3D Point Cloud Model of Süleymaniye Mosque Obtained by Terrestrial Laser Scanning

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Abstract

Cultural heritage is the totality of all kinds of works and values belonging to a society, inherited from the past and desired to be transferred to the future for various reasons. Suleymaniye Mosque is important as a UNESCO World Heritage site because of its architectural magnificence and because it represents the Ottoman cultural heritage. Suleymaniye Mosque, an exemplary work of Ottoman architecture, was designed by Mimar Sinan and built between 1550-1557. So, 3D documentation of cultural heritage sites is essential, and the most commonly used methods for 3D documentation are LiDAR and photogrammetry. This study documented Suleymaniye Mosque in Istanbul using the laser scanning method. Laser point cloud data fusion was performed to combine the point clouds, and an accurate and detailed representation of the monument was obtained. In the study area, TLS measurements were performed with Leica P40 TLS to obtain an accurate and detailed representation of the Suleymaniye Mosque. A data fusion process was also performed with the Cyclone Register 360 Program to obtain a complete model of the study area. Terrestrial laser scanning (TLS) was effectively used to document the Suleymaniye Mosque using a Leica P40 laser scanner.

1. Introduction

Cultural Heritage includes all the values, works, and traditions inherited from the past that a society wants to preserve and pass on to future generations. In its most general form, Tangible Cultural Heritage are Physical objects like historical buildings, monuments, and sites and Intangible Cultural Heritage are Nonphysical elements like traditions, music, and languages (Can, 2009). Documenting Tangible heritage, such as historic buildings and monuments, needs proper documentation to ensure its preservation and It helps maintain these structures, monitor their condition over time, and restore them when needed. For many years, photogrammetry (using photographs to create detailed maps or models) was widely used to document cultural heritage. This method provides dimensional drawings and 3D models, creating a comprehensive database for documentation and restoration. Modern advancements, especially laser scanning technology, have significantly improved the detail and precision of data collected. Laser scanners produce highly accurate 3D models, making it easier to analyze and preserve heritage sites. (Wang, H. et al., 2016). With these technologies, By using precise tools, professionals can monitor changes, plan restorations, and ensure the longevity of historic sites. (Kuçak, et al., 2016).

The Süleymaniye Mosque is a cultural heritage of the Ottoman heritage of culture and architectural magnificence, which is recognized as a UNESCO World Heritage site. Designed by the famous architect Sinan and built between 1550 and 1557, this mosque is an extraordinary work of art and a vital component of a complex of buildings serving various community needs. In addition, the mosque was a crucial role in their social and spiritual lives. Also, this emphasizes the value of the mosque beyond religious worship because it advances society. The beautiful design and innovative construction techniques of Islamic architecture represent helping to understand global change better the advances of their time. (Akyürek, M. E., & Kahraman, G., 2021). The mosque was part of a larger complex of buildings that served various community needs (e.g., education, charity, and healthcare) (Faroqhi, S., & Frisch, 2009). The Süleymaniye Mosque played a vital role in the social and spiritual lives of the local population, making it more than just a place of worship and its multifunctionality emphasizes how architecture can support societal development and foster a sense of community.

The most used methods for 3D documentation of cultural heritage sites are LiDAR and photogrammetry. TLS focuses on detailed scans of structures. It accurately captures ancient structures' complex geometries and spatial relationships and produces high-resolution data and precise 3D models essential for restoration and preservation. On the other hand, in photogrammetry, it has become easier and faster to obtain 3D models of historical sites with the advancements in UAV (Unmanned Aerial Vehicle) technology. UAVs (Drones) Capture aerial photos quickly and efficiently, covering large areas. They help cultural heritage documentation and provide an overview of historical sites.Therefore, LiDAR (Light Detection and Ranging) and photogrammetry have strengths and weaknesses. LiDAR is known for precision and works well in low-light or dense vegetation. Photogrammetry can be costeffective but may struggle with fine details (Kuçak et al., 2016; Yakar, 2021).

