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STRUCTURAL HEALTH MONITORING OF THE ANCIENT SHEIKHANTAUR MAUSOLEUM IN TASHKENT (UZBEKISTAN) BY LASER SCANNING AND AMBIENT VIBRATION STUDIES

Shakhzod Takhirov[1], Anvar Yuvmitov[2], Elbek Kosimov[2], Dilmurod Akhundjanov[2], Salimjon Toshpulatov[2], Sukhrob Bozorkulov[2], Khasan Sherniyozov[2], Nematulla Nishonov[2], and Ravshan Shamansurov[3]

[1] University of California at Berkeley
337 Davis Hall, Berkeley, California, USA
e-mail: takhirov@berkeley.edu

[2] Institute of Mechanics and Seismic Stability of Structures, Academy of Sciences of the Republic of Uzbekistan
70 Gulomov Street, Tashkent, Uzbekistan
{ anvar.sayfullaevich11@gmail.com, elbekqosimov1985@gmail.com, dilmurod.88@mail.ru, toshpolatovsalimjon@gmail.com, cssukhrob@gmail.com, sh.hasanjon@gmail.com, nishonovnematilla@gmail.com }

[3] Sigma Innovative Tech
28B, Kvartal 19, Unusabad, Tashkent, Uzbekistan
shamansurov@rambler.ru

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Abstract. *Sheikhantaur is an ancient heritage complex, with the centerpiece being the Mausoleum of Sheikh Hovendi at-Tahur (Sheikhantaur). It was built in the 14th century and is one of the most important architectural monuments in Tashkent, Uzbekistan. It is a masonry structure with thick walls, consisting of two halls connected by a small door. Each hall has its own dome. The domes are connected to form the structure's roof. Two structural health monitoring studies were performed on the structure. First, the structure was investigated using a terrestrial laser scanner to obtain a high-accuracy 3D digital twin. Both the interior and exterior surfaces of the structure were laser scanned. Second, an ambient vibration study of the monument was conducted using high-sensitivity accelerometers. The resonant frequencies and vibration modes were obtained from this investigation. In addition, the level of vibration caused by nearby construction was studied. The paper presents the results of these two studies.*

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1 INTRODUCTION

Sheikhantaur (also known as Shaykhantahur) is an ancient heritage complex, with the centerpiece being the Mausoleum of Sheikh Hovendi at-Tahur (Sheikhantaur). It was originally built in the 14th century and is one of the most important architectural monuments in Tashkent, the capital city of Uzbekistan. Over the years, it went through a few restoration efforts. Nowadays, it is a well-preserved heritage monument under the protection of the government of Uzbekistan. It is in downtown Tashkent and surrounded by many modern buildings. A recent photo is shown in Figure 1.



Figure 1: A recent photo of the Sheikhantaur monument.

There are very few publications that provide any information about the monument. There is a short mention of the monument in a detailed publication on medieval Tashkent [1]. More details are presented in [2]. Some of the legends about this place are discussed, including the one about the water of “eternal life” that once flowed from a nearby source. It has attracted many famous people, and, according to one legend [2], Alexander the Great once rested here. Some additional information about the mausoleum and its surroundings is provided in [3]. In addition to other information, it indicates that it is roughly oriented toward Mecca, which is important for this type of monument. Some additional information about the mausoleum is discussed in [4].

From a structural point of view, it is a masonry structure with thick walls, consisting of two halls connected by a small door. Each hall has its own dome. Only the overall dimensions of the mausoleum are mentioned in [2], namely, its length and width are 16.2 m and 9 m, respectively. The height was reported as 12.8 m.

