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Comparative Accuracy Analysis of Lidar Systems

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MLS
TLS
Point Cloud
Accuracy

ABSTRACT

The use of high-precision and sufficiently collected point clouds for 3D data modeling is very important for geomatics and other branches of engineering (such as mechanical and construction), and architectural applications. For this reason, various filtering and interpolation methods are improved for 3D modeling. However, if the point cloud is collected inaccurate or missing, the 3D data modeling is always an issue. Therefore, before the 3D modeling process, the point positioning accuracy and resolution of the point cloud should be investigated. For this purpose, accuracy assessment can be performed by comparing with data obtained from a measurement system that is considered to be more accurate. This comparison is used for the accuracy assessment of the maps produced by different Lidar (Light Detection and Ranging) point clouds. In this study, the accuracy of the point clouds obtained using Terrestrial Lidar Systems (TLS) and Mobile Lidar Systems (MLS) were determined. The reference measurements were obtained by Total Station (TS) surveys. Yılmaz Akdoruk Student Dormitory located in Ayazaga Campus of Istanbul Technical University was selected as a test-area in order to evaluate the TLS and MLS performance for applications in urban areas. The results showed that the accuracy of the TLS system was better than the MLS system. In addition, while TLS should be preferred in studies requiring high accuracy, such as 3D cultural heritage documentation, MLS may be preferred in applications such as various topographic maps and 3D city models.

Lidar Sistemlerinin Karşılaştırmalı Doğruluk Analizi

Anahtar Kelimeler
Lidar
MLS
YLS
Nokta Bulutu
Doğruluk

ÖZ

3B veri modellemesi için yüksek hassasiyetli ve yeterli miktardaki nokta bulutlarının kullanılması, Geomatik ve diğer mühendislik dalları (makine ve inşaat gibi) ve mimari uygulamalar için çok önemlidir. Bu nedenle, 3B modelleme için çeşitli filtreleme ve enterpolasyon yöntemleri geliştirilmiştir. Bunun yanında, nokta bulutunun yanlış veya eksik elde edilmesi, 3B veri modelleme için her zaman bir sorundur. Bu amaçla, 3 boyutlu modelleme işlemine geçilmeden önce nokta bulutunun çözünürlüğü ve nokta konumlandırma doğruluğu araştırılmalıdır. Bu amaçla, doğruluk değerlendirmesi, daha doğru olduğu düşünülen bir ölçüm sisteminden elde edilen veriler ile karşılaştırılma yapılarak gerçekleştirilebilir. Bu şekilde bir karşılaştırma, farklı Lidar (Light Detection and Ranging) nokta bulutlarından üretilen ölçülerin doğruluk değerlendirmesinde kullanılır. Bu çalışmada, Yersel Lidar Sistemleri (YLS) ve Mobil Lidar Sistemleri (MLS) kullanılarak elde edilen nokta bulutlarının doğruluğu belirlenmiştir. Referans ölçümler Total Station (TS) ile elde edilmiştir. İstanbul Teknik Üniversitesi Ayazağa Yerleşkesinde bulunan Yılmaz Akdoruk Öğrenci Yurdu, kentsel alanlardaki 3D model uygulamalarında YLS ve MLS performansını değerlendirmek amacıyla test alanı olarak seçilmiştir. Sonuçlar, TLS sisteminin doğruluğunun MLS sisteminden daha iyi olduğunu göstermiştir. Buna bağlı olarak 3 boyutlu kültürel miras dokümantasyonu gibi yüksek doğruluk gerektiren çalışmalarda YLS tercih edilirken, çeşitli topoğrafik haritalar ve 3 boyutlu şehir modelleri gibi uygulamalarda MLS tercih edilebilir.

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1. INTRODUCTION

LIDAR (Light Detection and Ranging) is a measurement technique that allows the collection of large amounts of 3D data in a short time, from airborne, or terrestrial. LIDAR systems creates a point cloud with density values in the 3D coordinate system and also RGB values of the point cloud are usually provided by internal or external digital cameras of the system (Kuçak et al., 2016; Kuçak et al., 2017).