The ICP Algorithm aids in merging different point clouds (Besl & McKay, 1992). The Iterative Closest Point (ICP) algorithm aligns and merges 3D point clouds from multiple scans, which is crucial when documenting complex structures and ensures that different scans fit together seamlessly, creating an accurate 3D model of the object. This algorithm enables detailed comparisons over time, allowing researchers to analyze cultural heritage sites (Zhang, 1994). Furthermore, The ICP algorithm has given more accuracy against noise and outliers for 3D models of the structures. (Rusinkiewicz & Levoy, 2001).

In this study, the Süleymaniye Mosque located in İstanbul was documented with laser scanning. To obtain an accurate and detailed representation of the Süleymaniye Mosque, TLS measurements were carried out in the study area with Leica P40 TLS. A data fusion process was also carried out with the Leica Cyclone Register 360 Program to obtain a complete model of the study area. A laser point cloud data fusion process was carried out to combine the point clouds, and an accurate and detailed representation of the mosque was obtained. Terrestrial laser scanning (TLS) has been effectively employed to document the

Süleymaniye Mosque using a Leica P40 laser scanner, which produces high-resolution 3D data critical for preservation and restoration efforts.

2. Data and Methodology

Light Detection and Ranging (LiDAR) is a technology that uses laser pulses. LiDAR uses laser pulses to measure distances. A laser pulse is emitted, and the time it takes to return (reflected signal) is used to calculate the distance between the LiDAR device and objects. The result is a 3D point cloud, a collection of data points in 3D space that represent the scanned environment Types of LiDAR Systems can be divided into two categories (Yakar, 2021). Terrestrial Laser Scanning (TLS) is Best for detailed, close-range documentation, such as architectural features. Airborne Laser Scanning (ALS) is Ideal for large areas, like archaeological sites or landscapes, often operated from drones or helicopters. The advantages are Quickly capturing vast amounts of data from various perspectives and generating detailed and accurate 3D models of structures and landscapes. It's importance are providing precise measurements for creating digital models used in analysis and conservation, helping monitor changes over time, aiding preservation and maintenance efforts, enhancing the efficiency of data collection and the quality of gathered information, and supports informed decision-making in disciplines like architecture, construction, and cultural heritage preservation (Puri & Turkan, 2019).

The Süleymaniye Mosque is a remarkable testament to the architectural achievements of the Ottoman Empire in the 16th century. Builded by the famous architect Sinan between 1551 and 1557, this magnificent mosque contributes greatly to the breathtaking skyline of Istanbul. Commissioned by Suleiman (the Magnificent), the mosque was designed as a place of worship and a vibrant community centre (Figure 1). Sinan's masterful blend of beauty and functionality has etched the Süleymaniye Mosque into the history of classical Ottoman architecture. Its sheer grandeur and the harmonious design of its central dome are considered exemplary achievements in proportion and acoustics in Islamic architecture (Necipoğlu, 2005, Saoud, R., 2007). In this way, it has solidified its position as a global architectural treasure.

Architect Sinan's innovative approach to dome construction in the Süleymaniye Mosque marked a significant advancement in Ottoman architecture, setting a precedent for future mosques. The large dome rises on four elephant feet in the middle of the mass, whose external dimensions are 70mx61m. The diameter of the central dome is 26.20 m and its height is 49.50 m. Inside the mosque, the dome, side domes and arch connections are softened with pendentives (Kuban, 2010; Gül, Z. S., ÇALIŞKAN, M., & Tavukçuoğlu, A. 2014). Architect Sinan utilized advanced geometric principles and materials, such as lightweight brick, to minimize weight without compromising strength, pioneering techniques that influenced subsequent monumental structures (Gül, Z. S., ÇALIŞKAN, M., & Tavukçuoğlu, A., 2014). Significant light sources from various windows increase the grandeur of the dome, revealing Sinan's architectural philosophy of harmony between form and function. Thus, the Süleymaniye Mosque exemplifies the architectural sophistication achieved by Sinan, reflecting both technological innovation and aesthetic mastery within the context of Ottoman heritage (Gül, Z. S., ÇALIŞKAN, M., & Tavukçuoğlu, A. 2014).