The main goal was to collect sufficient measurement data to develop an accurate numerical model of the heritage structure. Numerical analysis will enable prediction of its structural performance under various loading conditions, including seismic loading. To achieve this, a comprehensive approach consisting of two phases was employed. In the first phase, a precise digital twin of the object’s geometry was obtained. A terrestrial laser scanner was used for that. To meet the size limitations for the paper, only major findings are reported herein, and the rest of the data will be used for the development of the numerical model. In addition, a few subsequent laser-scanning visits are planned, especially after moderate and large seismic events, to assess the development and progression of structural damage by comparing it with

this reference digital twin. This is very important for structural health monitoring of this heritage monument. In the second phase, the object's structural dynamic properties by measuring its resonant frequencies. This was conducted for the case of ambient vibration. These results will be used to calibrate the numerical model's performance under small excitations. In addition, a few ambient vibration studies are planned to monitor the structure's dynamic properties, especially after moderate and large seismic events. Changes in resonant frequencies could indicate structural damage in the monument and, as such, must be monitored over time as a key component of the structural health monitoring process. The resonant frequencies obtained in this paper will serve as reference data. One of the authors' intentions is to promote the installation of a permanent monitoring station to measure shaking levels and frequencies in real time during seismic events.

2 LASER SCANNING

This section provides information on the laser scanning portion of the project. It also discusses some key results obtained from the laser scanning.

2.1 Laser scanning procedure and overall orientation

On March 6, 2026, the current condition of the monument and its 3D geometry were captured using a terrestrial laser scanner, RTC360, from Leica Geosystems [5]. The scanning was conducted from several scanner positions, the so-called stations, and the point clouds from the individual stations were stitched together using the Cyclone REGISTER 360 PLUS software from Leica Geosystems [6]. A photo of scanning work at one of the stations is shown in Figure 2.



Figure 2: A photo taken during laser scanning (scanning from the roof).

The fully stitched point cloud is called the registration. This registration represents an accurate 3D digital twin of the monument. To capture all details of the monument, the point

cloud was collected at high resolution, yielding 178 million points. The obtained point cloud is presented in Figure 3.

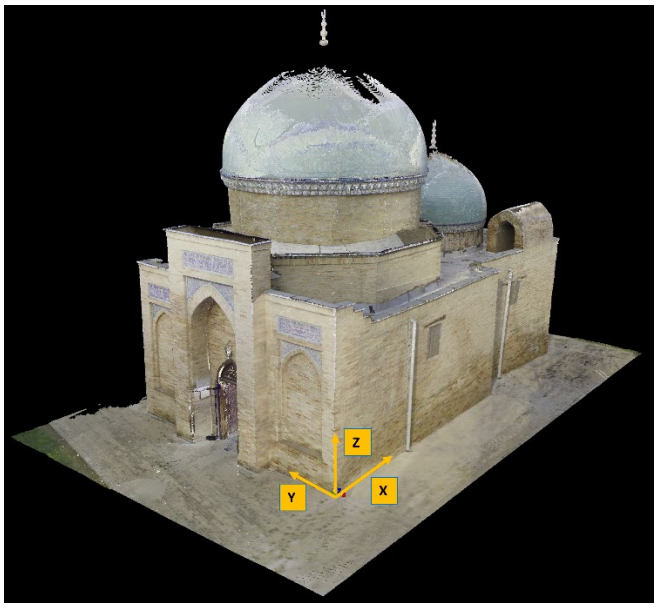
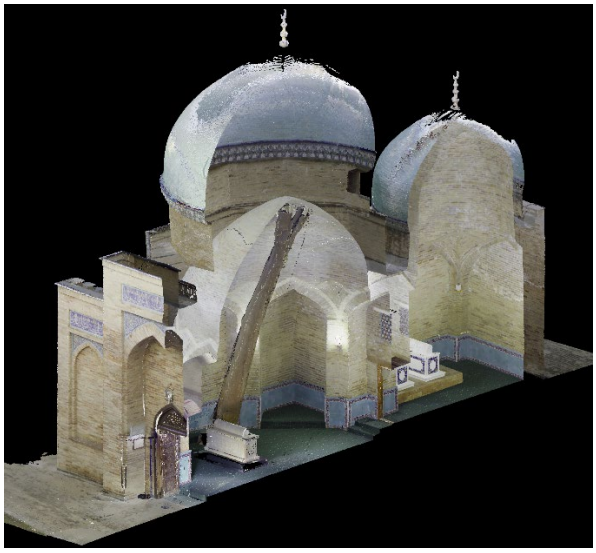


Figure 3: Point cloud of the monument.

