3D Documentation of Cultural Heritage Obtained by the Use of Point Clouds: The Case Study of Molla Hüsrev Mosque

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Abstract

The correct documentation of the structure of cultural heritage is necessary for its conservation, restoration, and 3D analysis. This paper explores the use of professional Terrestrial Laser Scanning (TLS) and iPad Pro LiDAR sensors to create accurate three-dimensional models for documenting cultural heritage sites. The case study was conducted on the Molla Hüsrev Mosque in Istanbul, which dates back to the 15th century and is an Ottoman structure. The TLS scans were performed using the Leica P40 scanner, while the iPad Pro LiDAR scans were conducted using the SiteScape app. The two datasets were registered using the Iterative Closest Point (ICP) algorithm, which achieved an accuracy of 0.007 m. The ICP algorithm was also used to determine registration accuracy in complex buildings, and recommendations for improving accuracy in such buildings are discussed in the paper. The results showed that the TLS system achieved high geometric accuracy and high resolution (0.029 m RMS). The iPad Pro LiDAR system improved the completeness of surface reconstruction on complex surfaces. The fusion of the two datasets produced a denser, more complete dataset of the mosque. The paper's results show that while the iPad Pro LiDAR system is less accurate than the TLS system, its portability and high frame rate make it an ideal supporting tool for multi-sensor approaches. The fusion of the two datasets saves time and operational costs in the field while preserving spatial consistency. The paper demonstrates the growing use of consumer-grade LiDAR sensors in digital heritage documentation and presents an approach that scales up support for both consumer and professional sensors.

1. Introduction

Heritage sites assume prime significance regarding historical context, cultural identity, artistic expression, social value, economic utility architecture, and society. However, the monuments are under severe threat from environmental and human causes. The preservation and recording of such valuable elements have an important role in the transmission of cultural heritage to future generations. Light Detection & Ranging (LiDAR) technology offers scientists exact information regarding 3D models of cultural heritage sites in the form of point clouds with millions of spatial data points. The 3D models that are created can be used for reconstruction, restoration, and architectural analysis. Advances in 3D documentation techniques, especially in recent years, have made this possible to help scientists, engineers, and architects acquire such models (Yakar, 2021).

LiDAR is one of the most common techniques for 3D documentation of cultural heritage sites. Terrestrial laser scanning and airborne laser scanning are the most common techniques of LiDAR. For documentation of wide areas or for documentation of archaeological sites, airborne laser scanning could be used. For documentation of architectural details, terrestrial laser scanning could be applied. For scanning architectural details, terrestrial laser scanning could also be used. Multiple views for scanning architectural details are made possible by the capability of the scanning device to scan quickly. Therefore, scanning of architectural details for documentation is done effectively. Accuracy and ability to analyze space are major advantages of laser scanning for architecture, buildings, and cultural heritage conservation. (Puri and Turkan, 2019).

Acquiring the upper parts of objects, in particular, can be difficult due to the position of the LiDAR device. Furthermore, modeling using only TLS data can lead to lacunae in data acquisition. Going back to the site to remedy these limitations is time-consuming and costly. It is therefore necessary to supplement terrestrial laser scanning data with another method. Integration of the two techniques has the potential of providing a practical solution to this challenge.

The combined use of multiple data acquisition techniques, i.e., data fusion, is rapidly acquiring relevance to counter the flaws of a single technique in capturing cultural heritage. Though TLS provides exceptionally precise and accurate geometric data, it can suffer from coverage restrictions in complex environments (Remondino 2011). Recalibration in the field to address such constraints can turn out to be costly and time-consuming (Ramos & Remondino, 2015). But to date, no research has been carried out where iPad Pro LiDAR and TLS scanning have been combined; it is a relatively new technological development.

This current research aims to investigate iPad Pro LiDAR scanning to record cultural heritage and the combination of TLS and data fusion. The objectives of the research are to evaluate the strength and weaknesses of iPad Pro LiDAR scanning in this usage and its applicability as an independent or complementary procedure in cultural heritage documentation phases. For this purpose, a historic mosque in Istanbul was captured using both TLS and iPad Pro LiDAR. The point clouds obtained using both techniques were integrated with the ICP algorithm for obtaining a complete 3D model of the monument. The ICP Algorithm is a registration algorithm between two different points clouds (Besl & McKay, 1992). Both data sets were combined with ICP. The data from the iPad Pro LiDAR was used to fill the gaps that were not thoroughly scanned or partially scanned by TLS. It is intended to provide a basis for future studies of cultural heritage.

