Measurements in Alhadba Minaret Using Robotic Total Station

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ABSTRACT

The old heritage of Alhadba Minaret in Mosul is famous for its considerable height and leaning. After approximately 800 years since its construction still withstanding degradation. It has to be clearly documented for restoration and maintenance works. Defining geometry and measurements using traditional surveying methods is not feasible due to its height and delicate surface. This paper introduces the results of measurements using robotic reflectorless total station of TOPCON (IS-Imaging Station) conducted in and around the minaret. We present new facts regarding the descriptions of shape and curvature of the minaret body as well as specific notes on using this instrument. These measurements compose a complementary part of data collection effort required for a major preservation project that is proposed to be conducted in the future.

Keywords: Al-Hadba, Geometry, heritage preservation.

قياسات في منارة الحدباء باستخدام جهازالمحطة المتكاملة الآلي

الخلاصة

منارة الحدباء ذلك المعلم التاريخي القديم في مدينة الموصل تتميز بارتفاعها وانحنائها الواضح و لاتزال تقاوم عوامل التلف والأنهيار حتى بعد نحو ٨٠٠ سنة من انشائها. ولأجل توثيقها لأغراض الحفظ والصيانة فان استخدام وسائل القياس التقليدية لايعتبر مجديا بسبب هشاشة سطحها و ارتفاعها الملحوظ. وفي هذا البحث نقدم نتائج اعمال القياس التي جرت باستخدام جهاز المحطة المتكاملة الآلي من نوع (IS-Imaging Station) TOPCON داخل المنارة وفي محيطها. وفيه تم تدوين الأوصاف المميزة التي حصلنا عليها من حيث الشكل الأبعاد والأنحناء وكذلك الملاحظات التي تخص استخدام هذا الجهاز. وتشكل هذه القياسات جزأ متمما لأعمال جمع البيانات التي تجري حاليا للتحضير لبرنامج صيانة شامل يجري التخطيط له في المستقبل.

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INTRODUCTION

Al-hadba is one of the oldest Islamic monuments in the middle east dated back to 1172 AD. It is located in the central part of the old city of Mosul on the right side of river Tigris. The minaret is clearly discernible from most of city locations (Figure 1). After eight centuries of construction, the minaret, as a cultural heritage is inherently vulnerable. Precise measurements and recording has always been a challenge. Researchers are urged to study this monument for many interesting reasons some are listed below.

1- Particular leaning of the minaret.
2- Noticeable height and age as compared to the nearby old city housings as seen in figure 1.
3- Resistance to centuries of deterioration due to weather, quakes, and human disturbance around the minaret.
4- Documentation of cultural heritage.
5- Preparation for restoration, maintenance, protection and safety.

The minaret has undergone maintenance operations at various stages of its life and probably the most obvious was that conducted by Fondedile S.p.A. company in the 1980s [1] which was performed to strengthen the body of the minaret as well as the foundation and the surrounding soil.
During the past decades, there were studies and tests to examine its construction materials, the carrying soil, foundations and record measurements in and around the minaret [2,3,4]. Of particular interest here is the unique geometry that have to be described accurately. Many attempts to record geometry of the minaret have been performed using classical measurement methods such as tapes, plumbs. etc. [4]. Unfortunately, many of these measurements were limited in performance, not well documented and their reference frames of monitoring was incomplete or have been lost. The exact 3D shape of the minaret was not well documented. Shape approximation was used for visualization and stress analysis modeling.
Presently, a committee of engineers from the governorate and municipality of Mosul is preparing to conduct a major conservation program to preserve and support the old minaret and develop the area in the near vicinity. A major requirement is to record the exact shape and dimensions of the minaret for the sake of documentations and stability monitoring. In this paper we introduce the use of Topcon robotic total station with reflectorless and scanning capability to measure the hard to reach and vulnerable locations inside and around the minaret. The output of this paper describes the techniques used for measurements and presents samples of results. The complete set of measurements are produced to the organizing committee of engineers for further analysis.

Materials and methods.