The monument was laser-scanned from the exterior at ground and roof levels. In addition, the monument's interior was scanned from several stations. As a result, the 3D twin consisted of all visible surfaces. A few sections of the point cloud are presented in Figures 4 and 5.

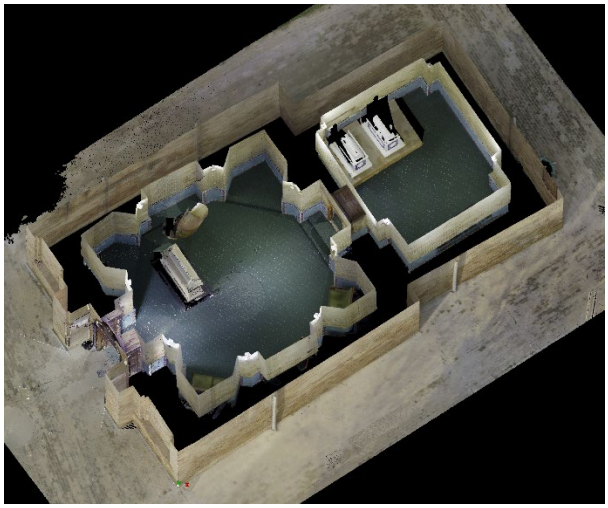


a) Vertical plane section along the longitudinal direction

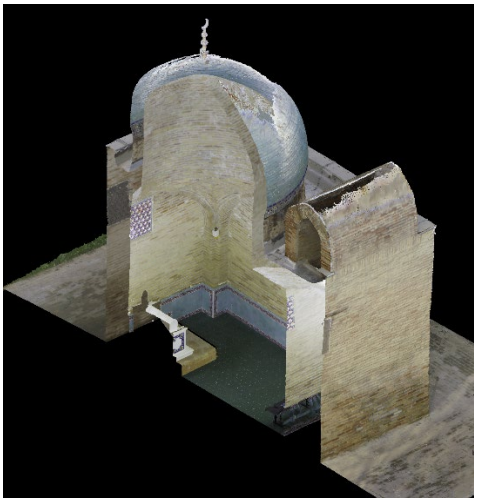


b) Vertical plane section along the transverse direction (1st room's center)

Figure 4: Sections of the monument's point cloud by vertical planes.



a) Horizontal plane section above the entrance door



b) Vertical plane section along the transverse direction (2nd room's center)

Figure 5: Sections of the monument's point cloud by vertical and horizontal planes.

As shown in Figure 3, the following local coordinate system was introduced. The origin of the system was selected at the ground level of the south-west corner. The X-axis was aligned with the south wall along the monument's longitudinal axis.

The overall elevations of various points of the monument in this local coordinate system are presented in Figure 6. It shows a cross-section of the point cloud taken along the line connecting two spires. As shown in the image, the tips of the two spires are 14.94 m and 11.01 m, respectively. The highest points of the big and small domes are 13.77 m and 9.85 m, respectively. The floor slopes toward the entrance on the left side of the image, with an overall elevation change of about 0.60 m. Based on the point cloud measurements, the thickness of the small dome at its tip is approximately 0.50 m. The main dome is most likely constructed from the inner and outer domes, with an empty space between them, which is quite common in ancient dome construction in Uzbekistan. The thickness of the small dome is close to 0.50 m at its tip.