In this study, Leica P40 TLS, a highly precise laser scanning instrument was used. A laser point cloud data fusion process was carried out to combine the point clouds, and an accurate and detailed representation of the mosque was obtained. To obtain an accurate and detailed representation of the Süleymaniye Mosque, TLS measurements were carried out in the study area with Leica P40 TLS. A data fusion process was also carried out with the Leica Cyclone Register 360 Program to obtain a complete model of the study area. Terrestrial laser scanning (TLS) has been effectively employed to document the Süleymaniye Mosque using a Leica P40 laser scanner, which produces high-resolution 3D data critical for preservation and restoration efforts.

The ICP algorithm estimates initial 3D transformation parameters between two point clouds and refines this transformation through successive iterations, resulting in highprecision alignment (Zhang, 1994). Leica Cyclone Register 360 employs the Iterative Closest Point (ICP) algorithm for registering point clouds produced from terrestrial laser scanning. This algorithm is widely recognized for accurately registering multiple scans by iteratively minimizing the distance between corresponding points (Besl & McKay, 1992). By utilizing the ICP algorithm, Cyclone Register 360 enhances the reliability of the data registration process, facilitating the 3D documentation and analysis of historical sites.

The Iterative Closest Point (ICP) algorithm is a known method for registering 3D point clouds in geomatics engineering, architecture, cultural heritage, computer vision, and robotics. It has significant applications in cultural heritage preservation. The basis of the ICP algorithm is the Helmert transformation. The ICP algorithm is based on minimizing the distance between corresponding points in two 3D point clouds, often acquired from different scannings of the same object (Besl & McKay, 1992).

Given two point clouds, A and B;

where A consists of N points $\{a1,a2,\ldots,aN\}$

and B consists of M points $\{b1,b2,\ldots,bM\}$,

the objective of the ICP algorithm is to find the optimal transformation T that minimizes the mean squared error (MSE) between the transformed points of A and the closest points in B. The transformation T (Helmert Transformation) can be expressed as:

$$T = R*P+t$$

where:

- R is the rotation matrix,
- P is the point in cloud A (expressed in homogeneous coordinates),
- t is the translation vector.

The ICP algorithm is usually used in cultural heritage for tasks such as 3D documentation and the alignment of point clouds acquired from laser scanning. For example, different scans can be aligned when documenting ancient ruins to assess preservation status and plan restorations. This registration process is a critical step for 3D model generation.

In summary, applying terrestrial laser scanning (TLS) techniques, especially for cultural heritage sites such as the Suleymaniye Mosque, is essential for cultural heritage documentation studies. This process benefits architectural studies by providing a detailed acquisition of the mosque's architectural features with highly accurate 3D point cloud data. Terrestrial laser scanning (TLS) techniques demonstrate remarkable progress in cultural heritage documentation. We can achieve exceptional precision in aligning and merging multiple scans by utilizing Cyclone Register 360—

a powerful software for processing point cloud information—and implementing the Iterative Closest Point (ICP) algorithm. Such extensive 3D documentation studies are essential for determining structural integrity and developing conservation plans for cultural heritage structures. As a result, these technologies provide a better knowledge of cultural heritage and provide long-term study prospects.

3. Case Study

In this study, the Süleymaniye Mosque, located in İstanbul, was documented with laser scanning (Figure 1). A laser point cloud data fusion process was carried out to combine the point clouds, and an accurate and detailed representation of the mosque was obtained. The Süleymaniye Mosque was selected as the study area for this research due to its historical and architectural significance as one of the masterpieces of Ottoman architecture. Designed by the architect Sinan, the mosque represents a pivotal moment in the evolution of Islamic architectural practices, showcasing innovative construction techniques and a harmonious design that has influenced numerous structures thereafter. Furthermore, its status as a UNESCO World Heritage Site emphasizes the need for precise documentation and preservation efforts. Its design's complexity, intricate details, and vast spatial dimensions make it an ideal subject for advanced technologies like terrestrial laser scanning. By focusing on the Süleymaniye Mosque, this study aims to provide valuable insights into the application of modern survey methods in cultural heritage conservation.

Figure 1. The Studied Structure: The Süleymaniye Mosque.