Due to the vulnerable surface of the old minaret and its location within old city terraces having narrow access, it was not feasible to make disturbances around the

minaret to perform extensive measurements. In this study, we are using mainly indirect method of measurements using Imaging Station of Topcon model IS-203, a motorized total station which is suitable for difficult points on the higher portions of the minaret [5,6]. Particular interest of this instrument is the reflectorless and automatic scanning with imaging capabilities. This instrument can be manually operated to measure single points as usual. Apart from the usual use of prisms, the IS-203 has two modes in reflectorless measurements; normal non-prism mode (NP) and long mode (LNP). The NP mode works upto 250 meters range while the LNP can measure upto 2000 m. Accuracy in distance measurement can reach ±5 mm mse. in 3 seconds per point. Automatic scanning function is used at a given pitch of angle or spacing in horizontal and vertical direction. Angle measurements have resolution of 1 sec. at accuracy of 3 sec.
The use of scanning function produces thousands of points with x,y,z coordinate values at average speed of 20 points/sec depending on the angle and type of the reflecting surface. The collection of scanned points is called point cloud. It is possible to use these points to construct the geometry of the target surface using 3D software. Most necessary measurements can be obtained from measurements made within this point cloud. The instrument is driven by the onboard TopSURV software offering a wide variety of commands for quick surveying [5]. The IS-203 uses Class 1 and 2 Lasers for distance measurement. See figure 2.
Necessary corrections of measured distances are calculated internally by the instrument after feeding in the air temperature and pressure [7]. All measurements were based on arbitrary local coordinate system from a set of distributed control points.
Steel tapes were used for referencing measurements in easily accessible locations. Care was taken to calibrate measurements of tapes through the use of standard tension force and temperature measurement.
The basic output of instrument is a set of point coordinates in 3D space (X,Y,Z). The required measurements are obtained by the operator using trigonometric calculations. In 3D space, all points along a vertical line have the same X,Y coordinates while the elevation Z is changing. For the small distances around the minaret geodetic correction is not required. The horizontal distance between any two points A and B is calculated from:

$$D = \sqrt{(\Delta X^2 + \Delta Y^2)} \qquad \ldots (1)$$

The slope distance of line AB in 3D space is:

$$SD = (\Delta X^2 + \Delta Y^2 + \Delta Z^2) \qquad \ldots (2)$$

Where:
$\Delta X, \Delta Y$: changes in horizontal coordinates m.
ΔZ: Change in elevation m.
D: Horizontal distance m.
SD: Slope distance m.
The angle between the vertical line and an intersecting sloped line AB in space represents angle of inclination (example on Figure 5):

$$\theta = \sin^{-1} (D/SD)$$
$$\text{or} \quad \theta = \tan^{-1} (D/ \Delta Z) \qquad \ldots (3)$$

For a solid horizontal circular section, the inaccessible center and the radius can be calculated if the coordinates of at least three points on the perimeter are known. The following set of equations will produce the radius of the circle and the coordinates of the center.
If (Xn, Yn), represent coordinates of (n >=3 non collinear points) on the perimeter. And (X,Y) represent the coordinate of the center point of the circle having radius of R, then for each point n on circumference we have.

$$(Xn-X)^2 + (Yn-Y)^2 = R^2. \qquad ... (4)$$

These calculations are performed on horizontal section, (Z = constant).
The three simultaneous equations will solve for the three unknown quantities (X,Y, and R)

Production of 3D model

The scanning function of the imaging total station provides the geometric shape in the form of point cloud. Control points were used for setting up the total station for the scanning process. The locations of control points ensure complete coverage around the minaret. All resulted coordinates were unified to a local coordinate system to provide real 3D positions in a single drawing. More than 110000 points have been produced with x,y,z space coordinates. Rendering and texturing of these points produced realistic views that can be moved or rotated in any direction using 3D software as shown in figure 3. Editing is required to remove unwanted points that may be caused by errors in scanning. The produced 3D point cloud of the minaret was used in measurements that will be explained in the following text.