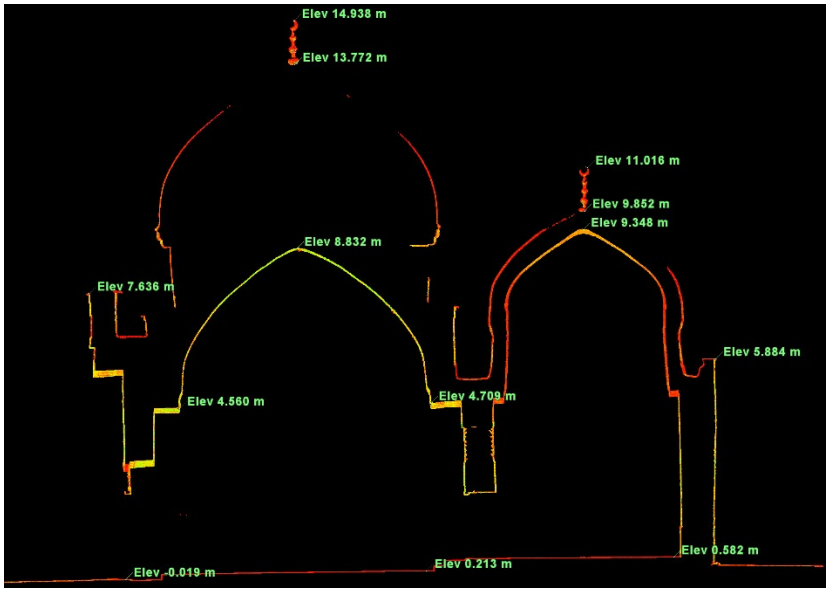


Figure 6: Elevations at various locations.

It is worth noting that the measured overall elevation is much higher than that reported earlier in [2].

2.2 Overall orientation

Although a local coordinate system was employed for point cloud analysis and ambient vibration studies, it was important to measure the monument's overall orientation. It was conducted by aligning a digital compass with the monument's north wall, as presented in Figure 7a. Based on this measurement of 257 degrees from north, the overall orientation of the monument was compared to the orientation toward Mecca from Tashkent's geolocation [7]. The result produced in the latter was 240 degrees from north, which is very close to the measured orientation. The overall orientation is shown in the plan view depicted in Figure 7b.

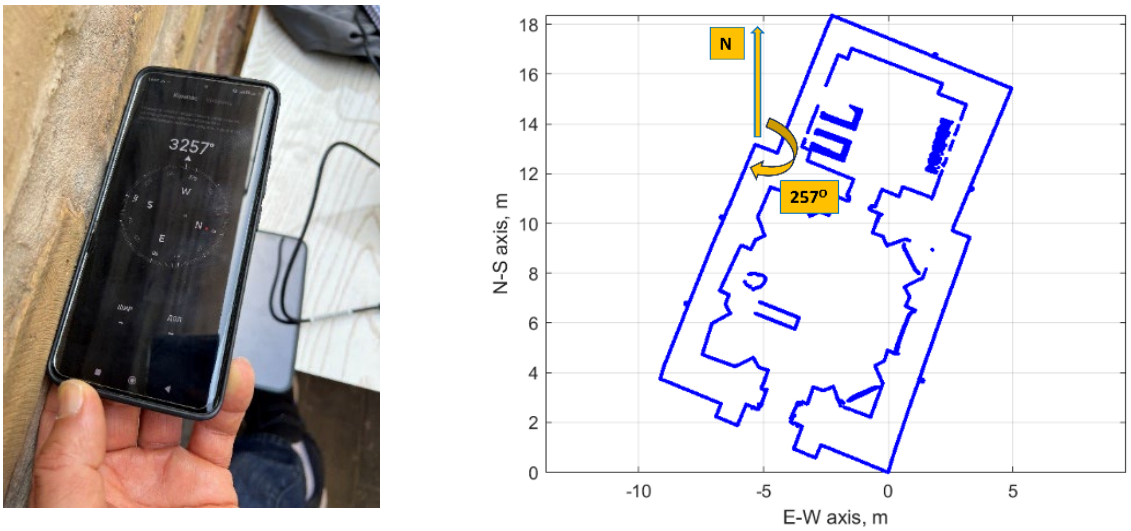


Figure 7: Overall orientation of the mausoleum: measured by digital compass (left) and plan view (right).

The image on the right side of Figure 7 was generated in the Matlab environment [8]. It shows the monument's overall orientation with respect to magnetic north in the global coordinate system.

The overall dimensions of the plan view in the local coordinate system are presented in Figure 8. As shown in the plot generated in Matlab [8], the length of the monument is about 16.6 m, and its width is 9.9 m. Both numbers are different from those reported earlier [2]: 16.2 m and 9 m, respectively.

It is worth noting that the monument's construction reveals a few imperfections. First, the outer walls are not parallel to each other. Second, the corner angle is different from 90 degrees.

