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3D Dense Reconstruction of Road Surface from UAV Images and Comparison of SfM Based Software Performance

İHA Görüntülerinden Yol Yüzeyinin 3B Yoğun Rekonstrüksiyonu ve SfM Tabanlı Yazılımların Performansının Karşılaştırılması

Mustafa Zeybek[1]*, Serkan Biçici[2]

[1]Selcuk University, Guneysinir Vocational High School, Architecture and Urban Planning, 42490, Konya, Turkey.
[2]Artvin Çoruh University, Faculty of Engineering, Department of Geomatics Engineering, 08100, Artvin, Turkey.

ORIGINAL PAPER

***Corresponding author:**
Mustafa Zeybek
mzeybek@selcuk.edu.tr

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Abstract

Unmanned Aerial Vehicle (UAV) technology is one of the fastest-growing technologies especially used in image processing. Structure-from-Motion (SfM) based software are usually used to convert two-dimensional UAV-based images into three-dimensional (3D) data. Then, objects such as buildings, trees, and roads can be classified from the 3D data for further analysis. In this study, the road surface generated from 3D data was evaluated. There are several factors that affect the accuracy of the 3D data. In this study, two factors, namely UAV flight altitude and SfM based software, were evaluated. Two different flight altitudes, which were 35 meters and 50 meters, were used. It was found that the lower flights with closer altitudes did not make a significant difference on the results and produced similar results. Another factor is different SfM based software. Two well-known SfM based software were used in this study, which were the Agisoft Metashape and Pix4D Mapper. In this case study, it was found that the Agisoft Metashape software produced more accurate and faster results than Pix4D Mapper software.

Keywords: *UAV, 3D, Road surface, SfM, Software*

Özet

İnsansız Hava Aracı (İHA) teknolojisi, özellikle görüntü işlemede kullanılan en hızlı büyüyen teknolojilerden biridir. Yapıdan Hareket (SfM) tabanlı yazılımlar genellikle iki boyutlu İHA tabanlı görüntülerin üç boyutlu (3B) verilere dönüştürülmesinde kullanılır. Daha sonra binalar, ağaçlar ve yollar gibi nesneler daha fazla analiz için 3B verilerden sınıflandırılabilir. Bu çalışmada, 3 boyutlu verilerden yol yüzeyi değerlendirilmiştir. 3B verilerin doğruluğunu etkileyen birkaç faktör vardır. Bu çalışmada, İHA uçuş yüksekliği ve SfM tabanlı yazılım olmak üzere iki faktör değerlendirilmiştir. 35 metre ve 50 metre olmak üzere iki farklı uçuş irtifası kullanıldı. Alçak ve birbirine yakın uçuş irtifalarının sonuçlar üzerinde önemli bir fark yaratmadığı ve yakın sonuçlar ürettiği tespit edilmiştir. Diğer bir faktör ise farklı SfM tabanlı yazılımlardır. Bu çalışmada Agisoft Metashape ve Pix4D Mapper olmak üzere iki iyi bilinen SfM tabanlı yazılım kullanılmıştır. Bu çalışmada, Agisoft Metashape yazılımının Pix4D Mapper yazılımına göre daha doğru ve hızlı sonuçlar ürettiği tespit edilmiştir.

Anahtar Kelimeler: *İHA, 3B, Yol yüzeyi, SfM, Yazılım*

1. Introduction

The mapping of road surface and its surroundings is important for various applications ranging from road safety and planning to road comfort (Biçici and Zeybek, 2021; Zeybek and Şanlıoğlu, 2019). Therefore, several methods and technologies have been introduced to obtain road surface and its environment. One common way is to extract road surfaces from three-dimensional (3D) data (Biçici and Zeybek, 2021; Jiménez-Jiménez et al. 2021; Zeybek and Şanlıoğlu, 2019).

There are several technologies to collect 3D data. For example, the mobile LiDAR scanning (MLS) system is one of them. In the MLS surveying technique, a laser scanner is usually mounted on the vehicle. The vehicle travels along the road and obtains 3D data of the road surface and its surroundings by sending and receiving a signal.
In this way, MLS systems provide a highly dense 3D point cloud with fast and high precision, providing accurate 3D data. Several studies from different fields have proven its effectiveness and accuracy in 3D mapping applications along with corridors (Guan et al. 2016; Tepeköylü, 2016). However, LiDAR technology is expensive. In addition, obstacles in front of the laser, such as the trees and vehicles, might cause a gap in the 3D data.

