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Using UAS-Based Point Clouds to Generate High Resolution Digital Terrain Model for Forestry Research and Applications*

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Abstract

Digital Terrain Models (DTMs) as well as Digital Surface Models (DSMs) have been widely used in many forestry applications, especially in locating forest roads, developing transportation planning, and determining the stand parameters. Generally, LiDAR (Light Detection and Ranging) point clouds have been used to generate DTMs, since LiDAR technology is able to provide multiple returns, which is very useful to separate the ground surface and non-ground objects such as trees, buildings etc. However, LiDAR technology generally requires a high cost and this, of course, has a negative effect on the use of LiDAR point clouds. In this study, the DTM of a study area was generated by means of the point cloud extracted from the aerial images taken from a UAS (Unmanned Aerial System). As the first step, the UAS-based point cloud was filtered to separate the points belong to the ground and non-ground objects. Thereafter, the filtered point cloud was interpolated to obtain the DTM of the study area. Finally, field measurements were conducted by using Real-Time Kinematic GPS (Global Positioning Systems) measurement technique to evaluate the accuracy of the produced DTM. Multiquadratic CRC, CP and CHTS surfaces were used as Q surfaces. Bi-linear surface was chosen as the trend surface when conducting the Multiquadratic interpolation algorithm. Accuracy evaluations revealed that it is possible to generate high-resolution DTMs by using UAS-based point clouds. The results indicated that the CRC and CHTS algorithms provided better results in representing the topography, compared to the CP algorithm.

Keywords: Unmanned Aerial System, Digital Terrain Model, Forestry, Point Clouds, Ground Filtering

1. Introduction

DTM is a mathematical surface calculated by using the position and elevation information to generate the 3D elevation model of the surface of the earth. A DTM does not contain any elevation information of above-ground objects such as vegetation, building and lamppost etc. Instead, it includes information relating to the bare land surface (URL-1). Digital Surface Model, on the other hand, represents the land surface with above-ground objects.

There are several methods to acquire 3D information (i.e. point cloud) of the surface of the earth, which can be in either raster (i.e. pixel) or vector (i.e. TIN-Triangulated Irregular Network) format. LiDAR, stereo aerial or satellite imagery, radar interferometry and field measurements are some of these methods. Accuracy of the acquisition method directly affects the accuracy of the DTM (URL-1). Since a DTM represents the bare earth surface, there is a need to remove the points belong to the above-ground objects, which is called 'ground filtering'. Ground points are then interpolated

to generate the DTM. In the literature, many algorithms have been reported to filter the point clouds to retrieve ground points (Kwak et al., 2007; Susaki, 2012; Kim et al., 2013; Pirotti et al., 2013).

Montealegre et al. (2015) compared the performances of six interpolation algorithms to generate DEMs with 1 m and 2 m spatial resolutions. They investigated the effects of the spatial resolution on the accuracy of the produced DTM. Besides, the effects of the slope of the study area, land cover and density of ground points on the interpolation error were also examined. They used 55 check points, whose 3D positions were measured using GPS technique, to assess the accuracy of the interpolation algorithms. It was concluded that the Inverse Distance Weighted (IDW) algorithm gave the best root mean squared (RMS) errors in both 1-m (37.10 cm) and 2-m (40.60 cm) DEMs. One of the main conclusions drawn by the authors was that the increase in the spatial resolution of the DEM leads to a decrease in the root mean squared

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error of the interpolated surfaces. Guo et al., (2010) investigated the effects of the topographical variety, point cloud density, used interpolation algorithm and spatial resolution on the accuracy of the produced DEM. They found out that the Natural Neighbour (NN), IDW and TIN interpolation algorithms were successful in producing DEM from LiDAR data. Kwak et al., (2007) used LiDAR data to detect individual trees and estimate the heights of trees. They computed the Digital Canopy Model (DCM) by subtracting the DTM from DSM. They detected the tree tops by applying an extended maxima transformation of morphological image analysis methods to the computed DCM. Examination of the studies in the literature reveals that the majority of the studies in which 3D elevation models have been produced use LiDAR point clouds. This is because LiDAR data results in multiple returns such as first return, last return etc. Laser beams are able to penetrate through the vegetation (unless the vegetation is not too dense) and reach the ground. This is the main reason that LiDAR data is very efficient in modelling the bare earth surface. However, LiDAR sensors are affected by bad weather conditions. In addition, increase in the acquisition range decreases the strength of each signal. Besides, the acquisition and processing of LiDAR data is still expensive. For this reason, the use of LiDAR data is not prevalent in Turkey. As an alternative for LiDAR data, stereo aerial photos can be used to generate point clouds. The use of stereo aerial photos enables the generation of point clouds for large-scaled areas with a less cost.