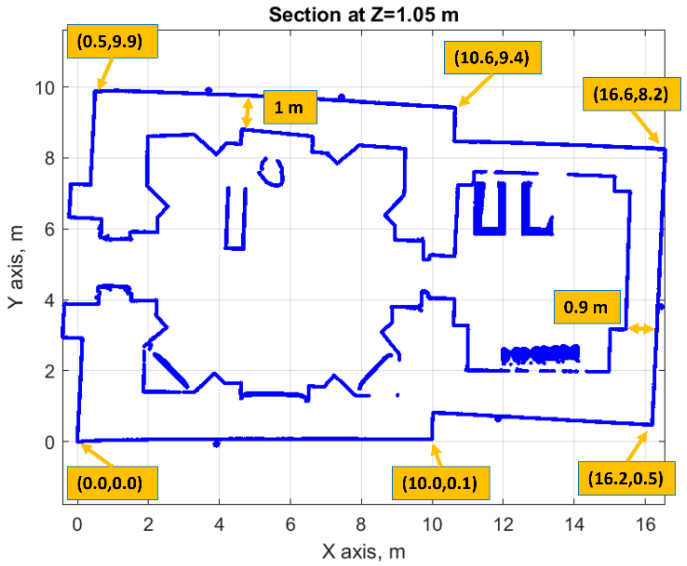


Figure 8: Overall dimensions in the local coordinate system

The wall thickness varies from wall to wall or even along the same wall. The thinnest wall measurement in the 1st room was about 1 m, and the thinnest portion of the wall in the 2nd room was about 0.9 m.

The results of the laser scanning are planned to be used to generate the finite element model of the monument, which is ongoing.

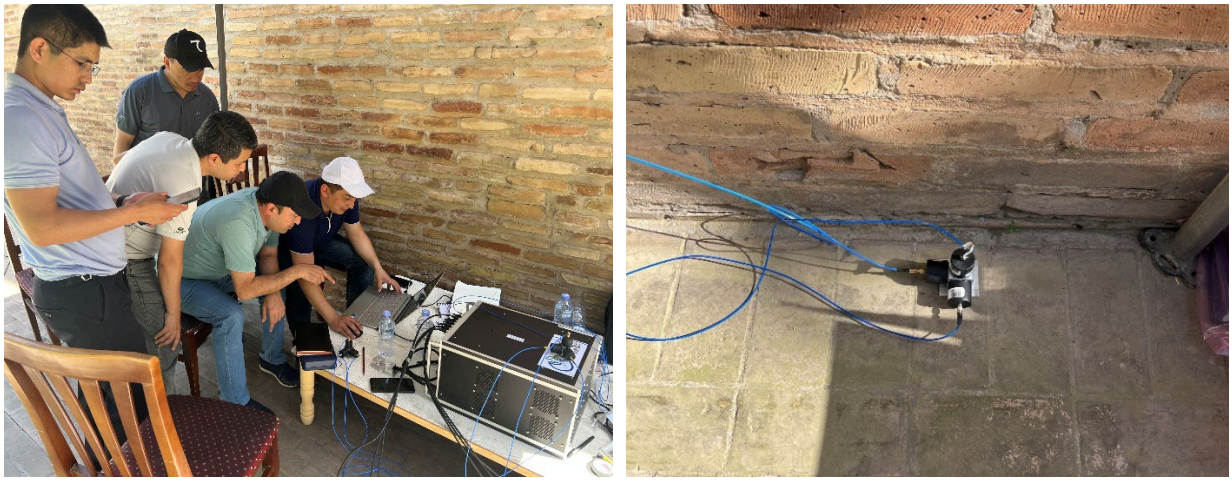
3 AMBIENT VIBRATION STUDY

The ambient vibration study of the monument was conducted on May 21, 2026. The structural response of the monument to ambient vibrations induced by traffic and ongoing nearby construction was measured. It is worth noting that this type of study is instrumental for measuring the actual structural performance of ancient monuments and subsequent finite element modeling. It has been successfully used for many heritage buildings and structures of Uzbekistan [9-11].

3.1 Sensors and their locations

High-sensitivity accelerometers integrated with Pacific Instruments' data acquisition system [12] were used in this study.