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2. Materials and Methods

LiDAR releases laser pulses on the surface and measures the return time of the pulses, which enables the calculation of the distance of the surrounding objects from the LiDAR system in operation, thereby creating a three-dimensional copy, which is called as the "point cloud." LiDAR data can be utilized in the capture of either the terrain, an object, or the surface. The LiDAR system can be installed in ground stations, cars, unmanned aerial vehicles, and helicopters depending on its use (Dassot et al.,2011).

ALS is appropriate for mapping large terrains or archaeological surfaces. Nonetheless, TLS is suitable for cultural heritage documentation or architectural mapping. The accuracy offered by TLS when collecting data from multiple angles will be greatly advantageous for mapping detailed models. LiDAR technology is valuable for applications in the construction, architectural, or cultural heritage sectors owing to the technology's effectiveness. The method can be employed for the generation of digital twin models, the examination of relationships, dynamic changes, and decision-making processes for different projects. (Puri & Turkan, 2019; Kuçak et al., 2016).

Advancements in smartphone and LiDAR sensor developments provide opportunities for scientific applications and the implementation of 3D mapping at lower costs. Research can be performed at standard deviations of 10 cm in comparison to those obtained using handheld laser scanners, and this has been noted in the study by Gollob et al. (2021).

A LiDAR scanner, once available in consumer-level products, is now easily accessible with the LiDAR sensors available on the iPad Pro tablet and iPhone 12 Pro/Max smartphones that Apple introduced in 2020. As a major player in communications and mobile technology, Apple has made this technology accessible to consumers (Luetzenburg et al., 2021). Many professional disciplines, including forestry, earth sciences, geology, accident site investigation, documentation of cultural assets, and production of large-scale 3D rapid maps, use point clouds and 3-Dimensional (3D) models created from measurements made using such intelligent devices, which are relatively less expensive than Professional Terrestrial Laser Scanners (Çakir et al., 2021; Desai et al., 2021; Gollob. et al., 2021; Luetzenburg et al., 2021; Mokroš et al., 2021; Murtiyoso et al., 2021; Plaß et al., 2021; Spreafico et al., 2021; Vogt et al., 2021; Wang et al. et al., 2021; Bobrowski et al., 2022; McGlade et al., 2022). This kind of hardware is anticipated to grow and be used more frequently in new application areas because of its many benefits, including ease of use, speed, and accuracy (Kuçak, R. A., et al., (2023).

Data fusion is a significant step when documenting cultural heritage. For successful data fusion, all datasets must be referenced to a standard reference system to ensure spatial accuracy and consistency. One of the most used techniques for recording and combining point cloud data collected from different systems is the iterative closest point algorithm (ICP). The ICP algorithm enables accurate data recording by iteratively minimizing the distances between corresponding points in overlapping datasets. In terms of TLS data acquisition, ICP makes it possible to combine high-resolution datasets with other data types such as UAV photogrammetry or handheld LiDAR scans. Hence, the reliability of TLS and flexibility of other technologies bridge data gaps and enable an integrative description of cultural heritage sites.

Iterative Closest Point (ICP) algorithm, also known as Iterative Corresponding Point, is widely used for the mesh geometry and color-based alignment of three-dimensional models (Rusinkiewicz & Levoy, 2001). It has significant applications in cultural heritage preservation. The basis of the ICP algorithm is the Helmert transformation. ICP begins with an initial approximation of its relative rigid-body transform for two-point clouds. It iteratively refines the transform by creating pairs of related points on the point cloud data and minimizing an error metric. (Besl & McKay, 1992).

Given two-point clouds, “A” and “B”;

where, A consists of N points {a1, a2,…,aN}

and B consists of M points {b1,b2,…,bM},

the objective of the ICP algorithm is to find the Helmert transformation “T” that minimizes the root mean squared error (RMSE) between the transformed points of “A” and the closest points in “B”. The transformation “T “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.