Results of measurements

The total height of the minaret above the current ground of the mosque is 50 m. For the sake of convenience we adopt partitioning the minaret into parts. Measurements are investigated separately for each part. These parts are: Prismatic base, trunk, upper portion (Kubba), and inside the minaret. These divisions are shown in figure 4 and discussed in the next paragraphs.

Prismatic base

Total height of the prism is 18.2 m. The prism is slightly tapered towards the upper direction. In the lower 10 m of base height the original ancient brick walls of the prism are hidden under the thick stone covering wall that was built recently. Here it was not possible to measure dimensions of the original brick masonry.
The exposed bricks wall of the upper part of the prism is 8.2 m height which is shown in figure 5. There is obvious inclination of this part towards the east due to probable long term differential settlement. As an example of measurements and calculations, we have the following arbitrary coordinates of two points A, and B obtained from scanned point cloud. These points are located nearly on a vertical line on the western face of the prism.
A (915.75, 953.53, 17.98).
B (915.29, 953.51, 10.01)Using equation (3)
$\theta = \tan^{-1}((915.75-915.29) /(17.98-10.01)) \approx$ approx . 3°

Accordingly, This measurement shows that the western face is inclined at about 3˚ degree to the east from the vertical line. Similarly, the eastern side of the prism is inclined by 1˚ degrees to the east. We can anticipate that the prism has been tilted by about 2˚ degrees towards east as compared to the symmetrical position. The prism contains openings and stairs for entrance into the internal body of the trunk.

Trunk

The trunk part have cylindrical wall of average thickness of 1 m. The net vertical height of the leaning cylindrical trunk is 25.6 m. The trunk is composed of 7 distinct rings each has been engraved differently. Some portions have smoother engraves. This difference in surface harshness obviously affects the scanning process. Laser scanning of engraved surfaces produces harshness in cloud points as seen in Figure 6. The outer radius of the cylindrical trunk is tapering from 5.23 m at base (roof of the prism). The radius at the top of the trunk (height of 43.8 m) is only 3.37 m.

Moving upwards along the trunk, the central axis leans eastwards. Figure 7 shows circular sections near the upper and lower ends of the trunk. The total shift near the top of the trunk compared to point near the base is about 2.514 m. The amount of leaning is not linear as it is small near the base. At the 43.8 m. height the max leaning angle of the centerline of the trunk is about 9 degrees out of vertical towards east.

An interesting outcome of this work is the figuring of unusual bulge found in the circular section of the trunk at the end of 6^{th} ring (elevation 41 m). Which is not easily detectable by the naked eye and traditional surveying methods. At this elevation, the shape of the cross section is shown in figure 8.

We observed a northward component of leaning of trunk centerline of approximately 1˚ .

The wall of the trunk have small openings (windows), at varying locations and shapes. Openings help wind circulation and provide partial view of the city and provide sky light for inside. See figure 9.

The highest portion of the trunk carries a circular disc forming a passage around the Kubba. The disc diameter of 4.9 m. The disk is inclined downwards to the east. Eastern portion is 0.30 m lower than the opposite side which produces an approximate slope angle of 3.5˚ with horizontal plane.

Inside

Within the trunk, there are two helical stairs moving together around the core (shown in figure 10.). Inspectors can ride the stairs to climb the minaret. The stairs provide structural link between the minaret wall and the inside core.

The width of the stair passage inside the minaret is in the range of 0.85 m to 0.95 m. Stairs have high angle of rise at average of 46˚ up near the outer edges of the passage. Average rise is 0.18 m. Stair treads have triangular shape tapering from 0.0 m at the core side to 0.24 m near the outer wall. The core of the minaret is approximately circular in section with decreasing radius upwards.

Radius of the core is calculated from point cloud shown in figure 10. Using equation 4, three points located horizontally along the circumference of the core are used to calculate the radius of the core. At the helical stair location shown in figure 10, the radius of the core is 0.82 m. while that of the inside face of the trunk wall is 1.75 m. see the measurement in figure 11

Kubba:. The upper portion of the minaret (Kubba) rests on wooden beams and circular passage described earlier. Kubba was newly built after the collapse of the original and suffers from serious cracks in the brick and stone binding material.