In order to obtain an accurate and detailed representation of the Süleymaniye Mosque, TLS measurements were carried out in the study area with Leica P40 TLS. A data fusion process was also carried out with Cyclone Register 360 Program to obtain a complete model of the study area. The resulted point cloud that was generated with laser scanning can be seen in Figure 2.

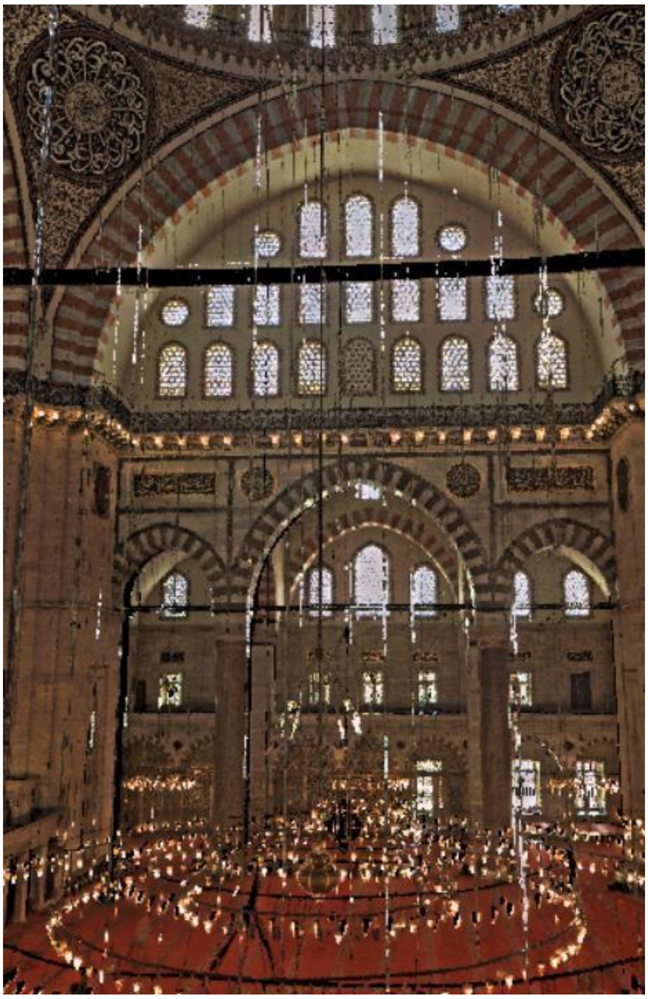

Figure 2. The point cloud of Süleymaniye Mosque with TLS.

The Leica P40 laser scanner (Figure 3) was used for the scanning process, and an accuracy assessment was conducted by comparing the laser data with measurements from a total station.

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Figure 3. The Leica P40 Laser Scanner Used in This Study.

The data was obtained by merging from 13 scans made with the Leica P40 device on the Cyclone Register 360 software (Figure 4). No ground control point was used for the scans of the Rectorate building. All scans were registered with 0.005 m precision without using this keypoint. These data were registered with ICP Algorithm according to Cloud to Cloud principle.

Figure 4. The register process with Leica Cyclone Register 360.

Only indoor scans were made in Suleymaniye Mosque, approximately 13 scans were performed again at a scanning frequency of 3.1 mm. All data were combined by taking a single scan as reference in each local coordinate system. The specifications of the Leica P40 terrestrial laser scanner used in the study are as follows (Table 1).

Parameter	Value
Maximum Distance	270 m
Measurement Method	Impulse Method (Time of Flight)
Wavelength	1550 nm / 658 nm
Distance Accuracy	1.2 mm + 10 ppm at full range
Angular Accuracy	Horizontal: 8” , Vertical: 8”
3D Position Accuracy	3 mm at 50 meters
Scanning Rate	Up to 1 million points per second
Field of View	Horizontal: 360° , Vertical: 290°
Laser Class	Class 1 (IEC 60825:2014)
Camera Resolution	4 MP for each 17°×17° color image
Data Storage	256 GB Internal
Operating Time	5.5 hours (2 Lithium-ion Batteries)
Scanner Weight	12.25 Kg (without battery)
Scanner Dimensions	238 mm × 358 mm × 395 mm

Table 1. The properties of Leica P40 TLS.

