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Fine Deformation Monitoring of Ancient Building Based on Terrestrial Laser Scanning Technologies

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Abstract. Laser scanning technology has been widely used to build high-precision three dimensional models in the preservation of ancient buildings. In this paper, we take the Tower of Buddhist Incense in the Summer Palace as our research subject. Combining laser scanning technologies with close-range photogrammetry, GIS and virtual reality technologies, we acquired comprehensive and high accuracy geospatial data of the tower, and built the 3D models with an average measurement error of a single point less than 2 millimeters and a registration error of 3D data less than 5 millimeters. After data registration of the whole tower with high-precision, deformation monitoring was conducted. Having been repaired many times, the cross-sections of the tower's pillars are not in a circular shape. In order to know the dip and dip direction of each pillar exactly, ellipse fitting algorithm was used to calculate the location of the centre of every pillar. And then, the coordinates of the pillars' centre points, the major and minor axes of the ellipses, and rotation angles were calculated. The technologies and methodology used in this paper could significantly contribute towards the long-term protection of endangered cultural relics using measurements and modelling with high-levels of scientific precision.

1. Introduction

As the material evidence of ancient civilizations, heritage buildings record the history of a nation's political, economic and cultural development in a particular period. However, due to poor maintenance, natural disasters, climate change and human activities, there are many ancient buildings that face significant threats of deterioration. Application of advanced technologies and methods to the documentation of the historical background and current conditions of heritage buildings and objects could provide sufficient and accurate data for their monitoring, preservation and restoration.

Laser scanning technology has been widely used to build high-precision three dimensional models in the preservation of ancient buildings as our ability to acquire geospatial data of the surface of such buildings has advanced significantly [1,2]. In addition, Geographical Information System (GIS)

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approaches that enable the integration of 2D and 3D geospatial and auxiliary data are playing an increasingly important role in the documentation and smart management of cultural heritage.

In this paper, we take the Tower of Buddhist Incense in the Summer Palace as our research subject. The Summer Palace is the grandest and best-preserved royal garden in China, which was included in the UNESCO World Heritage List in 1998. As the symbol of the Summer Palace, the Tower of Buddhist Incense, containing profound historical and cultural connotation, represents the highest achievement of traditional Chinese architectural art. The octagonal, three-storied and quadruple-eaves wooden tower is built on a 20-metre-high granite platform with the Longevity Hill in the north and the Kunming Lake in the south. There are eight solid lignumvitae columns standing in the centre of the building surrounded by another 24 shorter columns, all of which serve as pillars supporting the 36.47-metre-high tower. The eight main columns and the 24 shorter ones are known as the “Tongtian Pillars” and “Jin Pillars” respectively.

Combining laser scanning technologies with close-range photogrammetry, GIS and virtual reality technologies, we acquired comprehensive, high accuracy geospatial data of the tower, and built the 3D models with an average measurement error of a single point less than 2 millimetres and a registration error of 3D data less than 5 millimetres. Furthermore, a comprehensive database including 3D models, pictures and other auxiliary data has been established and based on which a 3D Information Management and Monitoring System has been constructed. The whole system contributes to a significantly advanced scientifically precise and long-term protection of the Tower of Buddhist Incense. The technology and methodology used could be applied to endangered cultural relics in China and elsewhere.

2. Layout of Ground Control Network

As the large construction is built in front of the Longevity Hill, we set up three points in the north of the tower as the ground control points (Fig.1.), and obtained their accurate coordinates by Connecting Traverse Surveying. Based on these three ground control points, the control survey was conducted around the tower using Closed Traverse Surveying.