MLS and TLS systems are widely used in 3D modeling studies thanks to their fast and accurate point cloud generation (Kuçak et al., 2020). MLS can obtain accurate 3D data faster over a wider area according to TLS (Rodríguez-Gonzálvez et al., 2017). However, TLS has more accurate point positioning capability compared to Airborne Lidar System (ALS) and MLS Systems (Fowler & Kadatskiy, 2011). For both methods, it is necessary to provide suitable conditions to obtain accurate 3D data in large areas. For example, the scanning strips must be registered correctly in TLS. In MLS, the forward and backward measurements must be carried out under the appropriate GNSS conditions for the accurate registration. Shortly, it is very important to obtain high accuracy and sufficient point cloud data in 3D modeling. If the accuracy and resolution of the point clouds are sufficient for the desired purposes, the registration or modeling stages of the point clouds can be performed. However, if the accuracy and resolution of the current point cloud are not sufficient, it should be registered with a more accurate point cloud using georeferencing or registration methods.

Mobile LIDAR systems (MLSs) are the integrated systems which are mounted on a moving vehicle such as cars, trains, boats etc. (Toschi et al., 2015). MLS is a widely used method to get rapid and detailed point cloud acquisition in various applications such as cultural heritage, GIS (Geography Information System), geodetic applications, and spatial decision support systems (Rusu, Marton et al., 2008) or 3D city modeling (Chen et al., 2018) and also rail and road deformation analysis systems (Wang et al., 2019). MLS consists of laser scanners, cameras, as well as IMU (Inertial Measurement Unit) and GNSS (Global Navigation Satellite System) systems. All of these systems work together to generate the point cloud in three-dimensional (3D) coordinate system. In this system, the reflected laser measurement from the surrounding objects are continually obtained by LiDAR while the vehicle is moving. At the same time, The GNSS and IMU systems determine the absolute position of the laser measurement for geo-referencing (Jing, et al., 2020).

The LIDAR systems having multiple laser scanners may suffer from noise and other error sources such as inertial drift, rigid platform calibration, GNSS errors, etc. The measurements with multiple scanners in Mobile Mapping Systems (MMS) require calibration in order to overcome the disadvantages by high noise rates and errors as well as the overlapping problem in strips. After the calibration steps, CCD Cameras and Laser scanners can become ready to use. However, the calibration may not be sufficient to eliminate all errors and provides an inappropriate point clouds for 3D modelling. In such situations, the registration of the multiple scans are necessary to minimize the discrepancies in LIDAR point clouds (Rieger et al., 2010). In proper GNSS measurement conditions, the accuracy of the MLS trajectory could be realized in cm-level (Haala et al., 2008a). On the contrary, in difficult conditions, the error increases to decimeters-level (Haala et al., 2008b). In such situations, the accuracy of point cloud can be increased with georeferencing or registration methods during the post processing stage.

TLS is a powerful technology for collecting 3D data spread over a large area in a very short time. (Kuçak et al., 2014). TLSs consist of lasers, precisely calibrated receivers, precision timing, high-speed micro-controlled motors, and precise mirrors (Fowler & Kadatskiy, 2011). The basic information obtained from each scan is the virtual point cloud formed by all of the 3D points of the surfaces measured in harmony with each other (Scaioni, 2005). The precision and accuracy of TLS make the TLS system a powerful technology for creating 3D dense point cloud according to the conventional measuring methods (Çelik et al., 2020). However, the registration of TLS scans must be done carefully because the registration errors affect the 3D model quality.

In this study, the accuracy of the point clouds, which were obtained by using the TLS and MLS were investigated. However, the error sources mentioned above which are GNSS and the calibration errors for mobile LIDAR systems and the registration errors for terrestrial Lidar systems are common problems (Kuçak et al., 2020). So, the accuracy comparison of the LIDAR systems carried out relatively using the distance differences of the points selected from point clouds to eliminate the error sources in the comparison. For the purpose of the study, (Istanbul Technical University) Yılmaz Akdoruk Student Dormitory was selected as test area. The dormitory is located in Ayazaga Campus of ITU in Turkey. (Figure 1). The facade of selected building has permanent and prominent points that can be easily measured repeatedly such as building corner points and window corner points. These type of points on the facade are used as test points in order to compare TLS, MLS and Total Station (TS) Surveys.