The development of smaller and lower cost sensors such as sensors on unmanned aerial vehicle (UAV) is also seen as the potential of these surveying tools to develop 3D data with high resolution and accuracy. Therefore, UAV is one of the fastest-growing technologies used in many disciplines (Biçici and Zeybek, 2021; Zeybek and Biçici, 2021). In this method, images taken from UAV flights are converted into 3D data using Structure-from-Motion (SfM) based software. However, there are several factors that affect the accuracy of the 3D data. In this study, two factors, namely UAV flight altitude and SfM based software, were evaluated.

The remainder of this manuscript is organized as follows: First, the proposed pipeline is summarized. Then, the results and discussion are presented in the next section. Finally, the manuscript ends with the conclusion section.

2. Material and Methods

The overall study is presented in Figure 1. First, the UAV flew over 35 and 50 meters above the study area and took several images. Then, two-dimensional images were converted into a 3D point cloud using two commercial SfM based software, namely, *Agisoft Metashape* and *Pix4D Mapper*. Two flight altitudes and two commercial software led to four 3D point clouds of the same interested region. For the rest of this manuscript, these four-point clouds are referred to as *Agisoft-35m*, *Agisoft-50m*, *Pix4D-35m*, and *Pix4D-50m*. Then, the road surface was extracted manually from these four-point clouds. Finally, the road surfaces clipped from four-point clouds were compared with the road surface extracted via the MLS technology to assess the effect of the UAV flight altitude and SfM based software. For this purpose, road surface extracted from the MLS technology was used as reference data since MLS technology produces more accurate 3D data than UAV image-based point clouds.

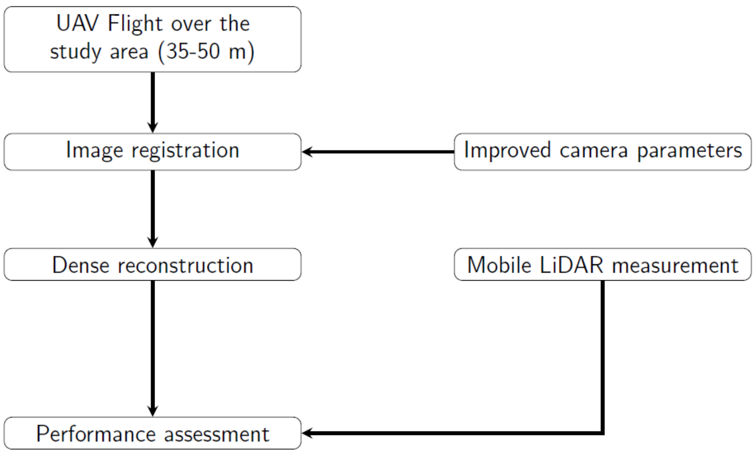

Figure 1. Flowchart of the overall study

The study area is located in Konya, a city in the middle-south of Turkey (see Figure 2). The MLS trajectory can also be seen in Figure 2. The MLS system collected data for the road in the study area and the roads in the other area for another mapping service. However, this study focuses only on the road in the study area, which is shown in the blue rectangle in Figure 2. The road focused on in this study is a local road without raised curb with one lane in each direction. Approximately 310 meters of the road was inspected in this study.

2.1 UAV Image Acquisition

The UAV used in this study was a DJI Phantom 4 RTK (P4RTK), which is an accurate low-altitude UAV platform used in many fields (Biçici and Zeybek, 2021; Nex and Remondino, 2013; Ruzgiene et al. 2015). This device was preferred because of its advantages, such as appealing to the end-user, ease of planning, durability, and compactness. Further details on its technical specifications can be found in DJI web page (https://www.dji.com/phantom-4-rtk).

