Axial tomography as a tool for the estimation of constructions' deformations

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ABSTRACT

Constructions' deformations are, traditionally, estimated through the displacements of the discrete control points of a geodetic control network, established for this purpose. Nowadays, however, modern technology, and specifically 3D terrestrial scanning technology, can provide detailed information about the way the construction has deformed. This information is obtained through the exploitation of the point cloud that provide a holography of the construction under consideration. Dense sections of this 3D model, perpendicular to a specified axis, produce a tomography of the construction. From these sections, all the information, that describes the way the construction has deformed, is derived. In this paper the above method is described in detail. The detection and estimation of the deformations of two brick chimneys, situated at the old gas factory of Athens, nowadays known as Technopolis, is presented. The chimneys were scanned from the points of a horizontal network, oriented to the Hellenic Geodetic System (G.G.R.S). From the tomography of the two chimneys, with respect to the plumb line, significant horizontal displacements ranging up to 22cm were estimated. Moreover, since the points clouds of the chimneys are referenced to the same reference system, relations between the chimneys' deformations are derived and the possible cause of these deformations is investigated.

I. INTRODUCTION

Constructions may deform during their life cycle due to causes of human or natural origin. During the last decade 3D terrestrial laser scanning technology is more and more used for the detection of constructions' deformations (Roberts and Hirst., 2005; Tsakiri *et al.,* 2006; Staiger, 2003). The dense point cloud, provided from the scanning, gives the holography of the construction, and, from this 3D model, all necessary information, concerning the construction's deformation, is extracted (Kersten *et al.*, 2009; Monserrat and Crosetto, 2008).

In this contribution, the axial tomography of constructions, as a tool to detect the deformations they have undergone, is presented in detail. The primary material of the tomography is the point cloud acquired from a TLS positioned on the points of a geodetic network. The detection of the deformations that two brick high chimneys of Technopolis, the old gas factory of Athens, have undergone during the last decades, is discussed. Moreover, the investigation of the possible causes of these deformations is presented.

II. ESTIMATION OF CONSTRUCTIONS' DEFORMATIONS THROUGH THEIR AXIAL TOMOGRAPHY

Terrestrial three-dimensional scanning is an immediate and fast process that offers the capability to capture the whole three-dimensional shape of constructions through the recording of a very big number of points with high density and accuracy, without having physical contact with the object (Schultz and Ingensand, 2004). Axial tomography uses the result of the scanning process in order to produce cross-sectional (tomographic) images (virtual "slices"), of the scanned object. It is, therefore, a useful tool for the estimation of constructions' deformations. The successive steps of the method are presented here in detail.

• A geodetic control network is established in the vicinity of the examined construction. Special care must be taken in the selection of the network points' position: since they are going to be used as stations for the scanning procedure, their position must ensure an overlap of at least 30% of the construction's view. After the measurement of the

network's elements, the network points' coordinates, together with their standard deviations, are estimated from the adjustment of the measured elements. It is proposed to orient the control network to the national geodetic reference system, if it is desirable to investigate the possible causes of the detected deformations, otherwise, the network points' coordinates are estimated in a local reference system.

• The construction's scanning is, following, performed from the network points. HDS spheres, positioned at the networks' points are used as targets. Thus, registration and georeferencing of each point cloud is direct and optimum accuracy is achieved. The sample density depends on the material used for the construction as well as on the magnitude of the expected deformations.

• After the complete scanning of the construction its three-dimensional model is created, using either the point-clouds or surfaces created from simulation of these points.

• Axial tomography is, following, used in order to produce the tomographic images from the 3D model of the construction. The sections are perpendicular to a specified axis (plumb line, horizontal line, line with a given inclination) at a selected position. The distance between the sections depends on the expected deformations, the kind and shape of the object and the material used for its construction (concrete, marble, bricks, wood etc.). The thickness of each "slice" depends on the way the 3D model is created; it is proposed to be between some mm up to 1cm.