Figure 1. Yılmaz Akdoruk Student Dormitory

1. DATA and METHOD

The study area scanned with Leica C10 TLS, which can get 50,000 points per second with 6 mm accuracy until 50 m and uses impulse method for distance measurement. Also, the point spacing of scan resolution is 1 mm until 50 m. 3D point cloud of the building scanned with Leica C10 was processed with Cyclone Software by Leica Geosystems (Figure 2).

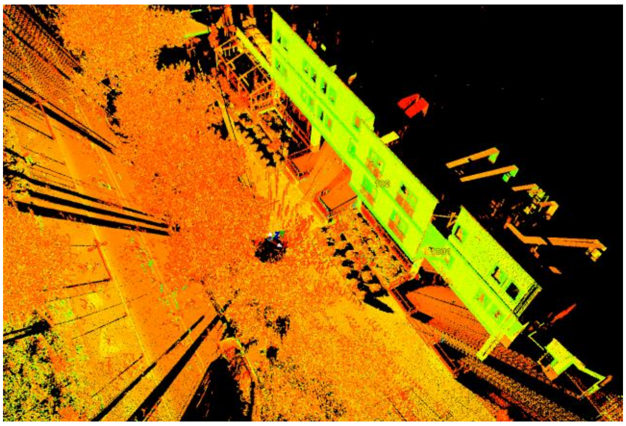

Figure 2. Point Cloud with Leica C10 Scanning

Mobile Mapping data was obtained by using the Riegl VMX 450 LIDAR System, which can get 1,000,000 points per second with 8 mm accuracy and use impulse method for distance measurement. (Figure 3).

Figure 3. ITU Ayazaga Campus Scanning by Riegl VMX 450 MLS

1.1. Error Propagation

The error propagation was applied for the test points from the surface to determine the point positioning accuracy of the instruments. The test points of the surface also positioned with "Pentax W1503" total station for the accuracy assessment of the TLS and MLS point clouds. The reflectorless distance measurement accuracy of the total station is "3 mm + 2 ppm" and the angle measurement accuracy is 3″. The Leica C10 TLS distance measurement accuracy is 4 mm, angle measurement accuracy is 12″ and the positional accuracy is 6 mm. The Riegl VMX 450 MMS system (Figure 4) includes VQ-450 laser sensors (2-laser scanners) and the laser sensors' accuracy is 8 mm. Table 1 also gives the technical specifications of the sensor' in VMX 450 (Toschi et al., 2015).

Figure 4. Riegl VMX-450 MMS System

Table 1. Technical characteristics of the RIEGL VMX-450 MMS (Toschi et al., 2015).

Sensor	**VQ-450**
Measuring principle	Time of Flight
Laser measurement rate	300-1100 kHz
Maximum range	140-800 m
Minimum range	1.5 m
Laser wavelength	Near infrared
Accuracy	8mm, 1σ
Precision	5mm, 1σ
Sensor	**IMU/GNSS**
Absolute position	0.020-0.050 m
Roll and pitch	0.005°
True heading	0.015°
Sensor	**VMX-450-CS6**
Resolution	5 Mpx
Sensor size	2452 * 2056 px
Pixel size	3.45 μm
Nominal focal length	5 mm

According to given measurement accuracies, the error propagation was applied to following equations.