P4RTK has the DJI FC6310R camera, Global navigation satellite system (GNSS), and inertial measurement unit (IMU) sensors. With these tools, camera locations with centimetre-level accuracy are obtained. The UAV flew over the study area on February 4, 2020, and 121 and 127 images were taken from 35 and 50 meters, respectively. Since congested traffic might affect the accuracy of the data, data were collected during light traffic hours of the day.

The difference between the images is due to the application of different covering areas during the measurement. Under normal circumstances, more images from 35 meters should be taken at the same area boundaries. However, no image deficiency will affect the road surface.

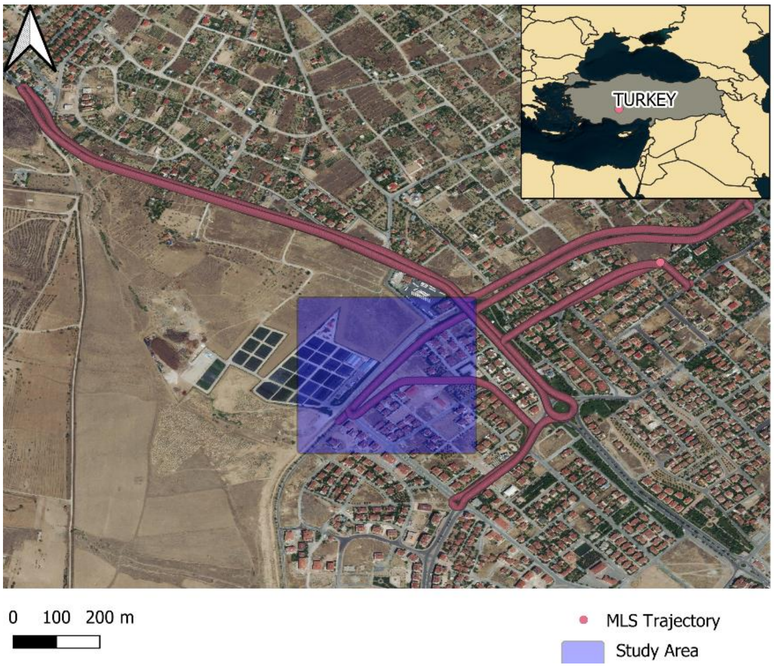

Figure 2. The location of the study area

2.2 Image Processing

In recent years, computer vision technology has made significant contributions to 3D modelling research (Biçici and Zeybek, 2021; Wang et al. 2018; Zeybek and Şanlıoğlu, 2019). High-resolution digital images are transformed into high-accurate 3D models. For this, it is possible to generate dense point clouds with multi-image stereo (MVS) and Structure-from-Motion (SfM) algorithms. A detailed explanation of the SfM algorithm can be found in several studies (Wang et al. 2018; Zeybek and Şanlıoğlu, 2019). In this study, two different commercial SfM based software were used to produce a 3D point cloud.

The first software used in this study was *Agisoft Metashape*. PhotoScan, later called Metashape, is a software package developed by the Russian company called Agisoft for 3D model reconstruction from images. It contains algorithms for processing digital images to produce 3D models. Specifically, it uses terrestrial photogrammetry and SfM-based algorithms from multiple locations to process images captured by a non-metric camera. In addition to 3D models, dense point clouds, Digital Surface Model (DSM), Digital Terrain Model (DTM), and orthomosaics can also be created in this software.

Agisoft Metashape automatically aligns all images and generates 3D models without the need for any pre-processing step. It only needs ground control points (GCP) to convert the models to the geographic coordinate system. Otherwise, there is no need for direct georeferencing. It was produced for the end-user, and it is not needed to be a very skilled photogrammetry specialist. For this reason, many previous studies reported in the literature used this software for 3D modelling applications (Li et al. 2016). It is sufficient that the images with regular or irregular overlap ratios with each other are taken in good light conditions. This data is imported into the software, and 3D models are produced for further analyses.

Pix4D Mapper is another SfM software package that is widely used in the processing of photogrammetric data (Elkhrachy, 2021; Spreitzer et al. 2019). The software interface is user-friendly, and 3D model products are simple to obtain. *Pix4D Mapper* improves the 3D model accuracy using the camera calibration values in its library. It also generates point clouds, Mesh models, DSM, DTM, and orthomosaics.