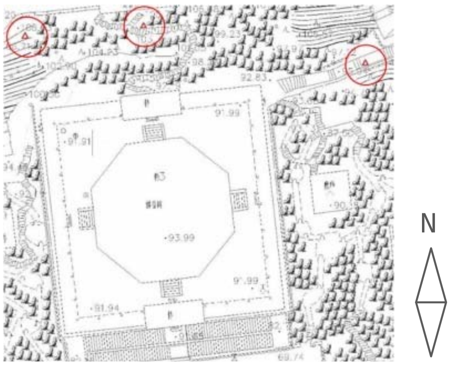


Figure 1. Layout of Ground Control Points

3. Data Acquisition by Laser Scanning

After considering the capabilities of different Laser Scanning devices, we chose Z+F IMAGER 5006i; a 3D laser Scanner made by Zoller + Fröhlich GmbH, to acquire high resolution point clouds at close range (less than 79 meters) by its phase ranging method. It has a horizontal field-of-view (FOV) of 360-degrees and a vertical FOV of 310-degrees. We also used Leica ScanStation C10 to obtain long-range (less than 300 meters) and high-accuracy data by its pulse ranging method. These two instruments complement each other, and through their combined use the integrity and accuracy of the tower’s 3D geospatial data can be assured. In this project, the average measurement error of a single point is less than 2 millimetres.

4. Registration of Terrestrial Scan Data

In the process of data acquisition, we found that due to the presence of overlapping objects when observing the Tower from different points of view and the geometric characteristics of the Tower itself, it was difficult to obtain complete information from one scan station alone. We had to obtain scans from different stations. As the point clouds acquired from each scan station is located within its own coordinate system, we faced the problem of translating all the point clouds from different scan stations to one unified coordinate system to create the Data Registration [3]. We resolved this problem by using the same group of artificial targets which are placed in each of the scenes; we also ensured that in obtaining measurements from each of the overlapping scan stations, there were no more than three common artificial targets, which are non-colinear and non-coplanar, between two neighbouring stations. We calculated the transformation parameters by the Least Squares Estimation method. Redundant observations, if any, were used in iterative solutions until the correction values of unknown qualities fell below established threshold levels. In this way, all terrestrial scan data were registered accurately.

As a three-storied and quadruple-eaves tower, we encountered the following problems in the registration process of the Tower of Buddhist Incense: 1) Data filtering [4]. 2) Data registration for corridors in a single story. 3) Data registration for the interior in a single story. 4) Data registration between the interior and the exterior in a single story. 5) Data registration between ancient wood structural components. 6) Data registration between different stories. 7) Data registration for the exterior of the whole building from different scan stations. 8) Data registration between the outside of the whole building and a single story. In order to improve the precision of registration, 92 scan stations were set up for data acquisition. Moreover, some artificial targets were placed to increase redundant observations, based on which there were still common targets between stations with one-to-two-station intervals. The absolute coordinates of these artificial targets were measured by two total stations, and data registration was completed by non-rigid transformation from the relative coordinate system to the absolute coordinate system of the point clouds. Fig. 2 shows the registration result of the three stories including the corridors and the interior, while Fig. 3 shows the registration result for the whole tower. The registration error of point cloud data is less than 5 millimetres.