3D elevation models have been used in many forestry applications. Determination of stand parameters and growing stock, forest road design, transportation planning, and analysing the effects of a natural disaster (such as erosion, flood, avalanche etc.) are some of the leading applications in which 3D elevation models are

used. Koç (1996) indicated that the accurate slope information should be known to decide whether a forestation study is conducted mechanically or by labour force. Slope information is also very efficient to decide appropriate agricultural crops (Koç, 1996). The aim of this study is to generate a high-resolution DTM, which can be used for various forestry applications as a base, by using a point cloud extracted from the aerial photos taken from a UAS. Multiquadratic method was used to interpolate the point clouds to generate the DTM. The accuracy of the produced DTM was investigated using terrestrial measurements.

2. Material and Methods

2.1. Study Area

A part of the Karadeniz Technical University (KTU) campus was chosen as the study area. The campus is situated in the city of Trabzon, which is located on the northeast of Turkey. The study area, with the dimensions of 178 m x 410 m, includes above-ground objects such as buildings, trees and a store. The elevation of the study area ranges from 18 m to 83 m. The study area can be seen in Figure 1.

In April 2013, 256 aerial photos (the resolution of each photo was 3648 x 2736) were taken along 9 lines from an altitude of 185 m with the RICOH GR DIGITAL IV digital camera, which was mounted to the Gatewing X100 UAS. 12 ground control points (GCP) were established before the flights to use for georeferencing. It should be noted that extra attention was paid to distribute the GCPs evenly over the study area. The aerial photos were then processed and the point cloud with a density of 61.1 point/m² was generated by using the Agisoft PhotoScan Professional software. As a final step, a 25-cm orthophoto image was produced.

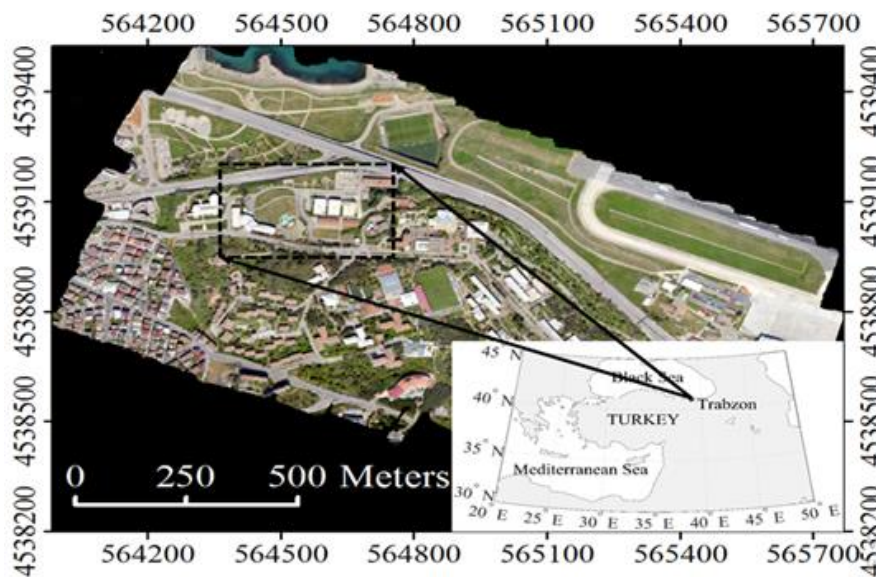


Figure 1. Study area

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2.2 DTM Generation

The produced point cloud was filtered with the Adaptive TIN (ATIN) algorithm to remove the points belong to the objects on the ground. The ground points were then interpolated in MATLAB environment by using the Multiquadratic interpolation technique to generate 25-cm DTMs. All points in the point cloud were used as input in interpolation process. A matrix, having the same size of the 25-cm orthophoto (703x1638), was generated and point cloud coordinates were assigned to related pixel positions in this matrix. At this stage, affine transformation was used to convert the land coordinates into the pixel coordinates. Since the interpolation of all ground points is a time and system source consuming process, interpolation was conducted using a sliding window to ease the process. Interpolation was done within the area corresponding to the window.

Bi-linear surface was chosen as the trend surface when conducting the Multiquadratic interpolation algorithm. Multiquadratic CRC, CP and CHTS surfaces were used as Q surfaces. The unknowns (a_0, a_1, a_2, a_3) of the bi-linear surface were solved with the least squares technique. z_{trend} elevation is calculated for each control point in the surface equation. Δz_i elevations of the control points were computed with Equation 2. Δz_0 residual elevation at a given x_0, y_0 interpolation point was calculated with Equation 3. Equation 10, which is used to determine the Δz_0 residual elevations, is obtained by substituting the right cone equation (Equation 7) into the Q surface function in Equation 4. C_i unknown coefficients in Equation 10 are solved with Equation 13. The trend surface of the interpolation points is obtained by substituting x_0, y_0 values into the bi-linear equation. Distances, which are the only unknowns in Equation 14, represent the distances between the interpolation points and control points. Once these distances are calculated, z_0 elevations of the interpolation points are computed. In the study, the equation proposed by Fasshauer was used for δ parameter.