In addition, it allows to make distance, area, and volume measurements. Finally, it provides a detailed and comprehensive technical report on each stage of 3D data production. This two software follow two basic steps to generate point clouds. The first step is sparse key-point detection and matching. Specifically, after the raw data is imported, the interior and exterior orientation camera parameters are iteratively adjusted. This automatically calculates camera locations and orientations with high accuracy, based on matching key points produced after evaluation and optimization. The second step is the dense point matching between images. Multi-view stereo image matching algorithms are applied to increase the density of the sparse point cloud created by key points and create a dense 3D point cloud model. There must be theoretical differences between the point cloud production procedures employed by these two software. Since they are commercial black-box software, the details on the theory behind the point cloud production is not discussed in this study. In addition, different quality parameters are available in *Agisoft Metashape* and *Pix4D Mapper* software. These parameters affect the accuracy, density, and resolution of the 3D model to be created. The lower the parameter or range, the lower the spatial resolution and accuracy of the created 3D model. 3D models of high accuracy and resolution can be produced by setting high parameter values, which increases the processing time. Therefore, the optimum solution range should be provided. Table 1 and Table 2 presents the parameters used to produce the 3D point cloud in the *Agisoft Metashape* and *Pix4D Mapper* software, respectively.

Table 1. Agisoft Metashape processing parameters

Alignment parameters	
Accuracy	High
Generic preselection	Yes
Reference preselection	Source
Key point limit	40,000
Tie point limit	4,000
Exclude stationary tie points	Yes
Guided image matching	Yes
Adaptive camera model fitting	No
Depth maps generation parameters	
Quality	High
Filtering mode	Mild

Table 2. Pix4D Mapper processing parameters.

Processing Options	
Keypoints Image Scale	Full, Image Scale: 1
Advanced: Matching Image Pairs	Aerial Grid or Corridor
Advanced: Matching Strategy	Use Geometrically Verified Matching: no
Advanced: Keypoint Extraction	Targeted Number of Keypoints: Automatic
Advanced: Calibration	Calibration Method: Geolocation Based Internal Parameters Optimization: All prior External Parameters Optimization: All Rematch: Auto, yes
Point Cloud Densification details	
Image Scale	multiscale, 1/2 (Half image size, Default)
Point Density	High (Slow)
Minimum Number of Matches	3
3D Textured Mesh Generation	no

Converting images to a 3D model using SfM based software is very efficient and low cost compared to LiDAR and terrestrial laser scanners, which provide similar measurements and geometry in appropriate conditions for image acquisition moment. In addition to these advantages, software usage has also some disadvantages. It requires a high-performance computer because it is processed graphically as a post-process in office and computer environments. The processing time depends on the number of images and other relevant hardware capabilities such as RAM and high-performance graphic cards. In addition, the accuracy obtained with image-based methods is lower than the accuracy values obtained from terrestrial laser scanners. Table 3 shows the processing times and densities of the point clouds produced with each software on a system with Windows 10 OS, 64-bit processor, 32GB RAM, i9-10850K CPU @3.60GHz NVIDIA GeForce GTX 1660 SUPER graphic card.

It is found that *Agisoft* Metashape software was faster than *Pix4D Mapper* software in producing 3D data. Different computer specifications may lead to different processing times when using this two software to produce a 3D point cloud. Table 3 also presents the average grid density for two software and two flight altitudes. As expected, images from 35 meter-altitude flight produced a denser point cloud than those from 50 meter-altitude flight.

Table 3. Processing time performance of the software.

Point Clouds Groups	Image	Initial Processing Time	Dense Reconstruction of Point Cloud	Average Grid Density (per m^2)
Pix4D-35m	121 (100%)	6 minutes 56 seconds	25 minutes 59 seconds	1908
Agisoft-35m	121 (100%)	58 seconds	19 minutes 51 seconds	2318
Pix4D-50m	127 (100%)	6 minutes 41 seconds	20 minutes 57 seconds	1064
Agisoft-50m	127 (100%)	2 minutes 42 seconds	21 minutes 01 seconds	1166