• For each cross section the best fitting geometric shape is estimated (e.g. square, rectangle, circle, ellipse, polygon, etc.) using least squares techniques. Using the resulting shapes, it is possible to estimate the change of their position and geometry between successive cross sections and check the statistically significance of these changes. These changes give the information about the deformation of the construction (displacements, torsion and overall inclination).

III. ESTIMATION OF DEFORMATIONS OF TWO HIGH CONSTRUCTIONS (CHIMNEYS A AND C, TECHNOPOLIS, ATHENS)

The deformations of two high constructions in the area of Athens were estimated through their axial tomography (Antoniou, 2017; Diakoumi, 2018). These constructions are chimneys A and C (Figure 1), situated in Technopolis, the old gas factory of Athens. The factory was operating until 1984 when its operation was considered harmful for the environment. Since then, the factory's gates were closed and in 1986 it was declared as a monument of Greek industrial revolution.

Their geometric and constructional characteristics are as follows:

Chimney A was constructed in 1857 and its total height is 28m. Its base has an area of 8.3m^2.

Chimney C was constructed after chimney A. Its total height is 35m. Its base has an area of 9m^2.

Both chimneys have the shape of a truncated pyramid, they are constructed from bricks and, despite their age, they are still in good condition.

Figure 1. Chimneys A (left) and C (right) in Technopolis, Athens.

A. Establishment of the Horizontal Control Network – Scanning of the chimneys

In order to perform the scanning of the two chimneys and process the merging and georeferencing of the point clouds with the desired accuracy, a horizontal control network was established in the surroundings of the chimneys (Figure 2).
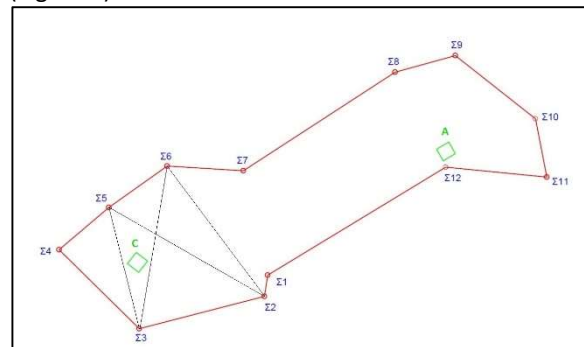

Figure 2. The horizontal control network

The network was oriented to the Greek Geodetic Reference System (GGRS87) in order to investigate the causes of the detected deformations.

A terrestrial pulse scanner, Leica Scanstation2, was used for the scanning of the chimneys. This Scanner has a rate up to 50,000 points/sec and its horizontal vertical fields of view are 360º and 270º respectively. According to the manufacturer, the accuracy in length measurement is ±4mm, the angular accuracy is ±38^{cc}, while the accuracy in a single point positioning is ±6mm.

The scanning of the chimneys (Figures 3 and 4) was performed from all the network's points. An HDS target was used for the registration and georeferencing of the clouds to the network's reference system (GGRS87). Sample spacing was 2mm. Scanning was carried out in parts and overlapping between the segments was about 30%.
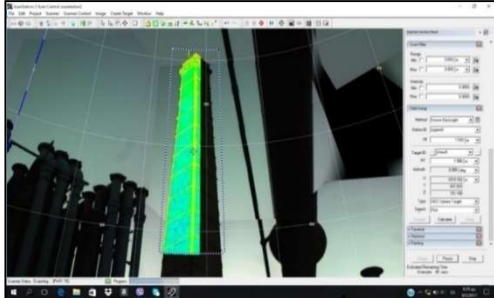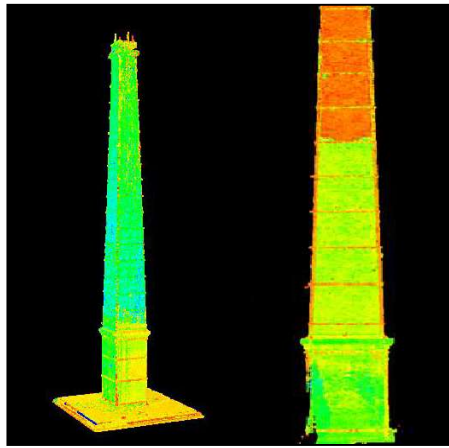