In this paper, combining LiDAR point clouds might conclude with sufficient results in terms of documentation of the cultural heritage sites. Thus, precision of LiDAR technology and visual richness of IPAD Pro LiDAR would be increased. Combining both laser scanning through data fusion creates a robust approach to enhancing the precision and detail of spatial data. This combination enhances the overall accuracy of models, offers detailed visual and dimensional insights, and improves applications in architecture, archaeology, and environmental monitoring. Also, the objectives include for evaluating the advantages and limitations of iPad Pro LiDAR scanning in this context and for assessing its potential as a complementary or standalone method in cultural heritage documentation workflows. So, in this study, a historical mosque located in Istanbul was documented by the use of TLS and IPad Pro LiDAR. Both point cloud models were integrated to each other to have a complete 3D model of the monument. Both point clouds with ICP Algorithm were merged. The aim is to combine iPad Pro LiDAR data with TLS data to address areas that could not be captured or were partially captured by the laser scanner. This approach is intended to serve as a foundation for future cultural heritage studies. Shortly, this study evaluates the interoperability of LiDAR data obtained using an iPad Pro and a Leica P40 terrestrial laser scanner (TLS). iPad Pro data was collected solely as a LiDAR-based point cloud via SiteScape software; no photogrammetric data was used in the study. The results show that when combined with terrestrial laser scanning data, the LiDAR data generated by the iPad Pro possesses a sufficient level of accuracy for use in numerous 3D modeling studies.

3. Case Study

Molla Hüsrev Mosque is located in the Vefa neighborhood of Istanbul. This historical Ottoman Mosque is named after Molla Hüsrev, who was an important 15th-century scholar who lived the reign of Sultan Mehmed II (the Conqueror). The mosque was built in 1460. It is one of the early examples of Ottoman architecture in the city. It boasts a classic single-dome design, including a rectangular prayer hall and a straightforward yet graceful minaret. Although it is smaller than the grander imperial mosques that followed, Molla Hüsrev Mosque is architecturally and historically significant due to its connection with the scholarly elite of the early Ottoman era (see Figure 1). The mosque was originally part of a larger complex that featured a madrasa, highlighting its role as an educational hub. Today, it remains a site of worship and maintains its historical heritage (URL 1).

Figure 1. The study area.

In order to obtain an accurate and detailed representation of the Molla Hüsrev Mosque, both TLS and IPAD Pro LiDAR measurements were carried out in the study area. SiteScape was preferred for creating a 3D point cloud model of a surface with the iPad Pro LiDAR sensor. The study area was scanned with iPad Pro. Also, The Leica P40 laser scanner was used for the study area. Thus, two-point clouds were obtained using two different techniques. In order to combine the strength of both techniques, a data fusion process was also carried out 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 and 3.

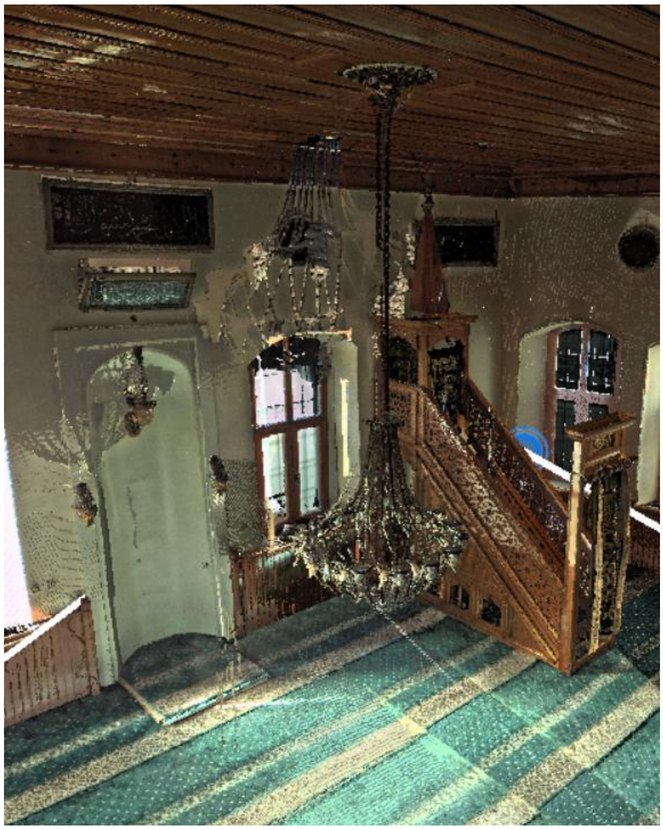

Figure 2. The indoor point cloud of Molla Hüsrev Mosque.