CONCLUSIONS

New information about exact shape and dimensions of Alhadba minaret are presented from the results of this work. Reflectorless, scanning imaging capabilities are much helpful in these measurements. It was difficult to obtain the same results using traditional surveying techniques. The use of scanning data in the form of thousands of points requires editing in some locations due to improper angle of incident rays or type of target surface.

1- We described the amount of leaning of the base prism, approximately 2˚ eastwards out of symmetry.

2- And the unique bulged irregular circular section of the trunk at the approximate height of 41 m.

3- The leaning of the top of the trunk of approx 9˚ out of the vertical line.

4- We have produced 3D shape of high accuracy to be used for measurements and modeling.

The results will be helpful in recording the geometry of Alhadba minaret and provide valuable data for maintenance works.

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Figure (1) The Minaret within the nearby old city of Mosul.


Figure (2) Topcon Imaging Station at work inside and outside the minaret.

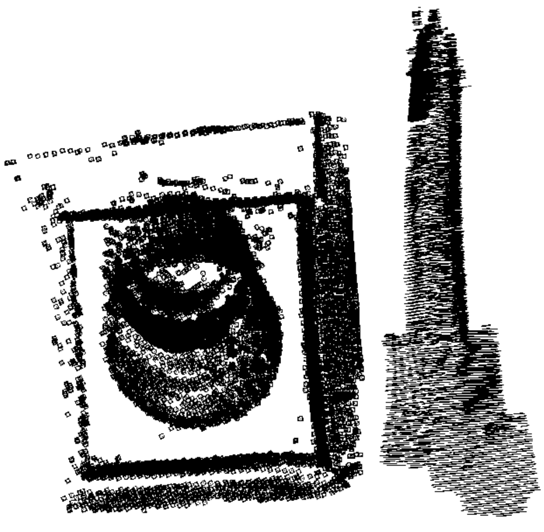

Figure (3) Point cloud viewed from top and side.

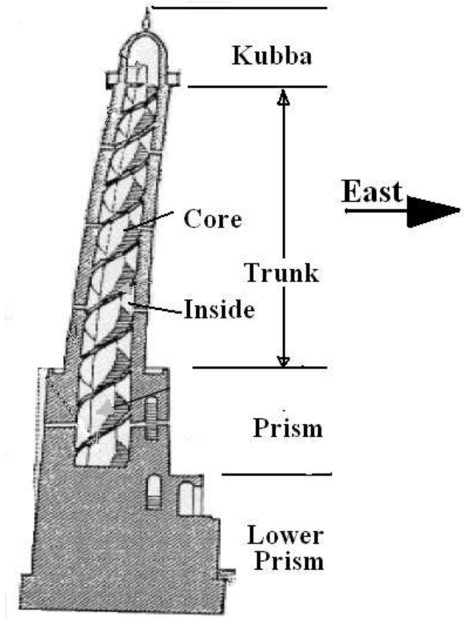

Figure (4) Parts of the minaret discussed in the text.

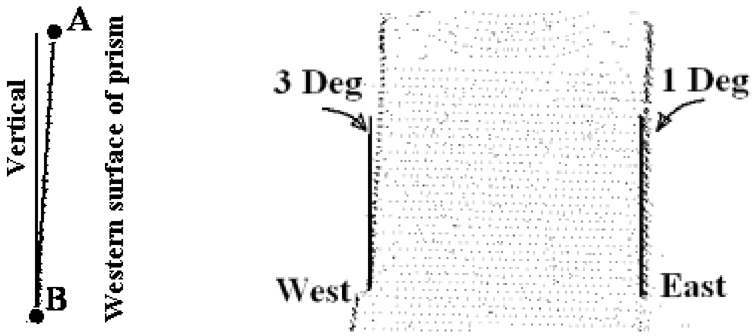

Figure (5) Approximate inclination of opposite faces of the prism. The 3D coordinates of sample points A and B are used to calculate inclination. See text.