The accuracy is directly related to the quality of the camera since digital images are used to produce the 3D model. Cameras used both in daily use and for measurement purposes are generally in the class of non-metric cameras. These cameras are not actually manufactured for photogrammetric purposes but are widely used because their calibration values are detectable and cost-effective. In addition, the camera calibration used in both software is one of the most important factors that directly and greatly affect the 3D model accuracy. The correct determination of the focal length and image distortion parameters are ensured in two basic ways. The first one is to determine by the preliminary (field) calibration or the self-calibration technique. The self-calibration technique is commonly applied in SfM software. However, ground control points independent of adjustment are of great importance for optimizing and verifying these calibration values. Pre-calibration values were used in this study. Before these measurements, the calibration parameters supported by dense images and viewing angles and obtained using dense ground control points were recorded in *Agisoft Metashape* and *Pix4D Mapper* software formats. These calibration values were obtained with 100 m and 75 m. This method is explained in detail by Zeybek (2021). In this way, high accuracy 3D models were produced from both software.

There are four-point clouds generated from two UAV flight altitudes and two software. Then, road surfaces were extracted manually from these four-point clouds. There are several methods to automatically extract the road surface from the point cloud (Zeybek and Biçici, 2021). However, this study does not focus on the automatic extraction of the road. So, the road extraction was done manually. Finally, four extracted road surfaces were compared with road surfaces extracted from the MLS technique to assess the effect of the UAV flight altitude and software.

2.3 Accuracy Analysis of Point Clouds

The coordinate information of the images provides spatial accuracy to have a certain level of accuracy in 3D digital models with the UAV measurement technique (Jiménez-Jiménez et al. 2021). This may require the collection of ground control points (GCPs) commonly used in practice. These GCPs should obtain true geographic coordinates and be detectable on images. GCPs should be distributed evenly over the measured area. The resulting data quality and spatial accuracy depend on this created reference network. In addition, additional control points (CPs) must be integrated to evaluate the created overhead triangulation pattern and compensation.

GCPs provide a geographic reference to the 3D point cloud while optimizing internal and external orientation parameters in the SfM process. In addition to its advantages, making field measurements brings extra time and cost. Therefore, direct georeferencing techniques are a hot research topic recently. These systems integrate sensitive GNSS receivers and antennas into UAV systems and transition to systems that give GCP accuracy and even better results with RTK or post-process (PPK) algorithms. With direct georeference and good calibration parameters, very high spatial accuracy values are obtained. In this way, the number of GCPs is minimized, and there is almost no need for field measurements. However, an external control measurement must always be performed to check the obtained positional accuracy. Instead of using CP, this study used MLS point cloud data of the test area. Thanks to this dense data, it was possible to analyse better whether the UAV system is sufficient in road surface extraction.

Applications for MLS accuracy studies are available in the literature. MLS systems are today's most effective and high-performance measurement technique to rapidly obtain dense point clouds with high spatial accuracy (Che and Olsen, 2019; Fryskowska and Wróblewski, 2018). In this study, the laser scanner distance measurement accuracy is around 8 mm and the absolute accuracy measures is ± 5 cm. The accuracy test between the point clouds was carried out based on the differences and comparisons between the point clouds.

Another analysis in literature is the digital elevation (DEM) of Difference (DoD) method, which is carried out using the differences in the DEM models in the vertical axis, i.e. the *Z* direction. Due to this analysis has a limitation and gives information for the only single-axis investigation of deviations, point cloud comparisons were applied in this study.

2.4 Point Cloud Comparison

There are several ways to compare two 3D point clouds (Barnhart and Crosby, 2013; DiFrancesco et al. 2020; Girardeau-Montaut et al. 2005). Point-to-point comparison is one of them. In this method, the closest distance between the point in one point cloud and the point in the other. However, outliers and different point cloud density levels might affect the accuracy of the results. In addition, similar problems might occur for mesh point cloud comparison (Lague et al. 2013). Lague et al. (2013) proposed the Multiscale Model to Model Cloud Comparison (*M3C2*) algorithm, which takes into account the roughness according to the surface normals in the point cloud comparison, detects the average change occurring in this direction, and also calculates the statistical significance of the changes. In this study, point clouds were compared by applying the *M3C2* algorithm. Please note that all point cloud distances/resolutions between points were reduced to 3 cm intervals before comparing point clouds to increase point densities and performance.