The workstation showing the data acquisition system and the work in progress is presented in Figure 9a. The accelerometers were installed on special blocks or cubes to enable recording data along the three principal axes. A typical installation on the ground level is shown in Figure 9b.



a) Workstation with data acquisition system b) Reference accelerometers at the ground level

Figure 9: Photos of ambient vibration testing in progress and ground-level accelerometer set.

Two additional triaxial sets of accelerometers were installed at different locations on the monument's top level. Figure 10 shows one of the typical installations. In this particular case, this set was installed on the north face of the main dome's supporting structure.



a) Overall view b) Close-up view

Figure 10: An example of a triaxial accelerometer set installed on top of the monument.

A total of 3 configurations for the sensor locations on the top were created. At least three data files were recorded for each configuration to ensure repeatability of the results. Typical results for one configuration are discussed herein.

3.2 Data reduction and results

The level of ambient vibrations was very low, as shown in Figure 11. This figure shows only a 5-second-long data sample as a representative example. It is plotted for the top and bottom accelerometers in Y-axis (both on the north side). It shows that the input signal's amplitude does not exceed 0.30 milli-g, while the vibration amplitude at the top of the monument is about 0.15 milli-g. This phenomenon was expected because the structure will act as a filter, attenuating all frequencies except its resonant frequencies.

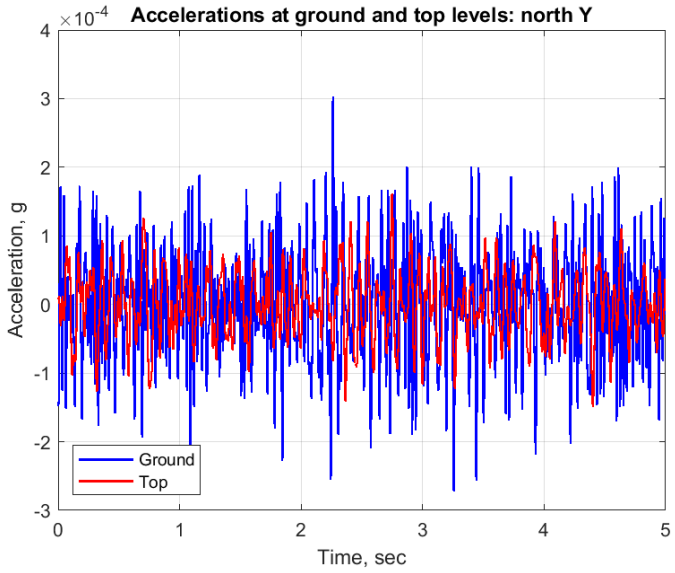


Figure 11: Accelerometer data: sample data in the Y-axis at the north side.

The frequency-domain analysis is presented below. It is conducted in the Matlab environment [8]. The Fast Fourier Transforms (FFTs) were generated for each data set. A typical result from the ground-level accelerometers is shown in Figure 12. The frequencies of the ambient vibration are shown in this plot.