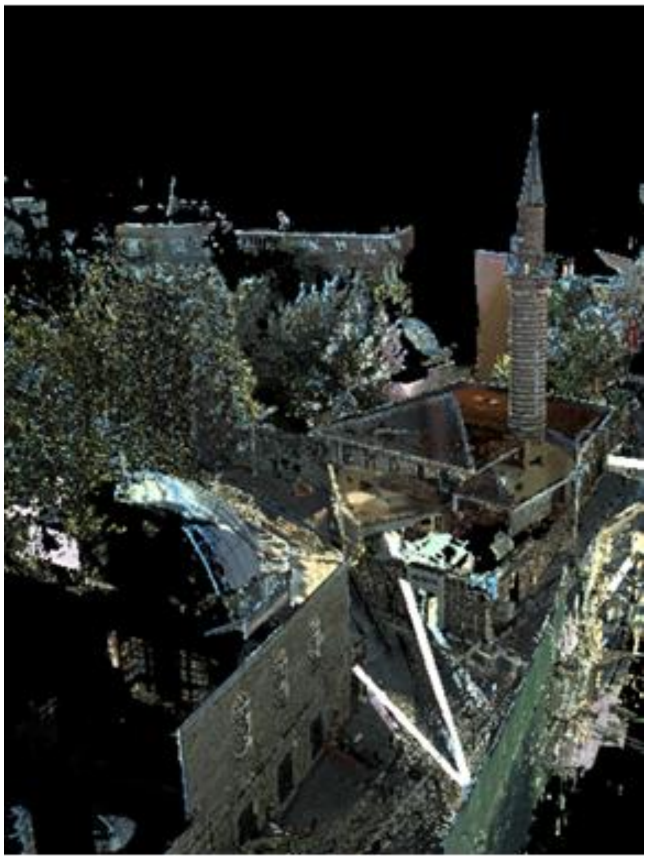

Figure 3. The outdoor point cloud of Molla Hüsrev Mosque.

The Leica P40 laser scanner (Figure 4) was used for the scanning process, and an accuracy assessment was conducted by comparing the laser data with measurements from a total station (Pentax R 1505).

Figure 4. The Leica P40 laser scanner used in this study (Kuçak, R.A., et al., 2025).

This data was collected by integrating 11 scans conducted using the Leica P40 scanner and the software used was the Cyclone Register 360 Software. No ground control point was used in scanning the Molla hüsrev Mosque. The data was registered at 0.007 m precision and without using this keypoint. This data was then registered using the ICP Algorithm along the Cloud to Cloud principle.

Scanning was done only inside in Molla Hüsrev Mosque, while around 5 scans were conducted at 6.0 mm resolution. This data was processed by taking one scan at a time for reference in each local coordinate systems. The specifications of the terrestrial laser scanner Leica P40, used in the experiment are shown in 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

The Leica P40 laser scanner was used for the scanning process, and a data fusion process was conducted for both point clouds. ICP Registration precision is 0.007 m. It is good registration result for point clouds since the accuracy of the terrestrial LiDAR point cloud is 0.029 m according to Pentax R1505 (2 + 2 ppm until 500 m) (Table 2). In a Danish study using the LiDAR sensors of the iPad Pro and iPhone 12 Pro, Luetzenburg et al. (2021) observed that absolute accuracy was approximately ±1 cm in small areas and approximately ±10 cm in larger areas (e.g., 130 × 15 × 10 m). In this study, a robust accuracy study could not be performed for the iPad Pro because the point cloud resolution was too low.

LiDAR	x (m)	y (m)	z (m)	Δ	P104	P105	P106	P109	P113	P114
P104	-23.540	1.184	3.227	P104	0.000	2.122	2.288	4.028	4.912	9.589
P105	-21.452	0.818	3.178	P105		0.000	0.836	6.140	6.763	11.668
P106	-21.502	0.718	2.337	P106			0.000	6.270	6.468	11.610
P109	-27.461	1.852	3.771	P109				0.000	3.302	5.877
P113	-27.595	1.748	0.496	P113					0.000	5.785
P114	-33.080	1.100	2.269	P114						0.000
Total Station	x (m)	y (m)	z (m)	Δ	P104	P105	P106	P109	P113	P114
P104	1012.612	1003.813	101.185	P104	0.000	2.120	2.272	4.015	4.921	9.588
P105	1014.115	1005.311	101.166	P105		0.000	0.848	6.126	6.767	11.667
P106	1014.116	1005.311	100.33	P106			0.000	6.233	6.448	11.584
P109	1009.742	1001.036	101.712	P109				0.000	3.279	5.865
P113	1009.796	1000.895	98.413	P113					0.000	5.801
P114	1004.814	998.376	99.928	P114						0.000
									vv	0.004
									RMS (m)	0.029