According to the results obtained, the interior scanning of the 13 Suleymaniye Mosque was completed, all scans were combined with the desired accuracy and detail, 0.005 m sensitivity. Various measurements were made from the combined data and compared with the values in the literature, and values close to the architectural measurements were obtained. Since 13 laser scanning data were combined with 0.005 mm precision, high resolution and detailed data was obtained for the Suleymaniye Mosque. Measurements were made for various analyses made from these point clouds. For example, in the analyses made for the measurements of the dome height and diameter, values close to the values in the literature were obtained.

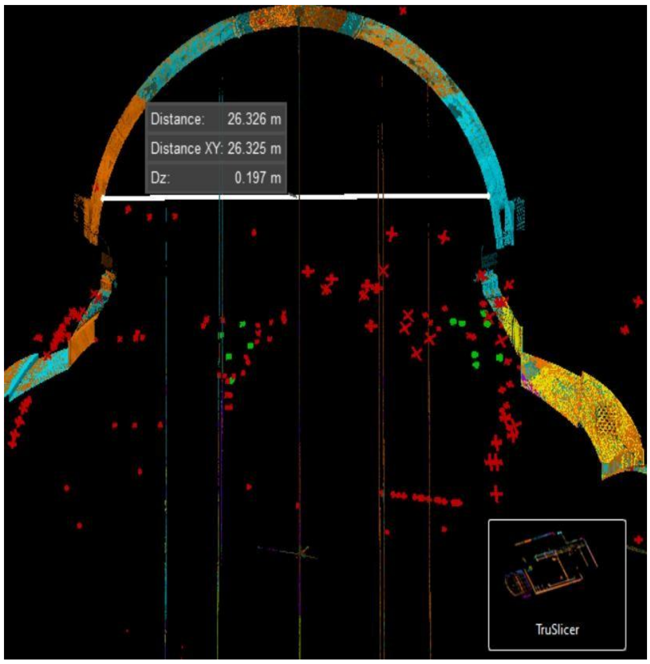

Figure 5. The measurement of the dome diameter from point cloud.

In literature, the diameter of the central dome is 26.20 m and its height is 49.50 m. Inside the mosque, the dome, side domes and arch connections are softened with pendentives (Kuban, 2010; Gül, Z. S., ÇALIŞKAN, M., & Tavukçuoğlu, A. 2014). In this study, diameter was measured 26.32 m (Figure 5), the dome height was measured 48.19 m (Figure 6).

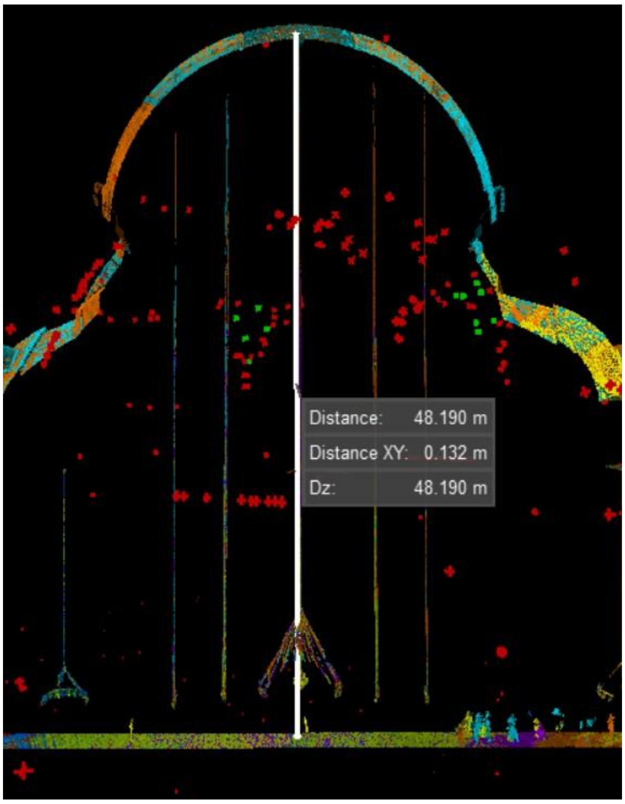

Figure 6. The measurement of the dome height from point cloud.

