Available online at www.eccomasproceedia.org
Eccomas Proceedia SMART (2023) 691-699

ECCOMAS Proceedia

X ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2023
D.A. Saravanos, A. Benjeddou, N. Chrysochoidis and T. Theodosiou (Eds)

EVALUATION OF COMBINED USAGE OF LASER SCANNER AND THERMAL IMAGING CAMERA FOR MONITORING THERMAL EXPANSIONS OF BIBI-KHANUM MOSQUE IN SAMARKAND (UZBEKISTAN): FIRST STEPS

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Abstract. This paper describes the research conducted on the Bibi-Khanum Mosque in Samarkand, Uzbekistan. This mosque was selected as a subject for the study because it has a set of permanently installed instrumentation for monitoring its dynamic response to nearby earthquakes. In addition, the mosque has been laser scanned to capture its 3D geometry with a few millimeters accuracy. The study was focused on the feasibility of measuring thermal expansion of the mosque during hot summer months. The field study was conducted in the summer of 2022. A terrestrial laser scanner was used for monitoring deformations of the mosque's south wall. The scans started in the morning and were conducted at one-hour intervals. A total of six scans were performed. All laser scans were completed in a single day. To increase the accuracy of point tracking, the scanner was also used to capture the locations of a few targets installed throughout the monument. A thermal imaging camera was also used

Peer-review under responsibility of the organizing committee of SMART 2023.
doi: 10.7712/150123.9823.445563

in the study to monitor the distribution of temperature on the wall's external surface. This work is focused on the correlation of the point cloud collected by the scanner to the thermal images collected by the thermal camera. In addition, the feasibility of monitoring thermal deformations by means of the terrestrial laser scanner was evaluated. The results will be used in the numerical modeling of the mosque subjected to high heat during summer, which is a common occurrence in Uzbekistan.

Keywords: Laser scanning, Structural health monitoring, Numerical modeling and simulation, Thermal expansion, Thermal imaging camera.

1 INTRODUCTION

The majority of ancient mosques in Uzbekistan are built with thick walls. One of the main reasons for this was to ensure somewhat comfortable conditions inside during both hot summers and cold winters. Extreme weather conditions are common for many areas of the country because Uzbekistan is located in a region with an arid and continental climate. Large variations in temperature within days and between seasons are common for almost all parts of the country. In addition, about 80% of Uzbekistan's area has a flat topography either in the form of semi-desert steppes or desert zones, these areas have even greater temperature variations. Hence the assessment of the structural performance of heritage structures under these extreme weather conditions is very important for the preservation of their structural integrity. This research was focused on the Bibi-Khanum monument, an ancient mosque in Samarkand. The paper discusses the preliminary results of the exploratory project focused on the detection and analysis of thermal expansion of Bibi-Khanum monument, an ancient mosque in Samarkand.

2 FIELD WORK

Figure 1a shows the main portal to the Bibi-Khanum mosque. This heritage monument was selected for the study because it was already extensively instrumented in the past [1,2] with accelerometers installed at critical locations throughout the monument.

a) main portal facing east b) laser scanner in front of the south wall

Figure 1: Main portal and the south wall of Bibi-Khanum.

For the purpose of this study, the following equipment was deployed for in-situ measurements at the heritage site. First, a terrestrial laser scanner, C10 from Leica GeoSystems [3], was used for laser scanning as presented in Figure 1b.

Second, a thermal imaging camera, CompactPRO from Seek Thermal, Inc [4], was used to measure the temperature on the mosque's surface. This project was focused on the south wall of the mosque which was fully exposed to direct sunlight during the day. The project was conducted in June, 2022 typically one of the hottest months of the year.

2.1 Laser scanning

The laser scanning of the south wall was done multiple times from the same position. One of the high-resolution settings of the scanner was selected for each scan. A total of six scans were conducted with a time interval of one hour between the scans. The scanning was started at around 11 am local time and was completed at around 4 pm local time. To track the displacements at critical locations a few black and white targets were installed on the walls of the monument as presented in Figure 2. A few of these were on the south wall of the mosque with full exposure to the sun as presented in Figure 2a. Two were placed on the wall of the courtyard which was continuously in shadow without exposure to direct sunlight as shown in Figure 2b.