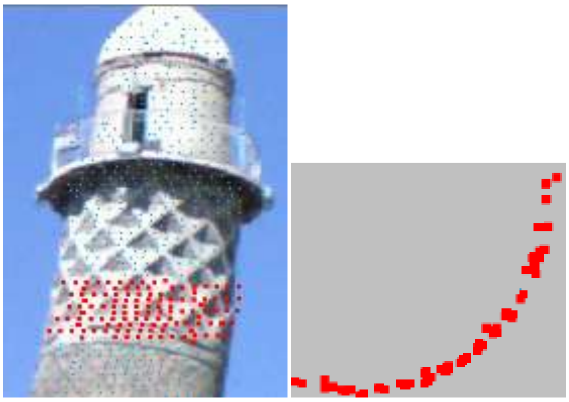

Figure (6) Scanned points superimposed on the harsh engraves around the surface of the trunk.

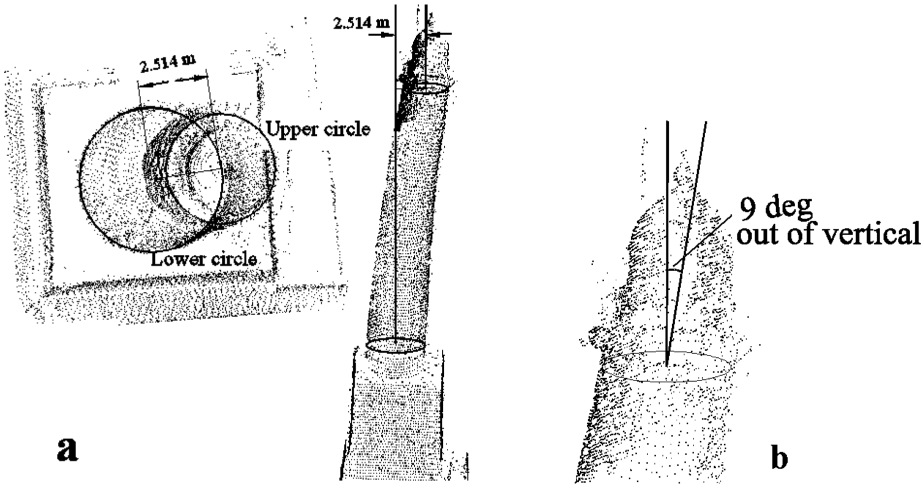

Figure (7. a) The relative eccentricity between two circular sections at ends of the trunk. b) Maximum leaning angle out of vertical at the top.

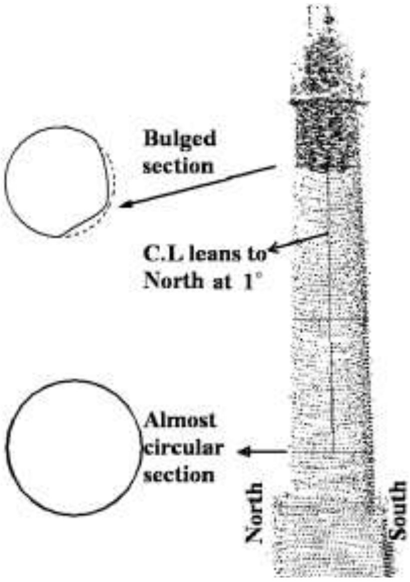

Figure (8) Two sections in the trunk. See particular bulge at height of approx 41 m. A northward component of leaning of centerline is also observed.

Figure (9) Small opening (window) through the thick wall providing ventilation and light.

