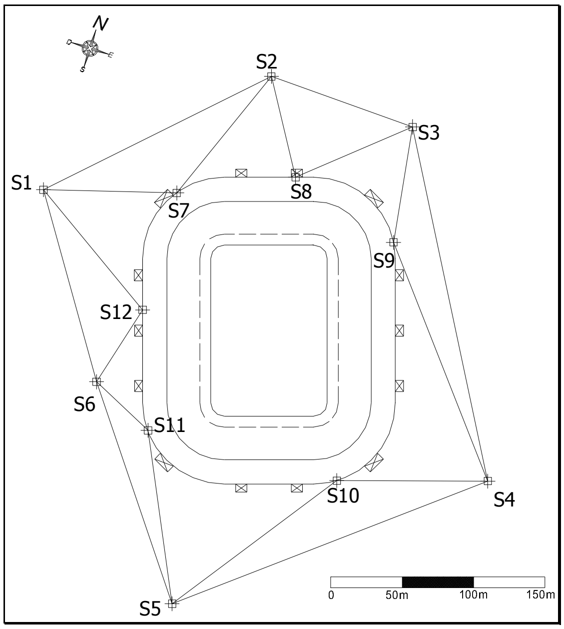


Fig. 3 The control network of ″Karaiskaki″ football stadium.

It is remarkable that the time needed for the measurements from each station was maximum 20 minutes, namely 2 hours were needed for all the measurements. This was achieved as the PMPs facilitate the placing and the levelling of both instrument and targets.
The network adjustment was carried out in an arbitrary local reference system.
The mean rms of the determined coordinates x, y, z is of the order of ±3mm. That means that displacements less than 1cm can be detected for confidence level 95%. Table 1 presents the points displacements between three measurement periods. The time period December 2006 – May 2007 there aren't vertical displacements but there are horizontal ones at the points S4, S5, S9, and S11. The next period May 2007 – March 2010, almost 3 years, there is a vertical displacement at the point S5 as well as horizontal displacements occurred at the points S4, S5, S6, S10 and S11.

Table 1. Horizontal and vertical displacements between three measurement phases

	December 2006 – May 2007		May 2007 - March 2010	
Point	Horizontal displacement δr (mm)	Vertical displacement δH (mm)	Horizontal displacement δr (mm)	Vertical displacement δH (mm)
S1	0.0	0.0	0.0	0.0
S2	0.0	1.0	0.6	-1.7
S3	2.2	1.0	3.1	-4.9
S4	13.0	-1.0	11.5	-1.8
S5	10.0	1.0	14.1	-9.2
S6	7.1	1.0	10.3	-0.1
S7	2.2	1.0	1.7	-0.2
S8	3.2	-1.0	2.3	1.2
S9	8.6	0.0	5.9	-4.8
S10	6.1	0.0	10.3	-1.7
S11	14.1	3.0	13.7	-4.7
S12	4.1	-1.0	6.1	0.1

5.2 The church of Megali Panayia in Samarina

Samarina, reportedly the highest village in Greece, at an elevation of some 1450 m, is situated on the wooded slopes of Mount Smolikas in the Pindos Mountains, approximately 70 km west of Grevena in northwestern Greece. Samarina's post Byzantine church of Megali Panayia (Great St. Mary's church) has been built in 1816 and is the area's main religious landmark, as well as a wonder of nature. The church is famous for its painted ceilings, frescoes, and a finely carved iconostasis (templon), but also that the roof of the altar, covering the apse, in the east side of the 40m long building, "accommodates" a big pine tree with no sight of the tree's roots to be found within the church or outside the wall (picture 3).

Pict.3 Samarina's Megali Panayia

The church is constructed of local stone and has very shallow foundations sitting on unfavorable ground, composed mainly of clay, silt and peat, with the solid rock found in depths of more than 15 m from the surface (Delikaraoglou, et al (2010)).

Pict. 4 Damage caused by structural deformation

As the church suffered from extensive structural deformations systematic monitoring should be started. The establishment of permanent concrete pillars was forbidden as it would destroy the sight of the monument. Additionally the accuracies for the geodetic measurements were to be at the level of a 1-2mm in order to detect every displacement up to 5mm for confidence level 95%.That means a high sensitivity network. (Delikaraoglou, et al (2010)), (Georgopoulos, et al (2010)).
A main 3D network was established inside and outside the monument, which consists of 15 station points. Six of them are located outside of the church and nine more in the interior (figure 4). Also many points were put on the church's body namely on the walls. These points are implemented by special self-adhesive retroreflectors.