3. Results and Discussion

To assess the accuracy of point clouds obtained from two UAV flights and two software, four-point clouds were compared with point clouds obtained from Mobile LiDAR data, which was collected on January 27, 2020. To make the comparison, 1000 points were randomly selected in the MLS point cloud. When selecting these points, it is important to distribute them evenly over the point cloud. Therefore, the distance between these 1000 points was not less than 15 cm. Finally, the deviation from one point cloud to reference point cloud at these 1000 randomly selected points was calculated. Table 4 presents the mean, median, interquartile range (IQR), and standard deviation of the difference across four-point clouds.

Table 4. Statistics results for four-point clouds.

Point Clouds Groups	Sample Size	Mean	Median	IQR	Std
Agisoft-35m	1,000	0.0646	0.0696	0.0209	0.0228
Pix4D-35m	1,000	0.0721	0.0762	0.0239	0.0233
Agisoft-50m	1,000	0.0159	0.0210	0.0265	0.0238
Pix4D-50m	1,000	0.0376	0.0414	0.0247	0.0251

The mean and median of the *Agisoft-35m* and *Agisoft-50m* are lower than the mean and median of the *Pix4D-35m* and *Pix4D-50m*, respectively, as seen in Table 4. This means that the deviations are smaller in *Agisoft Metashape* software than *Pix4D Mapper* software. A similar conclusion can also be observed when comparing the boxplots in Figure 3(e) and Figure 4(e). The boxplots of the *Agisoft-35m* and *Agisoft-50m* are lower than the *Pix4D-35m* and *Pix4D-50m. This indicates that smaller deviations were obtained in Agisoft Metashape* software.

In addition, a hypothesis test was used to test if the mean of the two distributions is the same or not. It is important to select the appropriate hypothesis test. Therefore, whether the distributions are parametric or non-parametric needs to be determined. To do that, Shapiro-Wilk and QQplots graphs for the normality test were plotted. Specifically, on the top of Figure 3 and Figure 4, there are histogram diagrams on the left and QQplots on the right. Please note that the data should be distributed around the 45-degree line in QQplots if the data is normally distributed. It was found that the deviations obtained from Agisoft-35m and Pix4D-35 were not normal since they are not distributed around the 45-degree line, as visually seen in Figure 3. Similarly, it was found that the deviations obtained from Agisoft-50m and Pix4D-50 were not normal since they are not distributed around the 45-degree line, as seen visually in Figure 4. Thus, deviations obtained from four-data are not normally distributed samples which means that they are non-parametric. Therefore, the mean comparisons were evaluated using the non-parametric Wilcoxon test.

The p-value is lower than the alpha (which is 0.05) comparison value, and the hypothesis is rejected. This means that both sample groups have different characteristics from each other in 35 meters and 50 meters data.