$$X_B = X_A + (S_s\ Cos\alpha_a)\ Cost_a \tag{1}$$

$$Y_B = Y_A + (S_s\ Cos\alpha_a)\ Sint_a \tag{2}$$

$$Z_B = Z_A + (S_s\ Sin\alpha_a) + i_a \tag{3}$$

In the Equations 1-3, X_A, Y_A, Z_A are the 3D coordinate components of the local coordinate system at the standing point, X_B, Y_B, Z_B are the 3D coordinate components of the measured point, "t_a" is horizontal angle, "α_a" is the vertical slope angle, "i_a" is instrument height, "S_s" is slope distance. The accuracy $(m_{X_B}, m_{Y_B}, m_{Z_B})$ of the measured point coordinate components (X_B, Y_B, Z_B) could be calculated as;

$$m_{X_B}^2 = m_{X_A}^2 + \left(Cost_a^2 . Cos\alpha_a^2\right) m_s^2 + (S^2.Cos\alpha_a^2.Sint_a^2)\ \frac{m_t^2}{\rho^2} + (S^2.Cost_a^2.Sin\alpha_a^2 *)\ \frac{m_\alpha^2}{\rho^2} \quad (4)$$

$$m_{Y_B}^2 = m_{Y_A}^2 + (Cos\alpha_a^2.Sint_a^2)m_s^2 + (S^2.Cost_a^2.Cos\alpha_a^2)\ \frac{m_t^2}{\rho^2} + \ (S^2.Sint_a^2.Sin\alpha_a^2)\frac{m_\alpha^2}{\rho^2} \quad (5)$$

$$m_{Z_B}^2 = m_{Z_A}^2 + (Sin\alpha_a^2)m_s^2 + (S^2.Cos\alpha_a^2)\ \frac{m_\alpha^2}{\rho^2} \quad (6)$$

In the Equations 4-6, m_t is the angle measurement accuracy, m_s is the distance measurement accuracy of the instrument, and $\rho = 200/\pi$.

According to error–propagation, the point position accuracy was calculated between 4.02 – 4.21 mm for the TS, and was calculated between 5.56-5.67 mm for the TLS.

2. RESULTS

In the building facade, the most prominent and corner points were selected as test points. The coordinates of the test points obtained from the Total station measurements are accepted as reference coordinates and the Euclidean distance between the surface test points were calculated. Then, the distances between the test points derived from TLS and MLS point clouds compared with the reference distance calculated from the total-station. The position of the selected test points is given in Figure 5.

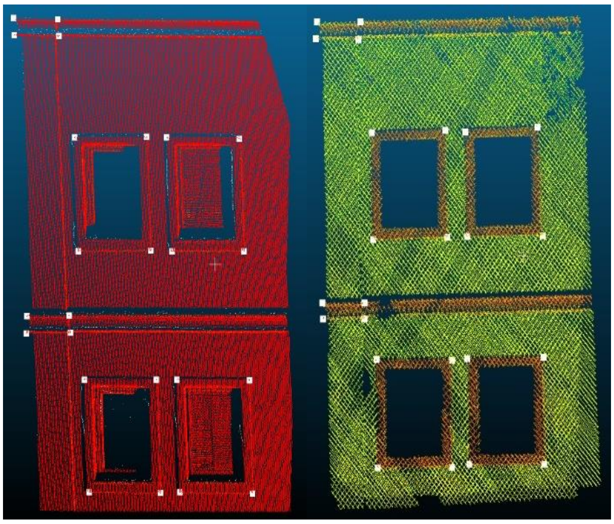

Figure 5. Key points TLS (Left), MLS (Right)

The distance differences between the TLS and MLS key points distances and total station test points distances are given in Table 2.

Table 2. The distance differences between TLS, MLS key points' distances and TS test point distances (cm)

TLS-TS	0	1	2	3	7	8	10	11	16
1	-2.1	-							
2	-0.9	1.1	-						
3	-2.0	0.0	-1.6	-					
7	-2.3	-0.4	2.0	-1.0	-				
8	-4.2	-2.0	3.9	1.7	-0.3	-			
10	-2.7	-0.5	4.1	1.0	-2.0	1.3	-		
11	-2.3	-0.1	4.0	0.6	-1.1	1.8	-0.3	-	
16	-1.9	0.2	2.3	1.1	-1.5	2.0	0.7	-0.2	-
18	-1.8	0.4	3.0	0.5	-0.3	2.4	0.6	0.7	-1.0
MLS-TS	**0**	**1**	**2**	**3**	**7**	**8**	**10**	**11**	**16**
1	0.8	-							
2	8.6	8.0	-						
3	4.9	4.2	-4.2	-					
7	3.8	6.4	6.4	0.2	-				
8	1.0	2.1	6.9	1.9	3.2	-			
10	4.8	5.1	4.0	-2.0	2.5	3.3	-		
11	2.7	4.4	7.8	2.0	-2.8	2.5	3.7	-	
16	8.3	8.3	2.9	1.9	3.5	6.2	3.0	5.7	-
18	8.8	9.7	4.4	0.8	4.7	7.7	4.6	7.5	-0.2