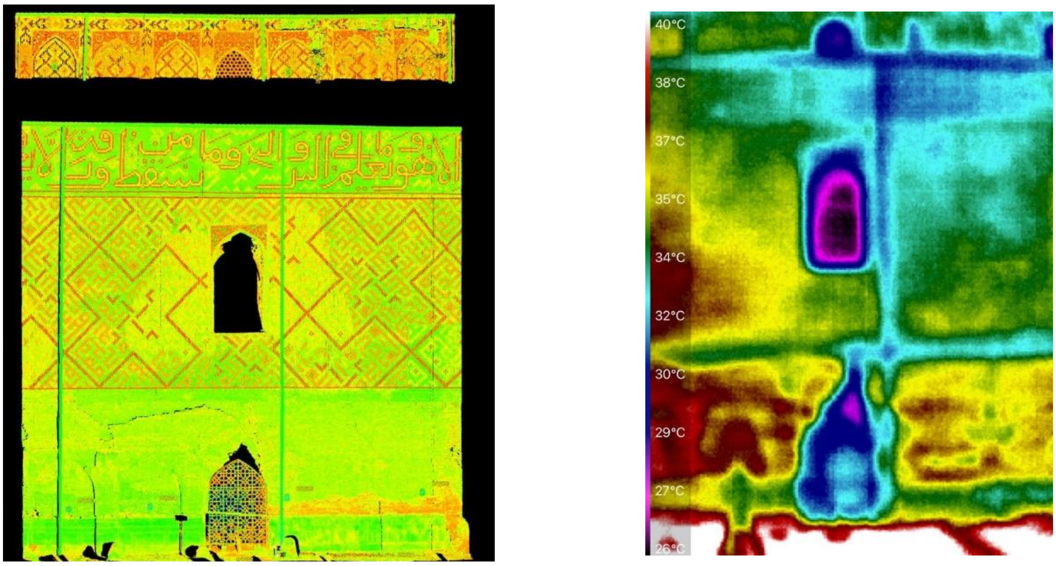
a) Typical target on the sunny side b) Targets on the wall without direct sun exposure

Figure 2: Black and white targets were used for monitoring displacements with increased accuracy.

As mentioned earlier, the scanner was set to acquire the point cloud at one of the high-resolution settings, and as a result, each scan was about 30 minutes long.

2.2 Correlation between regular and thermal images

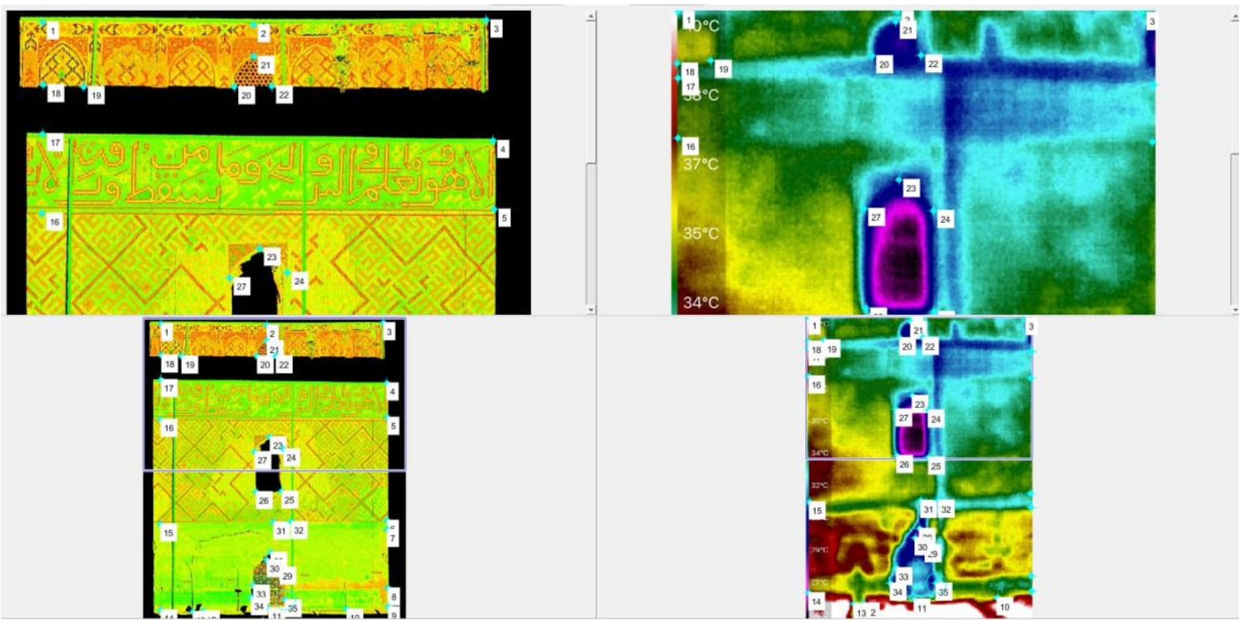
This part of the project was to find a correlation between the image taken by a regular still imaging camera and the image taken by the thermal camera with a measured temperature distribution in the plane of the frame. An example of the regular image is the image of the point cloud as presented in Figure 2a. This image was taken from Cyclone [5] that shows the point cloud of the south wall in the intensity colors of the returned laser beam. Figure 2b shows the image of the same wall taken by a thermal imaging camera. The goal was to find the correlation between the two images and to overlay the thermal image on top of the regular image, and as such, to estimate a temperature at each pixel of the regular image. This is considered to be an intermediate step toward finding a correlation between the point cloud points and the temperature measured by the thermal imaging camera.