2.3 Interpolation Methods

In the study, the DTM was interpolated by using the Multiquadratic interpolation technique. This technique represents the land surface with a single function by using all control points at the same time. The most common equation of the Multiquadratic interpolation algorithm is;

$$z_0 = \sum_{i=1}^m C_i [Q(x_0, y_0, x_i, y_i)] + z(x_0, y_0) \quad (1)$$

In the Multiquadratic algorithm, a trend surface is first generated by using m control points in conjunction with an n -degree polynomial (Hardy, 1971). Leberl (1973) stated that a 1-degree or 2-degree polynomials are adequate for many applications. Unknown coefficients of the n -degree polynomial are determined with respect to the least squares technique. Then, x_i and y_i values of the control points are substituted into the equation and z_{trend} values, which are the elevations of the control points, are calculated. Residuals of the elevations (Δz_i) are determined by subtracting the z_{trend} values from the actual elevations of the control points (z_i);

$$\Delta z_i = z_i - z(x_i, y_i) = z_i - z_{trend} \quad (2)$$

Residual of an elevation at any interpolation point (x_0, y_0) is calculated as;

$$\Delta z_0 = z_0 - z(x_0, y_0) = z_0 - z_{trend} \quad (3)$$

Calculation of the unknown Δz_0 with respect to the Multiquadratic technique results in the elevations of the interpolation points (z_0) (Yiğit, 2003). According to Equation 1, Δz_0 can also be obtained as;

$$\Delta z_0 = \sum_{i=1}^m C_i [Q(x_0, y_0, x_i, y_i)] \quad (4)$$

C_i coefficients, which are determined from the residual elevations of the control points (Δz_i), specify the slopes and signs of the 2nd degree terms (Hardy, 1971; Güler, 1985; Çakır, 2012). Hardy's multiquadratic surfaces vary between each other. These are;

- Circular hyperboloid of two sheets (CHTS);
 $Q(x_0, y_0, x_i, y_i) = [(x_0 - x_i)^2 + (y_0 - y_i)^2 + \delta^2]^{1/2} \quad (5)$

- Circular paraboloid (CP);
 $Q(x_0, y_0, x_i, y_i) = [(x_0 - x_i)^2 + (y_0 - y_i)^2 + \delta^2] \quad (6)$

- Circular right cone (CRC);
 $Q(x_0, y_0, x_i, y_i) = [(x_0 - x_i)^2 + (y_0 - y_i)^2]^{1/2} \quad (7)$

Substitution of these equations into Equation 4 leads to multiquadratic surfaces (Güler, 1985; Yiğit, 2003);

- Summation of the series of the circular hyperboloid of two sheets;

$$\Delta z_0 = \sum_{i=1}^m C_i [(x_0 - x_i)^2 + (y_0 - y_i)^2 + \delta^2]^{1/2} \quad (8)$$

- Summation of the series of the circular paraboloid;

$$\Delta z_0 = \sum_{i=1}^m C_i [(x_0 - x_i)^2 + (y_0 - y_i)^2 + \delta^2] \quad (9)$$

- Summation of the series of the circular right cone;

$$\Delta z_0 = \sum_{i=1}^m C_i [(x_0 - x_i)^2 + (y_0 - y_i)^2]^{1/2} \quad (10)$$

x_i , y_i and Δz_i values, which are determined with the control points, are used to calculate C_i coefficients. In case where Equation 7 is selected as the multiquadratic surface, m linear equation systems are formed depending on the control points to compute C_i coefficients;

$$\begin{array}{ccccccc} C_1 a_{11} & + & C_1 a_{12} & + \dots + & C_m a_{1m} & = & \Delta z_1 \\ C_2 a_{21} & + & C_2 a_{22} & + \dots + & C_m a_{2m} & = & \Delta z_2 \\ \dots & + & \dots & \ddots & \dots & = & \vdots \\ C_m a_{m1} & + & C_m a_{m2} & + \dots + & C_m a_{mm} & = & \Delta z_m \end{array} \quad (11)$$