The mean error value and standard deviation of Euclidean distances differences between the points were calculated. According to statistics of data groups, TLS mean error is 0.1 cm, Standard Deviation is 1.9 cm, on the other hand; MLS mean error is 4.0 cm, and Standard Deviation is 3.2 cm. (Haala et al., 2008a) mentioned that with the obtained cm-level positional accuracy, MMS could be used for some applications include mapping purposes.

Descriptive statistics can be also used to determine the normality of two data set given in Table 2. Skewness and Kurtosis can indicate the normality of a data set. Skewness refers to asymmetry of probability distribution around the mean value of data set (Toschi et al., 2015). The Kurtosis refers to how the data set is peaked or flat relative to normal distribution (Toschi et al., 2015).

If the data set has normal distribution, mean value and standard deviation can represent the main characteristic of data set. In this study, IBM SPSS Statistics 26 software was used to obtain skewness and kurtosis value for the data sets (Table 3). In the IBM SPSS Statistics Software Manuel (IBM, 2020) , it is stated that If the Skewness and Kurtosis values are zero, distribution of the dataset is perfectly normal (Wright & Herrington, 2011). IBM SPSS software was used to determine skewness and kurtosis values of the data sets (Bliss, 1967).

Table 3. Skewness and Kurtosis outputs of IBM SPSS Statistics Software for the data sets

TLS – TS Statistics	
Number of Valid Data	45
Number of Missing Data	0
Skewness	0.255
Std. Error of Skewness	0.354
Kurtosis	-0.221
Std. Error of Kurtosis	0.695
MLS –TS Statistics	
Number of Valid Data	45
Number of Missing Data	0
Skewness	-0.388
Std. Error of Skewness	0.354
Kurtosis	0.067
Std. Error of Kurtosis	0.695

Based on the results on Table 3, Skewness and kurtosis values are so close to the zero. Therefore, these results indicate the normality of the datasets.

Also, the Q-Q plot can be used to see how data set distributed relative to the normal distribution. (Toschi et al., 2015). If distribution of data set follows the Gaussian function, the Q-Q plot should be a diagonal straight line. The IBM SPSS Statistics software was used to produce Q-Q plot for the data sets (Figure 6a & 6b).