a) Point cloud's image b) Thermal image

Figure 3: Image of the point cloud and thermal camera image.

The correlation between the two images shown in Figure 3 is conducted in the Matlab environment [6]. It is based on finding control points between two related images. Since the images were not calibrated, a number of control points were selected as shown in Figure 4.



a) Point cloud (image) b) Thermal image

Figure 4: Control points between the thermal image and the image of point cloud.

Based on the correlation between the control points, the thermal image was transformed to overlay the thermal map onto the image of the point cloud as presented in Figure 5.

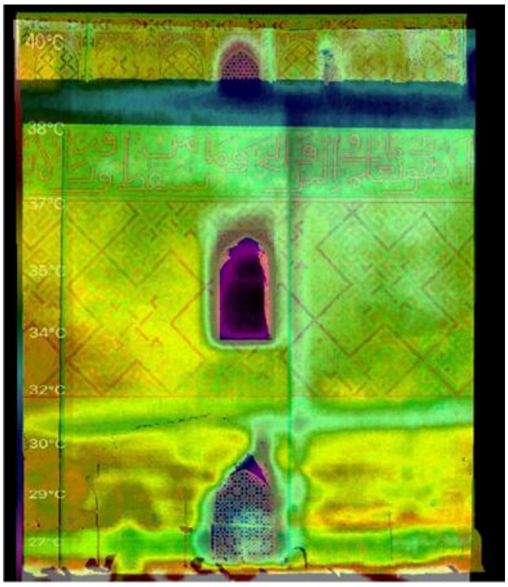
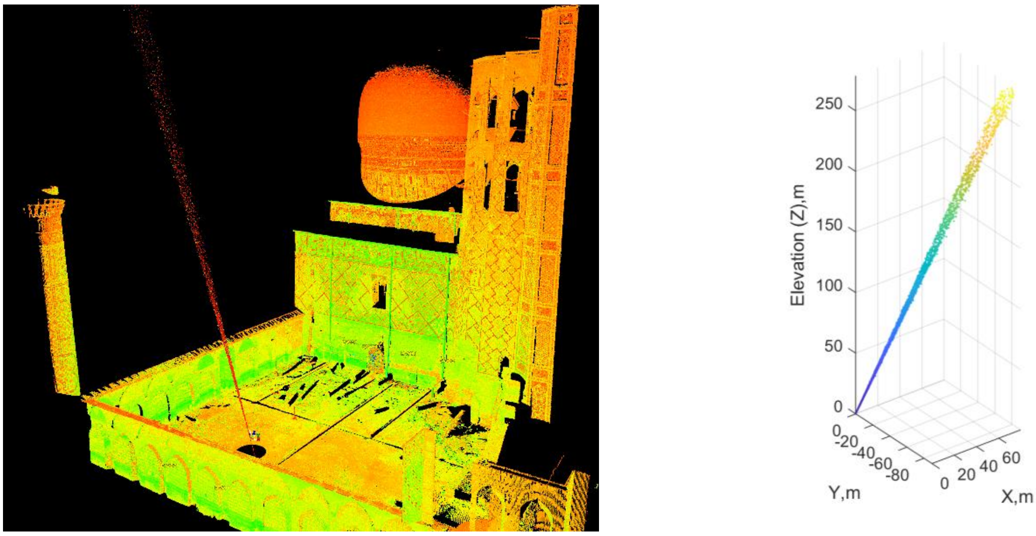


Figure 5: Final result overlaying temperature map onto the image of the point cloud.