Figure 3. Scanning process

Figure 4. Point clouds of the two chimneys

B. Estimation of the chimneys' deformations

In order to estimate the deformations of the two chimneys, cross sections of their 3-D models, perpendicular to the plumb line, were created: 16 horizontal sections for chimney A and 21 for chimney C. The vertical distance between the cross-sections was set at about 1.5m and the thickness of each "slice" was 1cm. A typical cross-section is depicted in Figure 5.

As it can be seen in figure 5, due to the chimneys' shape, the horizontal cross-sections resemble to a quadrilateral whose area gradually decreases with height.
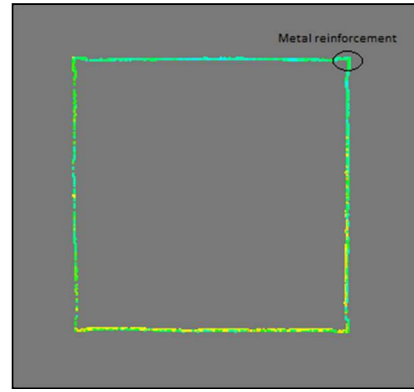

Figure 5. Point cloud of a typical cross section

For each one of the 4 sides of the quadrilateral a best fitting line was estimated using least squares techniques: 4 best fitting lines for every cross section. The result of this estimation is depicted in Figure 6. Following, using simple Euclidean geometry relations, the coordinates of its four edges were determined. Finally, the coordinates of the center (the intersection point of the corresponding diagonals) of each horizontal cross-section were estimated (Figure 7).
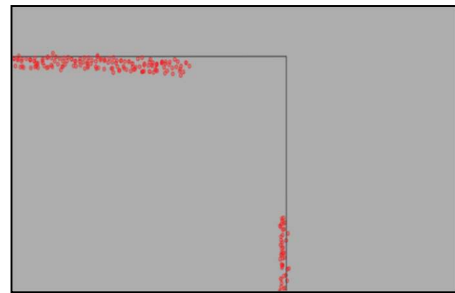

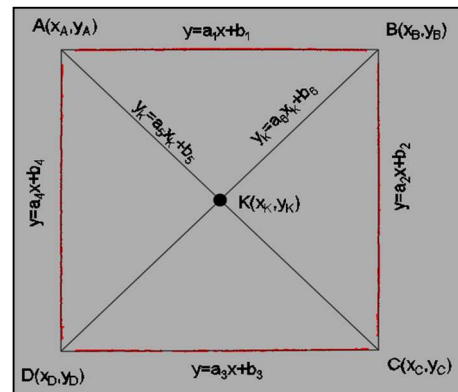Figure 6. Best fitting line of 2 sides of a quadrilateral from point cloud

Figure 7. Equations of best fitting lines of the sides of the quadrilateral

The *horizontal displacements* of each chimney were estimated from the displacement vectors (measure and angle of direction) of the centers of every two successive sections i, i+1 using equations (1) and (2).