Since the measurements here are indoors, although we obtained approximately the same values for the dome, there was a difference of approximately 1 meter for the height of the dome. This is due to the fact that it is not known exactly which height is meant in the values measured in the literature. The measurements of the dome were made from many angles and the accuracy of our laser system was tested. The measured height for the dome height was obtained as 48.19 m with a precision of 0.005 m in this study.

4. Conclusion

In this study, Süleymaniye mosque that is located in İstanbul was documented with laser scanning method. A data fusion process was carried out to combine the point clouds and an accurate and detailed representation of the monument was obtained.

The use of point clouds in the 3D documentation of cultural heritage offers significant advantages in terms of accuracy, preservation, and analysis. By employing such advanced techniques, researchers can enhance their understanding of historical sites and ensure their preservation for future generations. As technologies such as TLS continue to evolve, they will play an increasingly important role in how we document, conserve, and interact with cultural heritage sites. However, challenges such as data management, accuracy, and long-term digital preservation need to be addressed to fully realize the potential of point cloud technology in this field.

With this study, many measurements were made to obtain the 3D point cloud model of the Suleymani Mosque. However, the measurements could be compared with the data in the literature. A more detailed data comparison will be made with total station measurements. In addition, if the measurements produced from previous architectural drawings can be obtained more clearly, it was concluded that a healthier comparison could be made with the obtained laser data.

References

Akyürek, M.E., Kahraman, G., 2021. Structural Art in Sinan’s Mosques. *Journal of Art History*, 30(1), 255-283. (In Turkish) doi.org/10.29135/std.817575.

Besl, P.J., McKay, N.D., 1992. A Method for Registration of 3-D Shapes. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 14(2), 239-256.

Can, M., Kültür ve Turizm Bakanlığı Rapor, 2009. https://teftis.ktb.gov.tr/Eklenti/1279,muserrefcanpdf.pdf?0

Faroqhi, S., Frisch, S., 2009. *The Ottoman Empire: A Short History*. London: I.B. Tauris.

Gül, Z.S., Çalişkan, M., Tavukçuoğlu, A., 2014. On The Acoustics of Süleymaniye Mosque: From Past to Present. *Megaron*, 9(3). (In Turkish) doi.org/10.5505/MEGARON.2014.96168.

Kuban, D., 2010. A Symbol of Ottoman Architecture: The Süleymaniye. *Ottoman Architecture, Suffolk, Anti que Collectors’ Club*, 277-294.

Kuçak, R.A., Kiliç, F., Kisa, A., 2016. Analysis of terrestrial laser scanning and photogrammetry data for documentation of historical artifacts. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42, 155-158.

Necipoğlu, G., 2005. *The Age of Sinan: Architectural Culture in the Ottoman Empire*. London: Reaktion Books, with Princeton University Press, 2005.

Puri, N., Turkan, Y., 2019. A comparison of TLS-based and ALS-based techniques for Concrete Floor Waviness Assessment. In ISARC. *Proceedings of the International Symposium on Automation and Robotics in Construction*, 36, 1142-1148. IAARC Publications.

Rusinkiewicz, S., Levoy, M., 2001. Efficient Variants of the ICP Algorithm. *Proceedings of the 3D Data Processing, Visualization, and Transmission*, 145-152.

Saoud, R., 2007. *Sinan: a great ottoman architect and urban designer*. Foundation for Science Technology and Civilisation, 703(1), 1-15.

Yakar, İ. (2021). An Investigation on Multi Sensor Data Fusion Techniques in Historical Sites Monitoring. [Master’s Thesis, Istanbul Technical University]

Wang, H., Wang, L., Lu, Y., Chen, X., Qi-rong, G., Wang, W., Xia, Z., 2016. Long-term outcomes of different bortezomib-based regimens in Chinese myeloma patients. *OncoTargets and Therapy*. doi.org/10.2147/ott.s97457.

Zhang, Z., 1994. Iterative Point Matching for Registration of Free-Form Curves and Surfaces. *International Journal of Computer Vision*, 13(2), 119-152.