2.3 Estimation of sun's inclination to the south wall surface

It is well known that the degree between the sunbeams and a surface will affect the amount of energy transferred to the surface. As in the case of harvesting solar energy, a solar panel output is maximized when the sun's rays hit its surface perpendicularly (see [7], for example). This sun inclination was obtained from the point clouds using the following procedure. The terrestrial laser scanner utilized in this project interferes with the sunbeams when the laser scanner points toward the sun. It creates an artificial point cloud that looks like a cone pointing toward the sun's location during the scan as shown in Figure 6a. For each point cloud, this artificial cone was separated from the rest for further Matlab analysis as presented in Figure 6b.



a) Artificial cone in the overall point cloud b) Separated cone

Figure 6: Artificial point cloud pointing toward the sun.

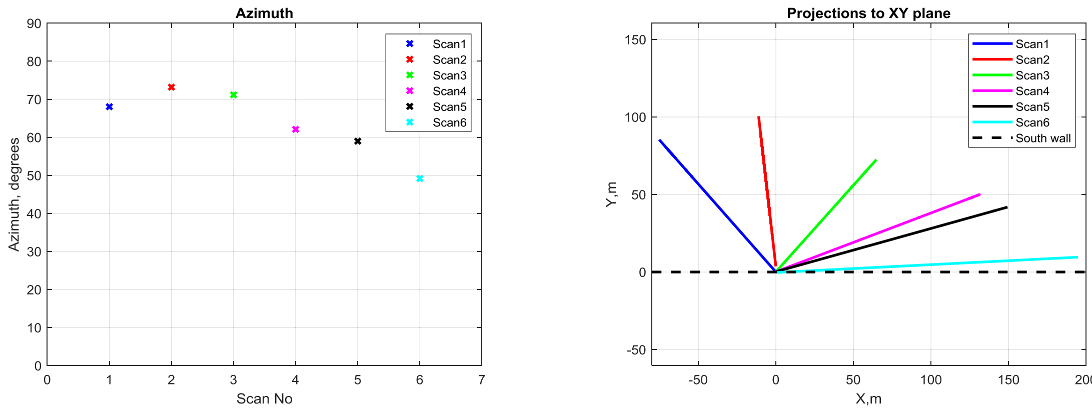
To conduct the analysis in the same coordinate system, the point clouds for each scan were transformed in such a way that the X-axis is parallel to the south wall and the Y-axis is orthogonal to the wall. The orientation of the cone in space was analyzed to obtain two angular coordinates of the cone's axis. The first angle is between the projection of the axis to the horizontal plane and the X-axis, the polar angle. The second angle is the angle of the cone's axis to the horizontal plane, the azimuthal angle. The results are presented in Figure 7.

As shown in Figure 7a, the azimuth of the sun had a peak at Scan2 and then it gradually decreased. Figure 7b shows the projections of the cone's axis on the horizontal plane. As noted earlier, the south wall runs along the X-axis, and the wall is shown as a dashed black line in Figure 7b. The projections shown in Figure 7b clearly present how the sun was turning around the south wall. The most effective angle of the sun to transfer heat is ninety degrees to the wall and the sun was close to this position in Scan2.

Table 1 summarizes a local time at which each scan was initiated. It is worth noting that the scan's duration was quite long (about 30 minutes) and the sun was in motion with respect to the laser scanner. This shortcoming will be addressed in the future field studies by having a short-duration scan pointing toward the sun.

Table 1: Local time of each scan (starting time shown in militatry format).

Scan1	11:12
Scan2	12:02
Scan3	12:58
Scan4	13:54
Scan5	14:37
Scan6	15:19



a) Variation of azimuthal angle b) Variation of the polar angle

Figure 7: Variation of the angles from scan to scan.