Table 2. Accuracy assessment

Table 2 gives a quantitative comparison between Total Station and Terrestrial Laser Scanning data using coordinate difference measures (ΔX, ΔY, ΔZ) and resultant RMS errors with respect to various common reference points. Total RMS errors for all points considered show that Terrestrial Laser Scanning features a high degree of geometric accuracy with Total Station measurements. The errors can be attributed to the nature of their measurements, as Total Station measures accurate point values unlike Terrestrial Laser Scanning measurements that involve point cloud values with some errors attributed to uncertainty in registering a best fit surface. In conclusion, as evidenced in the table, TLS provides a valid alternative to the Total Station method in high-precision surveying tasks, especially where a high level of spatial detail is needed. Though the Total Station is currently more precise in point-wise measurements, TLS provides a benefit of scanning the entire surface with only a slight difference in accuracy. These results validate using a combination of both methods in engineering surveying and deformation analysis.

Previous studies with the iPad Pro have shown location accuracy of up to 3 cm for point clouds obtained with the LiDAR sensor. For example, Kuçak et al. (2023) achieved accuracies of approximately 3 cm with the SiteScape and 3D Scanner Apps in their study using the iPad Pro LiDAR. On the other hand, Luetzenburg et al. (2021), using the LiDAR sensors of the iPad Pro and iPhone 12 Pro in a study in Denmark, observed absolute accuracy of approximately ±1 cm in small areas and approximately ±10 cm in larger areas (e.g., 130 × 15 × 10 m). In this study, a reliable accuracy study could not be conducted due to the very low point cloud resolution of the iPad Pro. However, both point clouds were co-registered using the Iterative Closest Point (ICP) algorithm, achieving a registration precision of 0.007 m with Cyclone Register 360 PLUS (Figure 5).

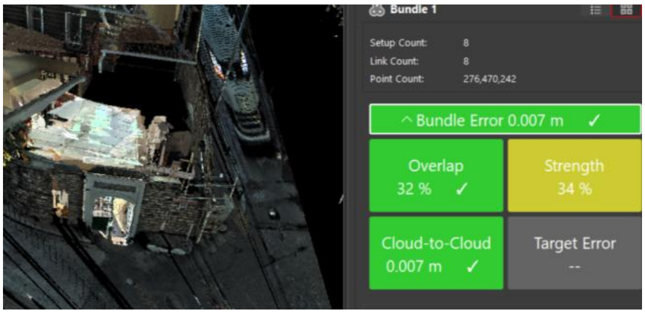

Figure 5. The registered point cloud data (TLS&Ipad Pro LiDAR) with Cyclone Register 360 PLUS.

After registering with Cyclone using Register 360 Plus, the same registration process was tested with CloudCompare Software. The results were compared. For this comparison, the cloud-to-cloud distance was calculated, and the Root Mean Square Error (RMSE) values were examined. The RMSE obtained by combining two scans in the Cyclone Register 360 program is 0.03 m according to Cloud to Cloud distance (Therotical overlap %7 for two point clouds). However, the RMSE value after combining all scans is 0.007 m. (Figure 6).

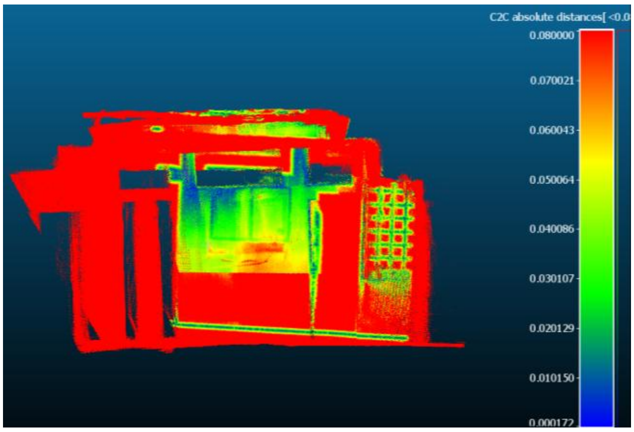

Figure 6. The registered point cloud data RMSE values.