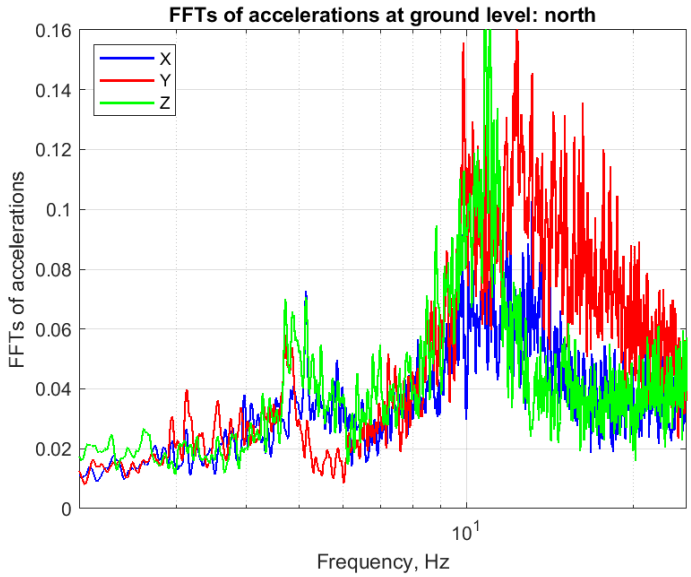
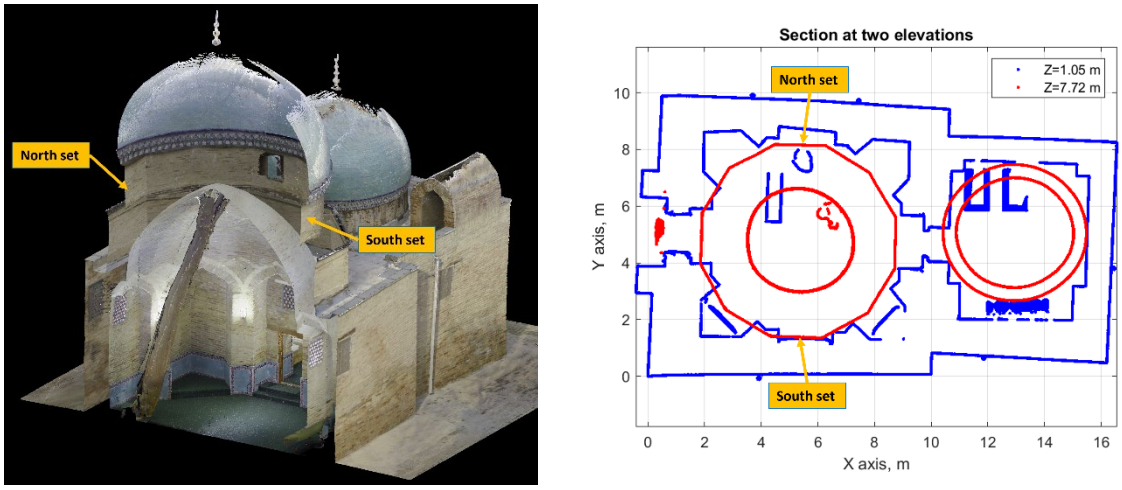


Figure 12: The Fast Fourier Transforms on the ground level.

Two sets of accelerometers were installed on the support structure of the main dome at an elevation of about 7.7 m, as shown in Figure 13. A photo of one set on the north side is presented in Figure 10. The average of the data collected from accelerometers on opposite sides of the dome will yield accelerations along the principal axes, X, Y, and Z. The difference between the data from accelerometers oriented along the X-axis will correspond to torsional acceleration. The Fast Fourier Transforms (FFTs) were computed for these accelerations.



a) 3D view in the section of the digital twin b) Plan views at two elevations

Figure 13: Two triaxial accelerometer sets installed on top of the monument.

The respective FFTs for the accelerations at the monument's top are presented in Figure 14. The peaks in the FFT plots correspond to the resonant frequencies of the monument along the X and Y principal axes. A 50-point moving-average smoothing procedure was applied to the frequency-domain plots.

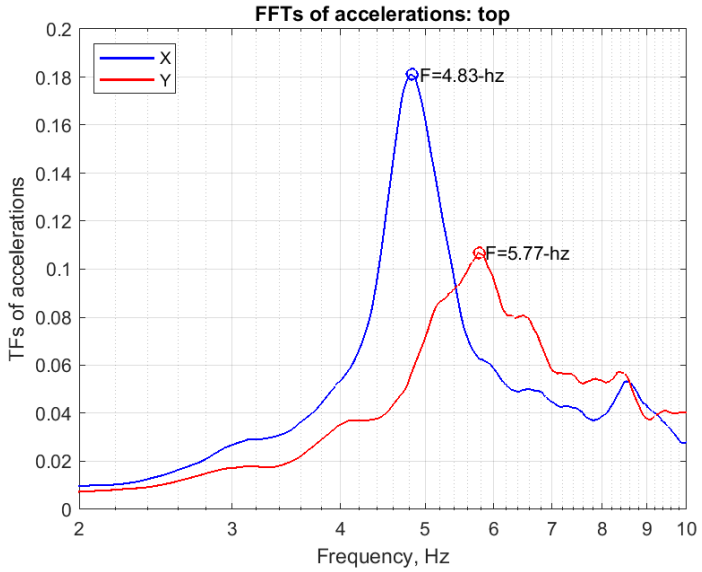


Figure 14: The Fast Fourier Transforms on the top: X and Y.