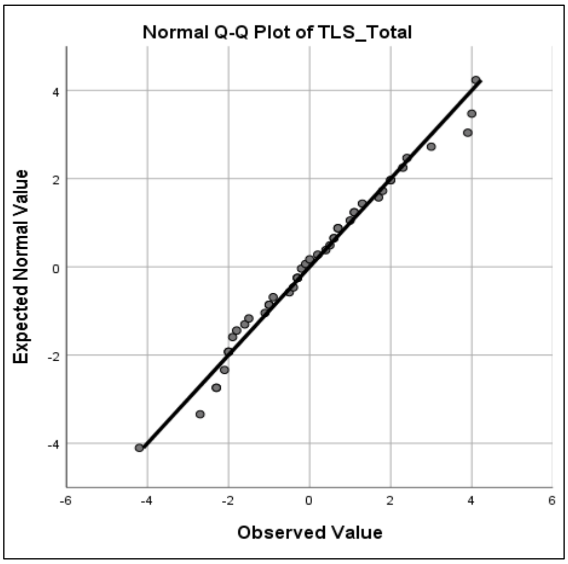

Figure 6a. Normal Q-Q plot of TLS- Total Station Differences Data

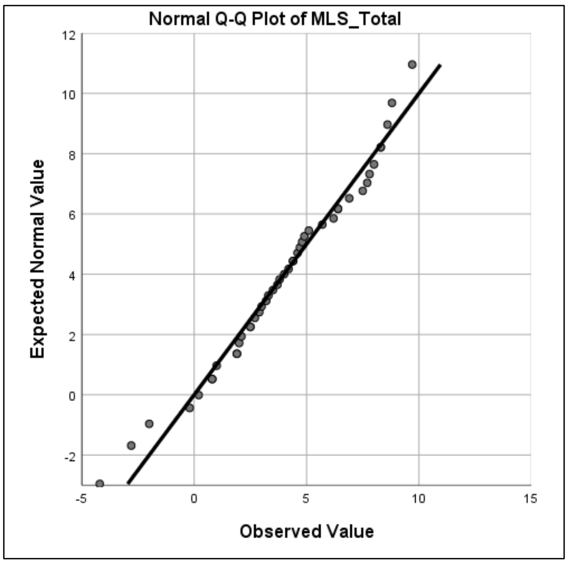

Figure 6b. Normal Q-Q plot of MLS- Total Station Differences Data

According to Figure 6, it can be stated that, the data set points are distributed around the diagonal straight line. Skewness and Kurtosis value for the data sets indicate that distribution of each data set can be accepted as normal distribution. Thus, characteristics of the data sets such as mean value and standard deviation can be used to analyze the data groups (Figure 6a & 6b).

Although the number of samples in the data sets was insufficient, the Kolmogorov-Smirnov tests and Shapiro-Wilks tests were also used in addition to Skewness, Kurtosis tests and Q-Q plots to determine the normality of the data sets. According to the given SPSS test outputs in Table 4, the Sig. values (or P values) of both normality tests are greater than the 0.05 value. Therefore, it is accepted that the data sets were not significantly different from the normal distribution. Therefore, the results of both Kolmogorov-Smirnov and Shapiro-Wilks tests showed that both data groups have normal distribution properties. However, these applied tests are not trustworthy for small size data groups. In this study, skewness and kurtosis values were used to support statistical test results.

Table 4. Normality tests for the data sets using SPSS software

Tests of Normality for TLS-TS					
Kolmogorov-Smirnov			Shapiro-Wilk		
Statistic	df	Sig.	Statistic	df	Sig.
0.062	45	0.200	0.979	45	0.577
Tests of Normality for MLS-TS					
Kolmogorov-Smirnov			Shapiro-Wilk		
Statistic	df	Sig.	Statistic	df	Sig.
0.075	45	0.200	0.976	45	0.456

In Figures 7a and 7b, the distributions of 45 Euclidean distances differences were shown for TLS and MLS data groups, respectively. Both data groups show the normal distribution curve. According to the differences between TS and TLS, the mean value was 0.1 cm, and the maximum difference was 4.2 cm. On the other hand; MLS had 4.0 cm mean, and the maximum difference was 9.7 cm. It can be stated that obtained results in our study are similar to the results of other related studies in the literature. (Haala, Peter, Kremer, & Hunter, 2008b) investigated the quality of a building facades of an existing 3D city model of the city of Stuttgart. They proved that an accuracy better than 3 cm (standard deviation of the differences between measured and reference data) can be achieved by the system in robust GNSS conditions. Similarly, the same accuracies have been obtained in many studies in the literature.

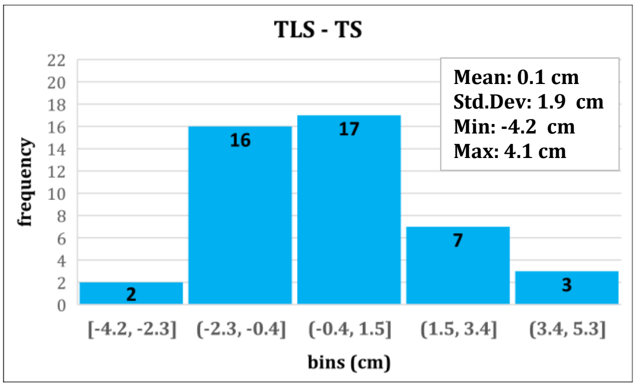

Figure 7a. The distribution of distance differences between TLS and Total station.