$$D_{i,i+1} = \sqrt{\Delta X_{i,i+1}^2 + \Delta Y_{i,i+1}^2} \qquad (1)$$

$$a_{i,i+1} = \arctan\frac{\Delta X_{i,i+1}}{\Delta Y_{i,i+1}} \qquad (2)$$

where $\Delta X_{i,i+1} = X_{i+1} - X_i$,
$\Delta Y_{i,i+1} = Y_{i+1} - Y_i$
$D_{i,i+1}$ = the measure of the displacement vector,
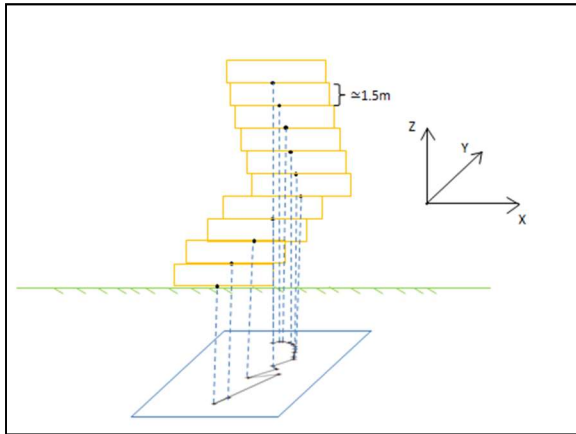$a_{i,i+1}$ = the corresponding angle of direction.

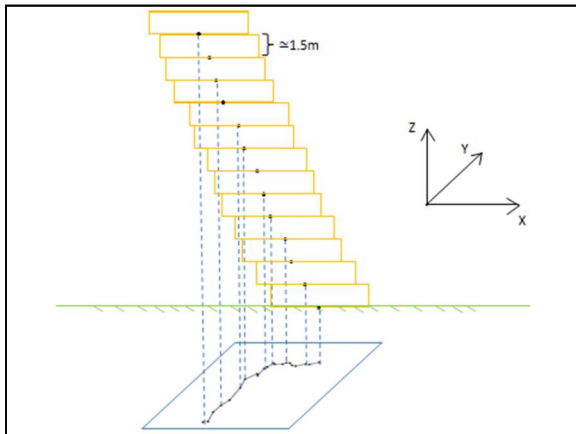Figure 8. Projection of chimney's A cross-sections' centers – Vectors of displacements

Figure 9. Projection of chimney's C cross-sections' centers - Vectors of displacements

Displacements ranging from 5mm up to 142mm were detected for chimney A (Figure 8), while for chimney C (Figure 9), displacements range from 3mm up to 18mm (Tables 1 and 2). All the displacements are statistically significant for confidence level 95%. The overall horizontal displacement, i.e. the displacement between the base and the top (cross sections 1 and n) for each chimney was also estimated. The displacement vector has a measure of 218mm and a direction of 18^g for chimney A, while for chimney C the overall horizontal displacement has a measure of 128mm and a direction of 222^g.

Table 1. Horizontal displacements of Chimney A

Sections	Horizontal displacements (mm)	Angle of direction (grad)	Distance from ground surface (m)
1 - 2	31	244	0.9
2 - 3	142	42	2.0
3 - 4	43	280	7.1
4 - 5	50	54	8.7
5 - 6	13	375	10.2
6 - 7	39	52	11.6
7 - 8	13	0	13.1
8 - 9	13	5	14.7
9 - 10	12	5	16.1
10 - 11	9	0	17.7
11 - 12	10	380	19.2
12 - 13	8	356	20.6
13 - 14	9	327	22.2
14 - 15	5	300	23.6
15 - 16	10	268	25.0
Base-Top: 16 - 1	**218**	**18**	**26.4**

Table 2. Horizontal displacements of Chimney C

Sections	Horizontal displacements (mm)	Angle of direction (grad)	Distance from ground surface (m)
1 - 2	9	281	0.7
2 - 3	3	308	3.6
3 - 4	9	282	6.4
4 - 5	3	316	7.7
5 - 6	4	362	9.3
6 - 7	3	307	10.8
7 - 8	4	271	12.3
8 - 9	7	299	13.8
9 - 10	2	346	15.2
10 - 11	7	253	16.8
11 - 12	3	260	18.2
12 - 13	11	236	19.8
13 - 14	3	395	21.3
14 - 15	13	263	22.8
15 - 16	12	223	24.4
16 - 17	18	234	25.9
17 - 18	10	253	27.4
18 - 19	11	242	29.2
19 - 20	13	223	30.5
20 - 21	4	292	32.0
Base-Top: 21 - 1	**128**	**59**	**32.6**

The *inclination* of each chimney with respect to the plumb line was estimated according to the following equation (3).

$$i = \frac{D_{1,n}}{\Delta H_{1,n}} \qquad (3)$$

where $D_{1,n}$ = the overall horizontal displacement from base to top, and
$\Delta H_{1,n}$ = the corresponding height difference.