The respective FFTs of the torsional acceleration and the Z-axis acceleration are presented in Figure 15. Similar to the previous plot, a 50-point moving-average smoothing procedure was used to smooth the plots in the frequency domain.

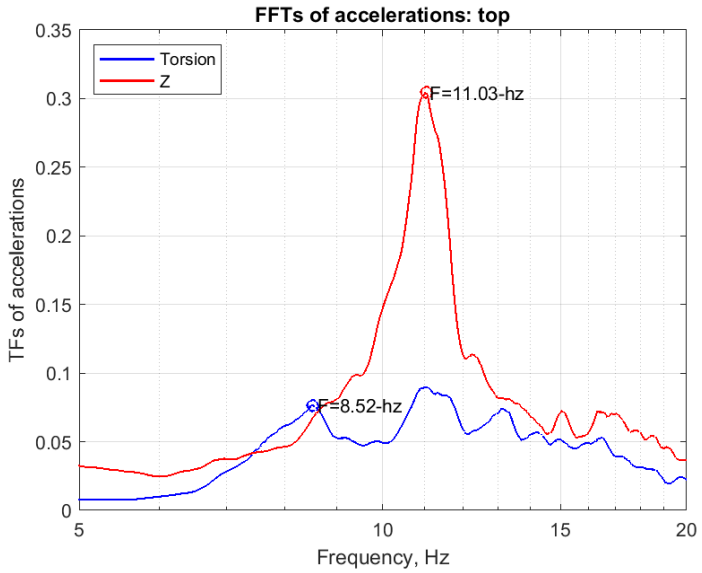


Figure 15: The Fast Fourier Transforms on the top: torsional and Z.

Table 1 presents a summary of ambient vibration tests. It is based on the results from the accelerometer set attached to the vertical supporting wall of the main dome, as shown in Figure 10. The average resonant frequency along the X-axis across these three data files was measured at 4.8 Hz. Across these four data files, the average resonant frequency along the Y-axis was 5.7 Hz. The torsional frequency was estimated at 8.5 Hz. The resonant frequency along the Z-axis was computed to be 11.1 Hz.

Test data No	X-axis, Hz	Y-axis, Hz	Torsion, Hz	Z-axis, Hz
1	4.83	5.65	8.38	10.96
2	4.83	5.77	8.52	11.03
3	4.87	5.58	8.54	11.28
4	4.81	5.78	8.38	11.08
Average:	4.8	5.7	8.5	11.1

Table 1: Summary of measured resonant frequencies.

4 CONCLUSIONS

Based on the accurate 3D twin of the monument, all major dimensions were measured. While the earlier reported height of the building was 12.8 m, the laser scanning results revealed the following. The tips of the two spires are 14.94 m and 11.01 m, respectively. The highest points of the big and small domes are 13.77 m and 9.85 m, respectively. In addition, it was observed that the floor slopes toward the entrance with an overall change in elevation of about 0.60 m. Based on the point cloud measurements, the thickness of the small dome at its tip is approximately 0.50 m. The main dome most likely has a space between the inner and outer domes, which is quite common in ancient construction in Uzbekistan and across Central Asia as a whole.

The analysis of the monument's overall dimensions in plan view revealed the following. Based on the laser scans, the monument is about 16.6 m long and 9.9 m wide. Both numbers differ from those reported earlier [2]: 16.2 m and 9 m for the length and width, respectively.

The first two resonant frequencies were measured in the ambient vibration study. Based on data recorded with high-sensitivity accelerometers, the resonant frequency along the X-axis

(longitudinal direction) is approximately 4.8 Hz. The respective resonant frequency in the Y-axis was measured at 5.7 Hz. The latter corresponds to the transverse direction. The torsional frequency was estimated at 8.5 Hz. The resonant frequency along the Z-axis was computed to be 11.1 Hz.

The results obtained in this study are intended for use in finite element modeling of the monument to predict its structural performance under various loading conditions, including strong earthquakes.

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