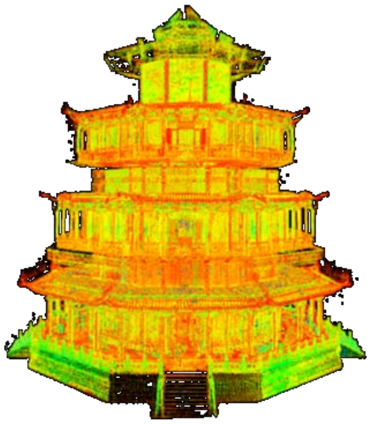


Figure 2. Registration result of the three stories

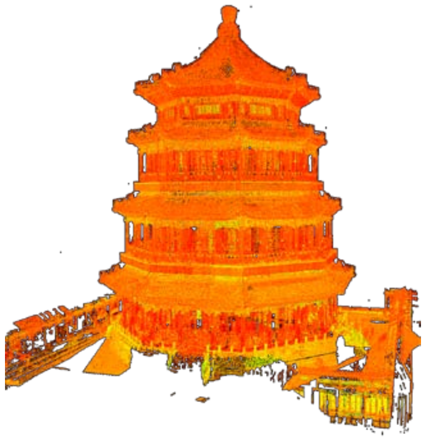
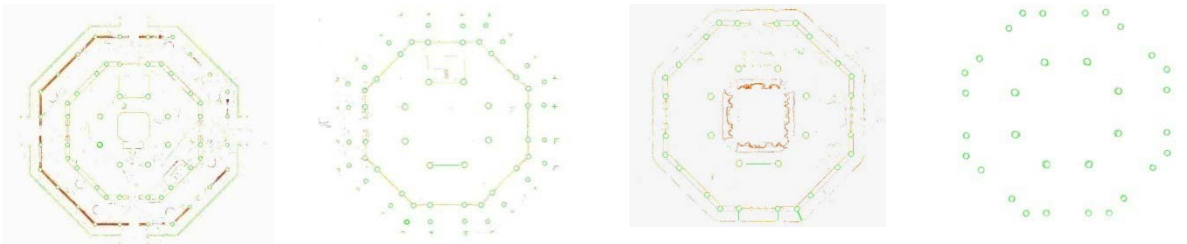


Figure 3. Registration result of the whole tower

5. Obtaining cross-sections of each pillar

In order to estimate the dip and dip direction of every pillar, we obtained the cross-sections from the top and the bottom part of the pillar segment in each story. The thickness of every cross-section is 2 centimetres; eight cross-sections were obtained from one integral pillar including the pillar segment inside the double eaves above the third story.



(a) (b) (c) (d)

Figure 4. cross-sections of the bottom of pillars in each story. Figure (a), (b), (c), (d) are the cross sections of the first, second, third story and the double eaves respectively.

(a) (b)

Figure 5. point clouds of cross-sections of the pillars in the whole tower (marked as green in the above figures). Figure (a) is the oblique view from above where the pillars are seen more clearly; Figure (b) is the view from the front where the cross-sections can be seen more clearly)

6. Deformation Monitoring by Ellipse Fitting

6.1. Ellipse Fitting

After having obtained the cross section of each story, deformation monitoring was conducted. In order to know the dip and dip direction of each pillar exactly, ellipse fitting algorithm was used to calculate the location of the centre of every pillar [5].

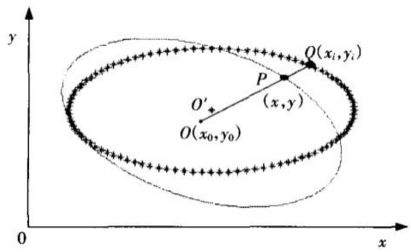


Figure 6. Ellipse Fitting of Boundary Points

As shown in Fig.6, the centre (x_0, y_0), the boundary $Q(x_i, y_i)$ and the fitting points along the ellipse $P(x, y)$ are located in one line. The Euclidean distance between the centre point and the boundary point was calculated as:

$$r_i = ((x_i - x_0)^2 + (y_i - y_0)^2)^{1/2} \tag{1}$$

The Euclidean distance between the centre point and the fitting point was calculated as:

$$r = ((x - x_0)^2 + (y - y_0)^2)^{1/2} \tag{2}$$

And then, the Euclidean distance between the boundary point and the fitting point was calculated as:

$$\Delta r = \left|((x-x_0)^2+(y-y_0)^2)^{1/2} - ((x_i-x_0)^2+(y_i-y_0)^2)^{1/2}\right| \tag{3}$$

The objective function determining the best fit by minimizing the sum of squared distance between the boundary point and the fitting point is:

$$J = \sum_{i=1}^{n}(((x-x_0)^2+(y-y_0)^2)^{1/2} - ((x_i-x_0)^2+(y_i-y_0)^2)^{1/2})^2 \tag{4}$$