After registration with CloudCompare Software, the results obtained showed better RMSE values compared to the Cyclone Register 360 Plus Software. However, this difference is the direct RMSE value (0.025 m) obtained in the RMS ICP algorithm (Figure 7).

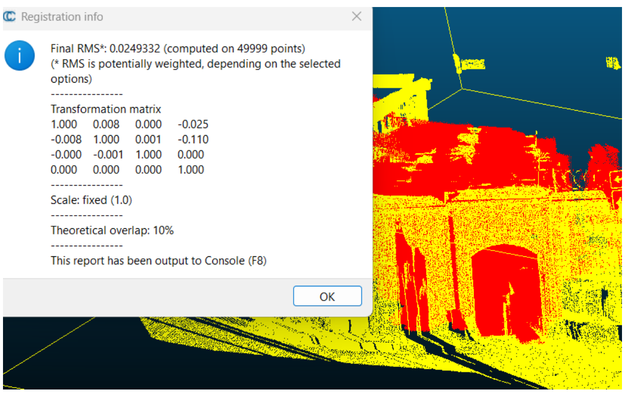

Figure 7. CloudCompare Software ICP Algorithm RMSE value.

The registraiton dataset provided a more complete representation of the mosque, especially in areas that were partially occluded or difficult to capture with TLS alone, such as complex and upper architectural elements. Figures 8 (a-c) demonstrate the comparative visual density of TLS and iPad Pro data, as well as the improved completeness after fine registration. The results confirm that while TLS remains superior in terms of accuracy and resolution, the iPad Pro LiDAR significantly enhances overall coverage and reduces data gaps when integrated within a fusion workflow.

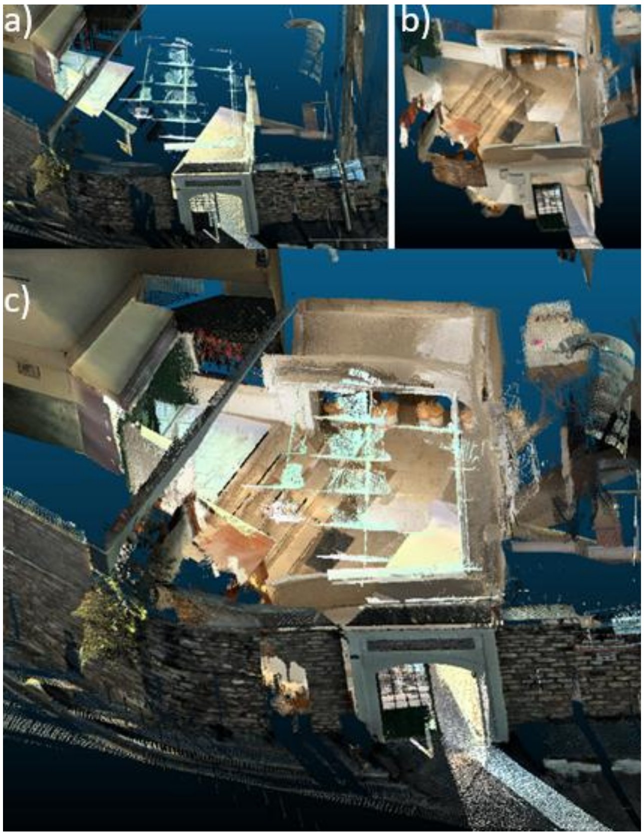

Figure 8. a) Terrestrial Laser Scanning Data b) IPad Pro Lidar Sensor Data c) The registered point cloud data (TLS&Ipad Pro LiDAR).

After registration with Cloud Compare Software, the RMSE value obtained in the results is the direct RMSE value obtained in the ICP Algorithm. If the RMSE is calculated by considering the cloud-to-cloud distance for comparison, the RMSE value obtained with the cloud-to-cloud distance algorithm in Cloud Compare is 0.04 m (Figure 9).

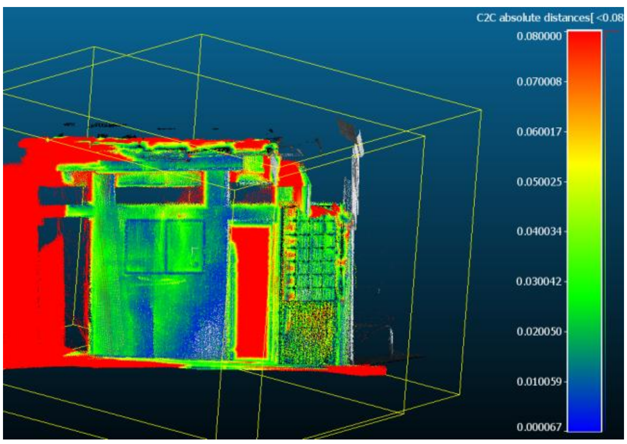

Figure 9. CloudCompare Software ICP Algorithm RMSE value.