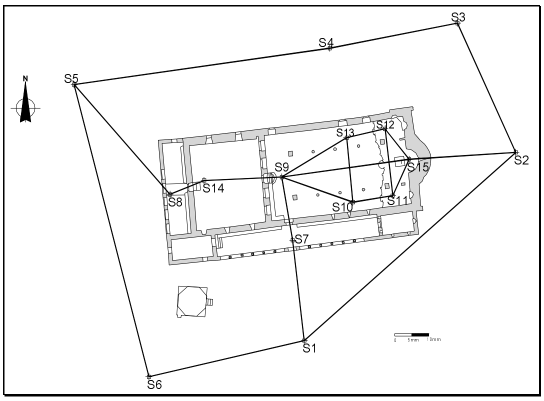


Fig. 4 The control network of Megali Panayia

The external six points, with inter-station distances ranging from about 19 to 69m, were implemented by using PMPs.
The network was measured four times, in intervals of about 45 days, June 2009, July 2009 September 2009 and October 2009. In all campaigns the total station Leica DTM 5000 was used which provide accuracy $\pm 1.5^{cc}$ for the direction and ± 0.5mm± 1ppm for the distance measurements. (http://www.leicageosystems.com/media/new/product solution/L3_TDA5005.pdf)
The network was also measured by using GNSS receivers.
The measurements from the six PMPs were carried out in about 4 hours ensuring the simultaneously of the procedure providing time efficiency.
The network adjustment was carried out in an arbitrary local reference system. The point S2 was considered stable as was placed at more stable ground. However its stability was checked by an external network of the wide area.
Thanks to PMPs the total accuracy of the determined coordinates x, y, z is of the order of ± 0.2mm. That means that even displacements of the order of 1mm could be detected. As it is presented in table 2 almost all the points have horizontal and vertical displacements.
Figure 5 illustrates the horizontal displacements vectors for all the network points.

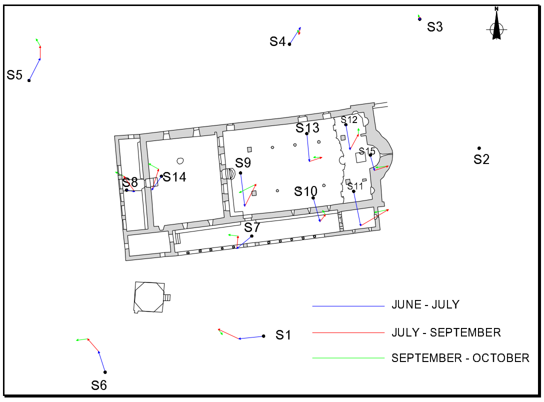


Fig. 5 The control network of Megali Panayia

Table 2. Planar (Δr) and vertical (ΔH) displacements of the network points

	Sep - Oct 2009		July - Sep 2009		June - July 2009	
Point	Δr (mm)	ΔH (mm)	Δr (mm)	ΔH (mm)	Δr (mm)	ΔH (mm)
Points outside the Church						
S1	4.8	+10.4	16.1	-2.9	18.3	+1.8
S2		0	0	0	0	0
S3	3.1	6.7	1.0	-7.0	1.2	-1.6
S4	2.7	-4.9	4.6	-1.5	14.3	1.5
S5	5.9	-3.7	8.6	0.1	18.3	-1.8
S6	8.5	-4.9	12.2	-3.2	15.6	-2.2
Points inside the Church						
S7	7.1	-9.3	9.4	5.0	14.6	-0.3
S8	7.2	-2.6	14.1	1.6	6.3	-1.9
S9	13.5	-2.7	17.9	2.2	23.9	-3.1
S10	3.8	-3.2	6.7	2.4	18.2	-3.4
S11	10.0	-4.0	23.1	1.0	25.4	-2.3
S12	4.3	-1.6	12.6	0.1	18.4	-5.2
S13	6.2	-3.4	9.2	1.6	19.7	-2.5
S14	7.9	-4.5	15.7	-0.1	12.2	0.9
S15	8.6	-4.0	10.4	0.9	11.5	-1.9

6 Conclusions

As now days the number and the requirements for 3D monitoring network are augmented the proposal of low cost and high sensitivity network seems to be attractive. Two erroneous crucial parameters that still remain at the geodetic measurements, the centering error and the instrument height measurement, provide significant uncertainties to the results of the impermanent 3D monitoring networks.
A prototype way for the implementation of network's points is being implied which ensures precise centering for the instrumentation. The special Portable Metallic Pillar (PMP) that is presented is used for marking accessible points. The PMP provides forced unique instrument's centering less than ± 0.1mm. It is light enough to carry, it accelerates and facilitates the centering and levelling of the instrumentation as well as it eliminates the time needed for the measurements.
Additionally PMP is environment – friendly as it is invisible but for ever permanent.
Additionally two simple procedures for both TS and GNSS receivers height measurement are presented by an accuracy of $\pm$ 0.2mm and ± 0.1mm

correspondingly. This permits the total 3D network solution achieving the same order of the rms for x, y and z coordinates.

The two applications were proved to be successful. PMPs use provides exceptional accuracy ±0.2mm at the Megali Panayia network where a first order TS was used. Also the duration of measurements was fairly shortened.

At the ″Karaiskaki″ football stadium PMPs allow for super quick measurements which are needed for this application and satisfied accuracy according to the used TS.

Consequently the use of the PMP it is recommended for the implementation of displacements' monitoring networks as combining with the accurate instrument height determination provides low manufacturing cost, easy establishment, no environment intervention, quick instrument setting and measurement acquisition and high coordinates accuracy. Thus it allows for high sensitivity 3D network achievement in order to detect displacements of the order of 1mm.

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