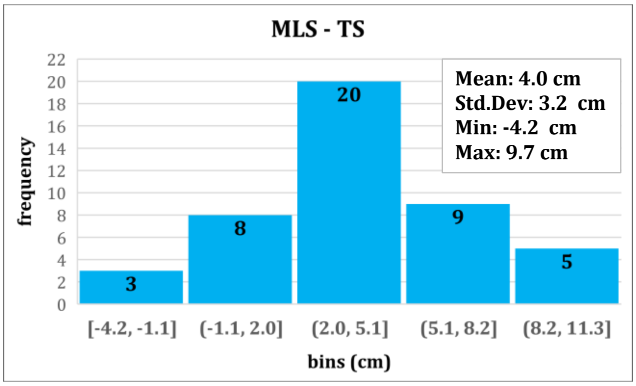

Figure 7b. The distribution of distance differences between MLS and Total station.

In this study, Total station data is accepted as the most accurate measurement system and the Euclidean distances between the surface points were calculated for the TLS and MLS point cloud validation. The accuracy $(m_{X_B}, m_{Y_B}, m_{Z_B})$ of the measured points was calculated to determine the point position accuracy as free of point cloud resolution errors. The primary reason for using the Euclidean distance between surface points is to compare the accuracy of the two systems, neglecting GNSS and calibration errors. The results show that the accuracy of the TLS system is much better than the MLS system as expected.

3. DISCUSSION

The distance differences between reference distances calculated by Total Station and the distances calculated from the TLS and MLS point clouds were obtained primarily, and then the statistics calculated. According to the calculated standard deviations of the distance differences, the accuracy of the point clouds was obtained as 1.9 cm for TLS and 3.2 cm for MLS. Also, mean values between the distance differences were obtained as 0.1 cm and 4.0 cm, respectively. The mean values show the bias (systematic error) between these systems according to Total Station measurements. The histograms show that the accuracy of TLS and TS are close to each other. However, the accuracy of the MLS is low due to the un-eliminated errors such as GNSS errors (multipath, cycle-slips, etc.), in the moving system.

The experiments performed in this study show that each of these methods has both advantages and disadvantages and one unique technique cannot recommendable for the documentation of historical artifacts (Kuçak et al., 2014). Both MLS-Total station and TLS-Total station differences show the normal distribution. According to results, TLS gave more accurate results than MLS because TLS scans were used directly without registration for accuracy assessment.

This study shows that each of these systems has both advantages and disadvantages. MLS (Mobile LiDAR System) is a product of the latest technology towards the fast acquisition of 3D spatial data. However, the lack of calibration in these systems leads to undesirable results. The errors mentioned above text, GNSS and calibration errors, are common problems in Mobile LIDAR Systems. Because of that, the point cloud coordinates are not compared directly in this study.

The results show that that the accuracy of the TLS is much better than the MLS. TLS can be preferred for studies that require high accuracy such as cultural heritage, Building Information Management (BIM) projects. However, MLS should be preferred in applications such as production of various topographic maps and creating 3D city models rather than 3D cultural heritage documentation. The obtained results are similar to other studies done with Riegl mobile LIDAR systems.

4. CONCLUSION

TLS and MLS Technology is a rapidly developing technology today. The experiments performed in this study show that each of these methods has both advantages and disadvantages. The ease of use in the field and the ability to measure millions of points in a very short time provide great convenience to the user. The advantages of the LIDAR systems are seen when compared with other 3D documentation methods in terms of time. Under proper GNSS conditions and with good calibration values, 3D models and topographic maps can be produced by MLS in a very short time and with the desired accuracy. The results obtained in this study show that LIDAR systems comply with the regulation (Regulation on Production of Large Scale Maps and Map Information, 2018) for 3D topographic map production.

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