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When all the above processes are evaluated, the value obtained with the cloud-to-cloud distance algorithm using Cloud Compare is 0.04 m. The RMSE obtained by combining two scans in the Cyclone Register 360 program is 0.03 m. However, while the RMSE value after combining all scans is 0.007 m, the RMSE value of the CloudCompare ICP program is 0.025 m. Based on these values, the Cyclone Register 360 program yielded better results in terms of precision and speed than the CloudCompare program. Furthermore, when the two programs are evaluated in terms of merging, they managed to reduce the coarse registration value from 0.08 m to 0.03 m and 0.04 m, respectively. These two results represent a study with sufficient accuracy for many orthophoto and 3D modelling studies.

During the registration process, the Cloud-to-Cloud (C2C) distance algorithm applied in CloudCompare software determined that the average difference between the two datasets was 0.04 m. Combining the two scans performed using Cyclone Register 360 software resulted in an RMSE value of 0.03 m. After combining all scans, the total RMSE value obtained with Cyclone Register 360 decreased to 0.007 m, while the RMSE value calculated with the CloudCompare ICP algorithm was found to be 0.025 m. These results demonstrate that Cyclone Register 360 software is more successful than CloudCompare in terms of both accuracy and processing speed. Furthermore, both software programs were able to reduce the coarse merging error from approximately 0.08 m to 0.03–0.04 m, and these accuracy levels are considered sufficient for many 3D modelling and orthophoto production studies. Furthermore, with the right algorithms and software, it is possible to reduce these values to more precise levels. As a result of this study, it can be confidently concluded that iPad Pro Lidar data can be used as a complementary point cloud for complex surfaces in conjunction with terrestrial laser scanners.

4. Conclusion

In this study, a historic mosque located in the Vefa District of Istanbul was scanned with terrestrial laser scanning (TLS) and an iPad Pro LiDAR sensor. Two-point clouds were collected during the process and combined using data fusion to generate an accurate and high-resolution model of the building.

The results demonstrate that the coupling of consumer-grade LiDAR sensors, such as the iPad Pro, with professional TLS systems holds enormous potential in the areas of efficiency and comprehensiveness of the documentation of cultural heritage. While TLS offers the accuracy and geometric precision required for scientific research and restoration, it has certain limitations such as the limitation of scan positions, hidden (obscured) areas, and the requirement of multiple visits to document hidden areas. Despite its lower point density and sensitivity, the iPad Pro LiDAR assisted TLS data in recording hard-to-access or missing surfaces with speed and efficiency.

This study evaluates the interoperability of LiDAR data obtained using an iPad Pro and a Leica P40 terrestrial laser scanner (TLS). iPad Pro data was collected solely as a LiDAR-based point cloud via SiteScape software; no photogrammetric data was used in the study. The results show that when combined with terrestrial laser scanning data, the LiDAR data generated by the iPad Pro possesses a sufficient level of accuracy for use in numerous 3D modeling and orthophoto generation studies. In this context, the iPad Pro's rapid data acquisition and practical usability advantages demonstrate its significant potential as a complementary tool to TLS data.

Point cloud technology for 3D documentation of cultural heritage sites is highly beneficial for conservation and analysis. However, with the development of low-cost technology such as the iPad Pro LiDAR scanner, its applications in cultural heritage environment documentation and conservation will become even more prominent in the future. Nonetheless, some gaps that must be addressed to realize the full potential of point cloud technology include handling large-scale data, ensuring measurement accuracy across different settings, and preserving data generated by point cloud technology.

In summary, the iPad Pro is not yet ready to replace the TLS in high-precision documentation. Still, it can be considered an auxiliary tool for combined workflows. The combination of both data sets not only enhances the integrity but also saves time and costs, which is highly promising for future documentation workflows in the field of cultural heritage. In summary, the accuracy comes at the price of increased operational difficulties. However, in terms of mobility, time, and user-friendliness, the iPad Pro's LiDAR scanner has the edge. In the future, this promotes the iPad Pro being used in combination, depending on the required geometrical accuracy.

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