The total inclination of chimney A was estimated 9‰, while the total inclination of chimney C is 4‰. According to the Greek regulations of reinforced concrete structures (E.K.O.S.-2000) the maximum permitted inclination is 4‰. In this case, where both chimneys are built with bricks, this limit should be much smaller, thus the inclination of both chimneys can be considered out of the permitted limits.

The *change of the shape* of each chimney was examined from the change of the inner angles of the successive sections. The inner angles of each quadrilateral were determined as the difference between the angles of direction of their sides. Considering the length of the sides, the angular differences correspond to a length of approximately 3cm and are within the tolerance of the constructional accuracy of the chimneys.

Each chimney's *torsion* was determined from the rotation angle $\delta a^{i,i+1}$ between two successive cross sections. The rotation angle was estimated from equation (4) as the difference between the angles of direction of the corresponding homologous side of every two consecutive cross-sections i, i+1.

$$\delta a_{AB}^{i,i+1} = a_{AB}^{i+1} - a_{AB}^{i} \qquad (4)$$

where, $\delta a^{i,i+1}$ = the torsion of side AB of the chimney for the cross-sections i and i+1.
a_{AB}^{i}, a_{AB}^{i+1} = the angles of direction of side AB for the cross-sections i and i+1 respectively.

Most of these angles are not greater than some dozens of c, the maximum one being 1.5^g and are assumed to be within the constructional accuracy of the chimneys.

C. Possible causes of the estimated deformations

One of the main advantages of georeferencing the point clouds is the possibility to:
i. Compare the detected deformations of adjacent constructions, and
ii. Investigate the causes of these deformations. As it can be seen in Figure 10, the horizontal displacement vectors of the chimneys are nearly parallel to each other but with opposite directions, while the measure of chimney's C displacement is nearly half the measure of chimney's A displacement. The chimneys' horizontal movements are due either to manmade causes (excavation of the subway tunnel in the chimneys' vicinity) or to tectonic activity, more specifically the major earthquakes that struck Athens on February 1981 and September 1999.
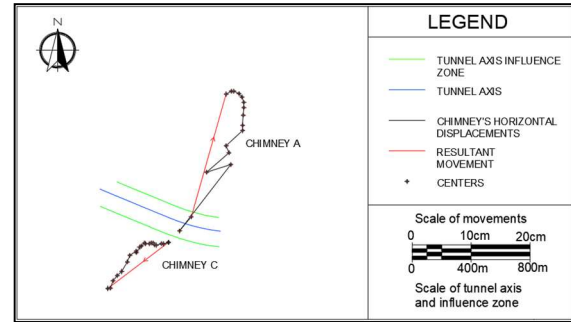

Figure 10. Displacements of chimney A and C with respect to the influence zone of the subway tunnel.

In Figure 10, the position of the two chimneys, as well as the horizontal displacement vectors, with respect to the influence zone of the subway tunnel, are presented. As it can be seen, chimney A lays within the influence zone of the tunnel, while chimney C is situated outsides it. Therefore, it is concluded that, at least, chimney's C horizontal displacements are not due to the tunnel's excavations.

Chimney's A horizontal displacement vector is perpendicular to the tunnel's axis but is diverging from it. However, when examining the horizontal displacements in detail, the following conclusions are withdrawn:
• The first part of the chimney, from the base up to 2m height has a direction towards the tunnel axis,
• From 2m height up to 11 m, the direction of the displacement vector is diverging from the tunnel axis,
• From 11m height to the top of the chimney the displacement vector changes progressively direction turning towards the tunnel axis.