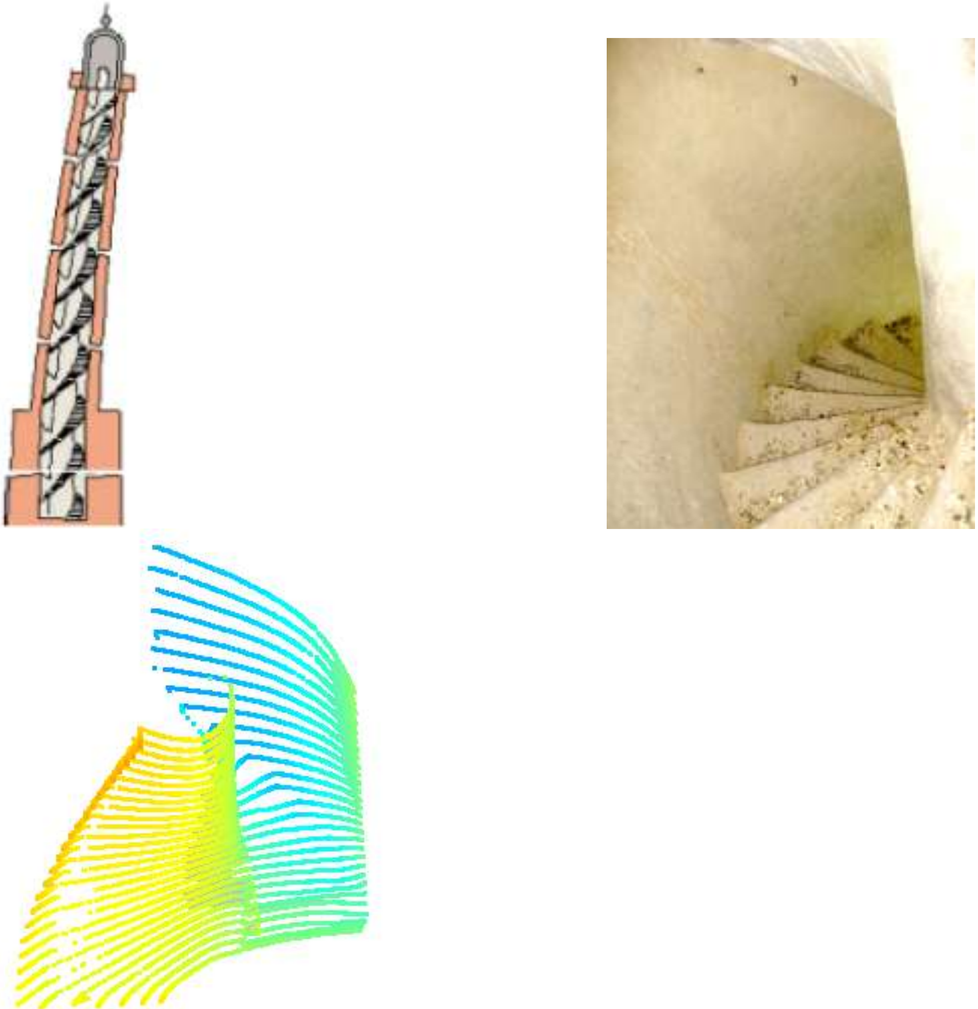

Figure (10) the helical stairs, inside photo, and the scanning point cloud.

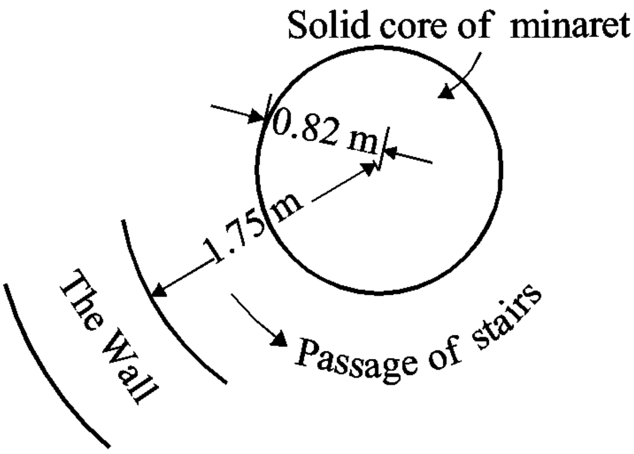

Figure (11) Dimensioning the inner solid core and the stair passage.