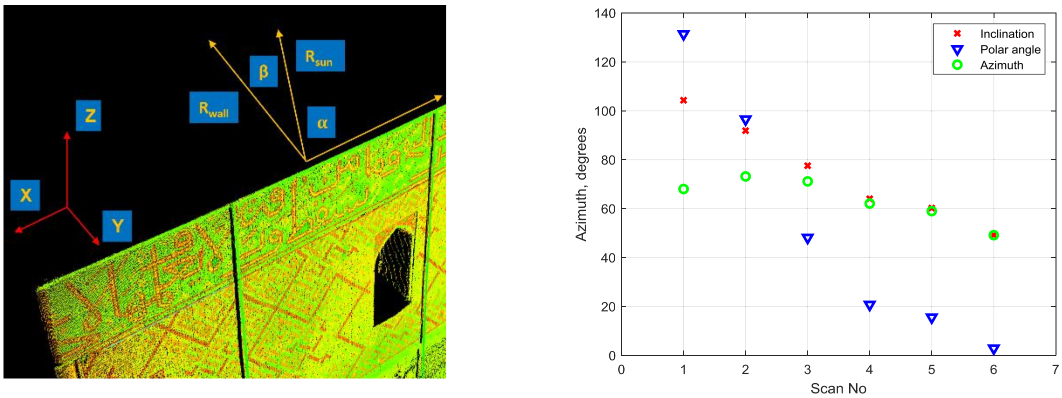
The overall angle of inclination of the sun to the south wall was estimated in the following way. Two unity vectors were introduced. The first vector coincides with normal to the south wall, so its coordinates are $R_{wall} = (0, -1, 0)$. The second vector is parallel to the axis of the cone and its coordinates can be expressed in the following way:

$$R_{sun} = (\sin\varphi\cos\theta, \cos\varphi\cos\theta, \sin\theta) \quad (1)$$

where θ corresponds to the azimuthal angle and φ corresponds to the polar angle. The angle between these vectors can be obtained from the cross-product of two vectors in three-dimensional Euclidean space as shown in Figure 8a. When two vectors R_{wall} and R_{sun} have multiplied the length of the resultant angle will be equal to the sine of the angle between the cone's axis and the wall's normal, denoted as β in Figure 8a. The angle between the wall's surface and the cone's axis (which is called an inclination angle for the purpose of this paper), will be complementary to β. Hence the inclination angle, α, is estimated from the following equation:

$$\alpha = 90^o - \arcsin(\cos\varphi\cos\theta). \quad (2)$$

Using equation (2), the inclination angle is computed and presented in Figure 8b. Figure 8b shows that the inclination angle peaked at Scan1 and then steadily decreased. Scan1 and Scan2 produced inclination angles very close to ninety degrees. Its overall trend is close to the polar angle, but the gradient is much smaller. In addition, for small polar angles, it is very close to the azimuthal angle. Another important conclusion was that the inclination is much closer to the ninety-degree angle for all scans.



a) Geometry of angle calculations   b) Inclination vs. other two angles

Figure 8: Inclination angle computation results.

The inclination of the sunbeams to the surface of the south wall is very important in assessing the amount of heat being transferred to the surface. In the next phases of the analysis, the sun's inclination will be correlated to the deformation of the surface. Due to the size limitations of this paper, all obtained results will be published in the paper's extended version.

3 CONCLUSIONS

A few intermediate results of the study focused on measuring thermal expansion of the thick wall of the ancient monument were discussed. The Bibi-Khanum mosque in Samarkand was selected for this study. The study was based on the combined usage of a terrestrial laser scanner and a thermal imaging camera. In this paper, a correlation procedure between the thermal map and the image of the point cloud was developed. In addition, the inclination angle of the sun to the surface of the south wall was computed for each laser scanner position. The combined analysis of the point clouds and the thermal images is ongoing and will be presented in the extended version of the paper.

ACKNOWLEDGMENTS

The project was partially sponsored by Turin Polytechnic University (Tashkent, Uzbekistan), which is greatly appreciated. Special thanks are due to Sigma Innovative Tech, LLC for providing access to the terrestrial laser scanner and the thermal imaging camera. The authors would like to acknowledge Holly Halligan of UC Berkeley for editing the paper.

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