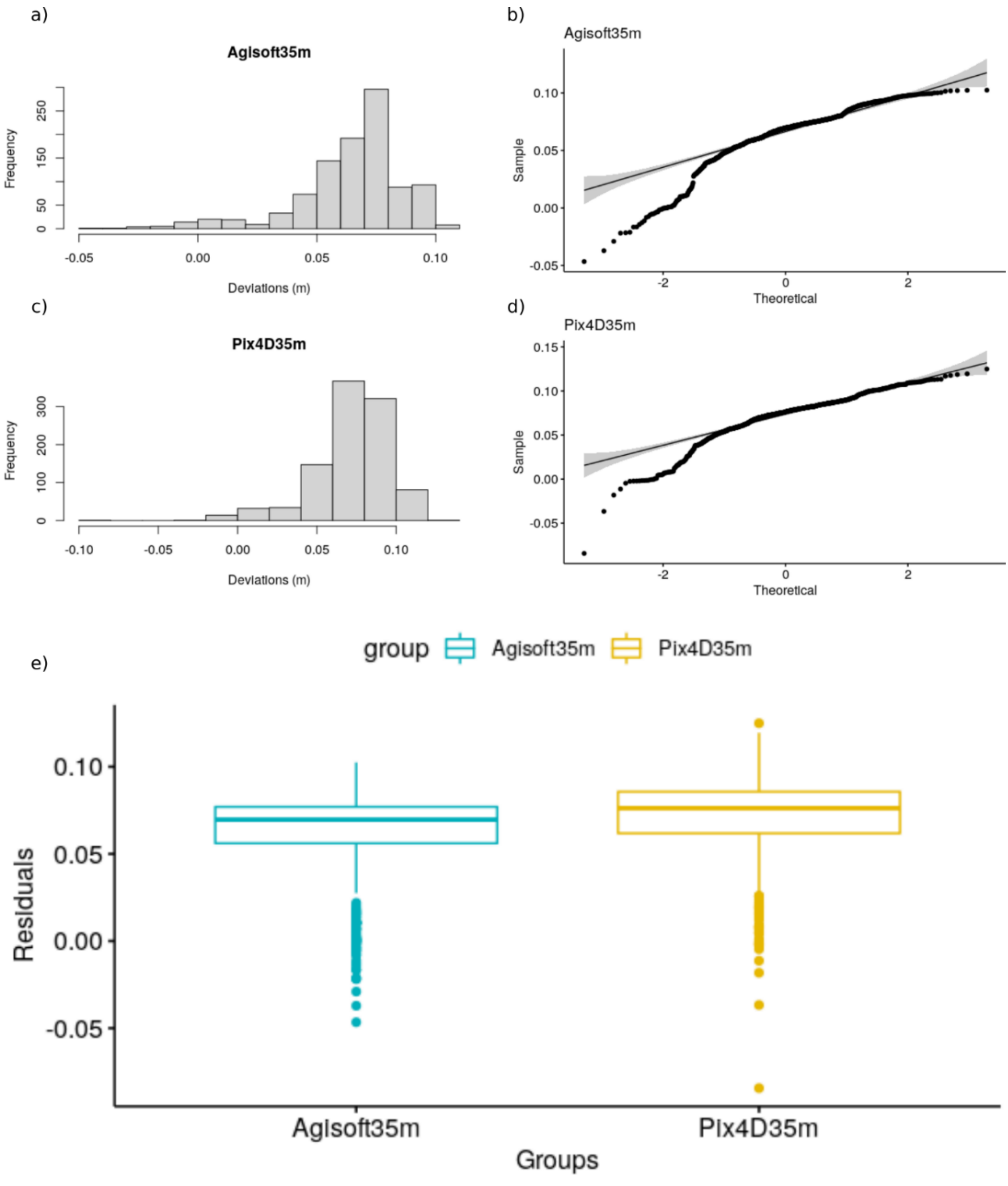

Figure 3. Comparisons of Agisoft and Pix4D from 35 meters altitude.