When the line OQ (Fig. 6) parallels with Y axis, $x = x_i = x_0$, the objective function becomes:

$$J = \sum_{i=1}^{n}(\sqrt{(y-y_0)^2} - \sqrt{(y_i-y_0)^2})^2 \tag{5}$$

When $x_i \neq x_0$, the following equation applies:

$$y - y_0 = \frac{y_i-y_0}{x_i-x_0}(x-x_0) \tag{6}$$

According to the elliptic equation

$$(\frac{xsin\theta - ycos\theta - x_0 sin\theta + y_0 cos\theta}{a})^2 + (\frac{xcos\theta + ysin\theta - y_0 sin\theta - x_0 cos\theta}{a})^2 = 1 \tag{7}$$

the objective function can be rewritten as:

$$J = \sum_{i=1}^{n}(((x_i-x_0)^2+(y_i-y_0)^2)^{1/2} - (\frac{(x_i-x_0)^2+(y_i-y_0)^2}{(x_i-x_0)^2}(x-x_0)^2)^{1/2})^2 \tag{8}$$

in which $(x-x_0)^2 = \frac{a^2b^2}{a^2(\frac{y_i-y_0}{x_i-x_0}sin\theta+cos\theta)^2+b^2(sin\theta-\frac{y_i-y_0}{x_i-x_0}cos\theta)^2}$ (9)

where a represents the major axis of ellipse, b represents the minor axis, and θ represents the rotation angle.

In optimizing the objective function J, the best fitting ellipse was obtained by nonlinear least squares estimation when J is of minimal value. And then, the coordinates of the pillars' centre points, the major and minor axes of the ellipses, and rotation angles were estimated.

6.2. Calculating Dip and Dip Direction of the Pillars

The centre point coordinates of every cross-section was calculated by ellipse fitting. The dip and dip direction of every pillar was estimated by connecting the centre points of each pillar (see Fig.7, Fig.8, Table 1 and Table 2). Based on the above results, we concluded that the tower has a slight inclination towards the southeast, and the average dip angle of the Tongtian pillars is 0.7 degrees and the average dip angle of the Jin pillars is 0.5 degrees.

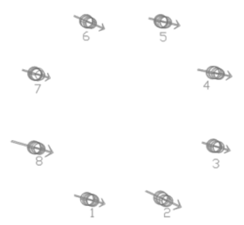


Figure 7. Dip Direction of the Tongtian Pillars

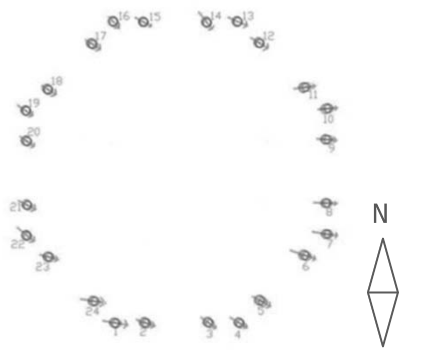


Figure 8. Dip Direction of the Jin Pillars

Table 1. Dip Angle of the Tongtian Pillars Calculated by Ellipse Fitting

Tongtian Pillar No.	1	2	3	4	5	6	7	8
Dip Angle	0.7362	0.8428	0.6810	0.8055	0.6732	0.6487	0.7051	0.6774

Table 2. Dip Angle of the Jin Pillars Calculated by Ellipse Fitting

Jin Pillar No.	1	2	3	4	5	6	7	8
Dip Angle	0.5026	0.5561	0.4974	0.4635	0.7892	0.6914	0.6007	0.5442
Jin Pillar No.	9	10	11	12	13	14	15	16
Dip Angle	0.6720	0.7124	0.7704	0.3580	0.2295	0.2401	0.2589	0.2115
Jin Pillar No.	17	18	19	20	21	22	23	24
Dip Angle	0.4828	0.3967	0. 2643	0. 3486	0.3642	0.3250	0.4736	0.5899

7. Conclusion

In this is paper we have solved some key technical puzzles in fine mapping of complex ancient structures and explored the workflow by combining terrestrial laser scanning, close range photogrammetry and 3D reconstruction technologies. Based on our results a high-precision, 3D model of the three-storied and quadruple-eaves tower has been built and a scientific basis for the accurate monitoring of the tower's status quo in the future has been established. Furthermore, the results demonstrate the feasibility of scientifically accurate and long-term preservation of important cultural heritage objects, and the establishment of a monitoring system for tracking changes in their evolution. The technologies used in obtaining the results reported here could have application to the conservation of objects in other sites included in UNESCO's World Heritage List.

Acknowledgments

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