From the above, in detail, description of chimney's A horizontal displacements, it can be concluded that the base of chimney A moved towards the tunnel axis. The change of direction of the displacement vector from 2m up to the middle of the chimney, as well as the twist of the upper part to the top, resembles to the response of the structure to a dynamic cause such as an earthquake.

Chimney's C horizontal displacement vector is also perpendicular to the tunnel's axis. However, since the chimney is located outside of the tunnel's influence zone, it is assumed that the excavation of the subway tunnel had minimum, if none, effect on the chimney's deformation.

In September 7th, 1999 an earthquake with a magnitude 5.9 of the Richter scale struck Attica basin, having as result 145 deaths and many buildings' collapse. 18 years earlier, in February 1981, another earthquake with a magnitude 6.7R had also struck Athens.

It is most probable that the reason for the chimneys' horizontal displacements is their response to these earthquake shocks. In Figure 11 the epicenters of February 1981 and September 1999 earthquakes

and, respectively, the direction of the major macro seismic intensities is depicted (Papanikolaou *et al.*, 2002). The main tectonic faults in Attica basin are presented in the same figure. As it can be seen, the direction of the total horizontal displacement of both chimneys coincides with the direction of the September 7th earthquake major intensity as well as with the direction of the Kifisos fault, located in the vicinity of the chimneys (Figure 11). Especially for chimney C, the direction of the horizontal displacement vectors, from its base to the middle (at a height of about 16m), appear to coincide with the direction of the major macro seismic intensity of the February 1981 earthquake, while the upper part of the chimney displays horizontal displacements that have a direction coinciding with the macro seismic intensity of September 1999 earthquake (Figure 11). It can, therefore, be assumed that the chimneys' horizontal movements are their response to the above earthquakes that struck the Attica basin the last 50 years.
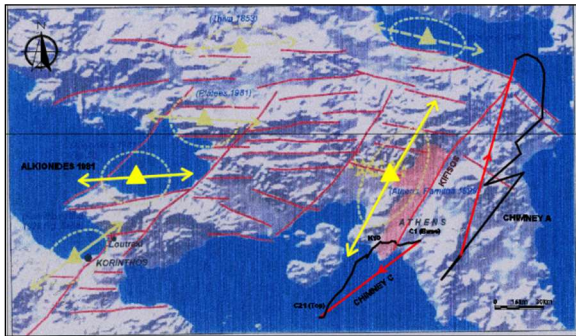

Figure 11. Relation between the chimneys' horizontal displacements and the 1981 and 1999 earthquakes.

IV. CONCLUSIONS

The method of axial tomography is a useful tool, that can be used in various occasions concerning the estimation of constructions deformations. More specifically, it can be used for the:
• Estimation of the structural health of constructions, through the monitoring of their bearing frame deformations that are due to their ageing. Using this information, it is possible to select the proper way to reinforce the construction.
• Deformation monitoring of structures' bearing frame after various causes of natural (e.g. earthquake shocks) or manmade origin (e.g. deep or underground excavations, underwater draw down) in order to examine whether it should be reinforced for people safety and to prevent irreversible damage.
• Investigation of the constructions response in a wide area affected from severe natural phenomena.

• The geometric check of the structures bearing frame as imposed by the Greek Regulation of Reinforced Concrete (E.K.O.S.-2000) (article 5, paragraph 5.2).
• Estimation of the deformations of cultural heritage monuments (ancient temples, theaters, bell towers etc.) for their restoration.

The axial tomography of the two chimneys has shown that underground works may not be the dominant reason of the constructions' deformations. The earthquakes that have struck the area of the Attica basin during the last decades can lead to deformations that exceed the limits as it happens with the horizontal displacements of the chimneys.

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