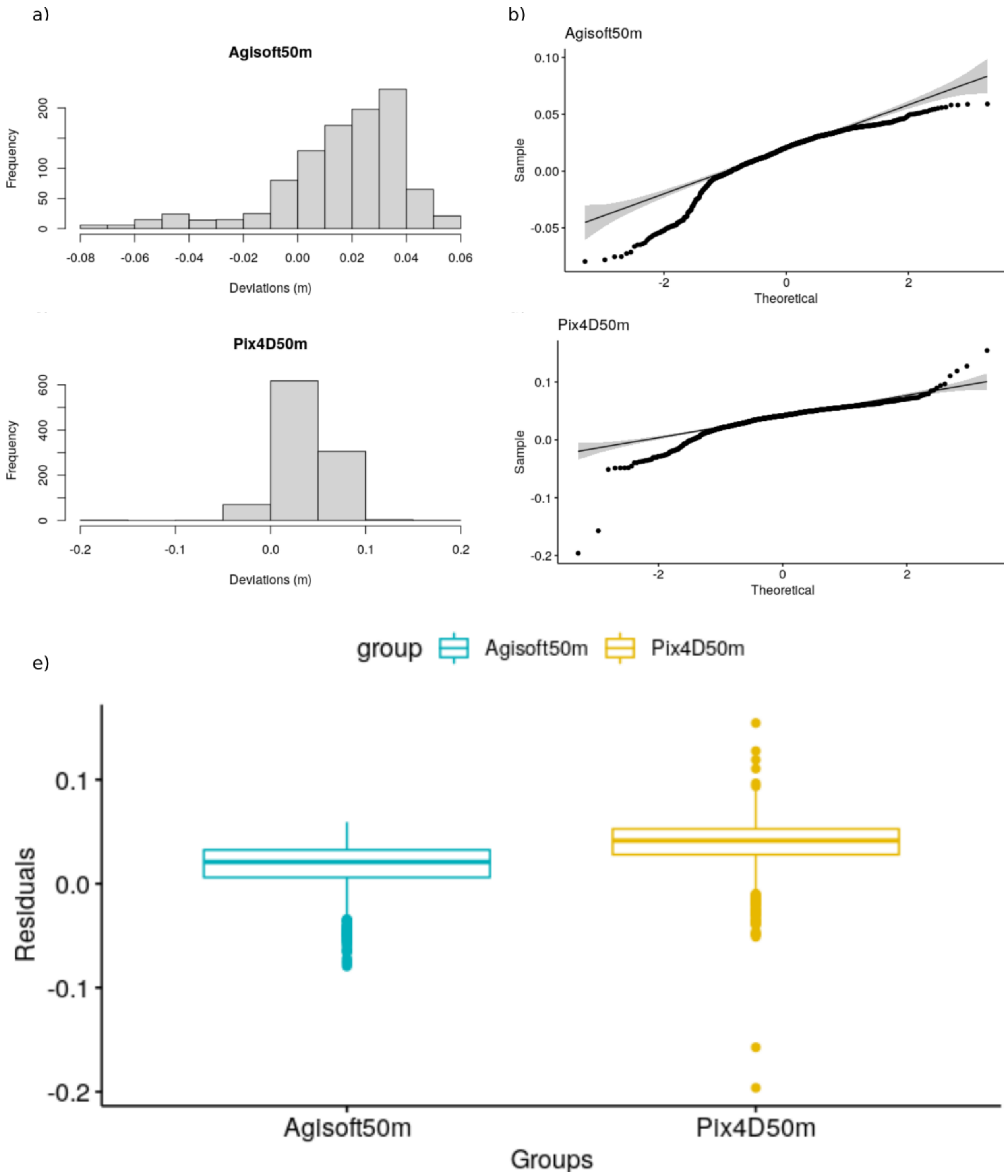

Figure 4. Comparisons of Agisoft and Pix4D from 50 meters altitude.

Finally, it was found that *Agisoft Metashape* software has lower standard deviation values in both 35 m and 50 m data than *Pix4D Mapper* software. The main reason for this difference is that the filtering results between the software may be different. It was also found that the point clouds obtained by the *Pix4D Mapper* software have more scattering. *Agisoft Metashape* results were found to be smoother. It was seen that the descriptive statistics were close to each other in the 35 meters and 50 meters data. However, it was seen that the standard deviation values were slightly better for the 35 meters data. However, it was also found that the mean and median of the Agisoft-50m and Pix4D-50m were lower than those of the Agisoft-35m and Pix4D-35m, respectively, as seen in Table 4. This is because UAV had low-quality GNSS signals at 35 meters since there were tall buildings around and UAV flew close to the ground. This leads to less accurate 3D data at 35 meters than 50 meters.

4. Conclusion

UAV technology is one of the fastest-growing technologies especially used in image processing. Images taken from a UAV flight can be converted into 3D data using Structure-from-Motion (SfM) based software. Then, several objects can be classified from 3D data. In this study, the road surface was extracted from 3D data. However, there are several factors that affect the accuracy of the 3D data. In this study, two factors, namely UAV flight altitude and SfM based software, were evaluated. Two different flight altitudes, which are 35 meters and 50 meters, were used. It was found that the flight altitudes do not make a significant difference to the results and produce close results. In this study, UAV flights were conducted from a low altitude, and there were only 15 meters between two UAV flights. Different conclusions might have been obtained if there were UAV flights at higher altitudes. Another factor evaluated in this study is different SfM based software. Two well-known SfM based software were used in this study, which were the Agisoft Metashape and Pix4D Mapper. It was found that Agisoft Metashape software produced more accurate results than Pix4D Mapper software. In addition, Agisoft Metashape software was found to be faster than Pix4D Mapper when producing 3D data.

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