This equation system can be shown in matrix format as;

$$AC = \Delta z \quad (12)$$

where, A stands for the coefficients matrix with a size of $m \times m$, C is the vector of the unknowns with a size of $m \times 1$, and Δz is the vector (a size of $m \times 1$) of the residual elevations. Unknown C_i coefficients are calculated as;

$$C = A^{-1} \Delta z \quad (13)$$

z_0 elevation value of any interpolation point (x_0 , y_0) is computed as;

$$z_0 = z(x_0, y_0) + \sum_{i=1}^m C_i [(x_0 - x_i)^2 + (y_0 - y_i)^2]^{1/2} \quad (14)$$

δ^2 in Equations 5 and 6 is a constant value and known as geometric parameter. Equation 7 is obtained by setting the δ^2 in Equation 5 as 0. Table 1 shows a few formulaic suggestions to determine the δ parameter (Franke, 1979; Hardy, 1990; Fasshauer, 2002).

Table 1. Suggestions for determination of the δ parameter

Proponent	Formula
Hardy	$\delta = 0.815s$
Franke	$\delta = 1.25 D/\sqrt{m}$
Fasshauer	$\delta = 2/\sqrt{m}$

The s parameter in Table 1 represents the average distance among control points and their neighbours, D is the diameter of the smallest circle covering all control points, and m is the number of control points (Çakır, 2012).

2.4 Accuracy Assessment

Accuracy of the produced DTM was investigated by means of the test points established in the study area. These test points were established in flat areas (test site

1), sloping areas (test site 2) and the areas in the vicinity of the above-ground objects (test site 3). Elevations of these test points were measured by RTK (Real Time Kinematik) GPS technique. 87, 163 and 129 test points were measured for test sites 1, 2 and 3, respectively. For each test site, measured elevations and the elevations on the DTM were used to calculate the Root Mean Squared Error, Standard Deviation of Differences (SDD), Mean Absolute Error (MAE) and Mean Error (ME) metrics. Minimum (MinE) and maximum (MaxE) elevation errors were also calculated (see Table 2). The equations of the RMS, MAE and ME metrics are given below (Montealegre et al., 2015);

$$\begin{aligned} RMS &= \sqrt{\frac{1}{n} \sum_{i=1}^n (DTM_{zi}(x, y) - M_{zi}(x, y))^2} \\ SDD &= \sqrt{\frac{\sum_{i=1}^n (DTM_{zi}(x, y) - M_{zi}(x, y)) - DTM_{zi}(x, y) - M_{zi}(x, y)}{n - 1}} \\ AE &= \frac{1}{n} \sum_{i=1}^n (|DTM_{zi}(x, y) - M_{zi}(x, y)|) \\ ME &= \frac{1}{n} \sum_{i=1}^n (DTM_{zi}(x, y) - M_{zi}(x, y)) \end{aligned}$$

where, M_{zi} stands for the measured elevation of a given test point, $(DTM)_{zi}$ is the elevation of the same test point on the DTM and n is the total number of test points (Montealegre et al., 2015).

3. Results and Discussion

In this section, the results of the interpolation algorithms were investigated for each test site. Table 2 shows the RMS, SDD, ME, MAE, MinE and MaxE values of the multiquadratic interpolation techniques. As seen in Table 2, interpolation algorithms gave similar RMS values in test sites 1 (flat areas) and 2 (sloping areas). RMS was determined as 5 cm for test site 1 and as 18.4 cm for test site 2. The CRC algorithm gave the best RMS value (19.2 cm) in test site 3. The CHTS algorithm follows the CRC algorithm with an RMS of 19.8 cm. The CP algorithm yielded the worst RMS value (28 cm) in test site 3. The CRC algorithm yielded the best SDD value with 14.4 cm in test site 3. The CHTS algorithm is the second most successful one in test site 3 with an SDD value of 16.4 cm. In test site 3, the CP algorithm gave the worst SDD value with 27.3 cm. For test site 3, the CP algorithm gave the best ME value (6.6 cm); whereas the same algorithm yielded the worst MAE with 16.9 cm. It can also be inferred from the table that the CHTS algorithm performed best with a MAE value of 15.1 cm. The CHTS algorithm also yielded the highest MaxE value with 53.8 cm (see Table 2); whereas the CP algorithm resulted in the greatest minimum elevation error (-169 cm) in site 3.

Table 2. Calculated RMS, SDD, ME, MAE, MinE and MaxE values (cm)

Interp. Alg.		Test site 1						Test site 2						Test site 3					
		RMS	SDD	ME	MAE	MinE	MaxE	RMS	SDD	ME	MAE	MinE	MaxE	RMS	SDD	ME	MAE	MinE	MaxE
Radial Basis Functions	CRC	5.2	4.6	2.5	3.8	-10.9	16.3	18.4	16.5	8.2	14.1	-42.5	73.6	19.2	14.4	12.6	15.3	-45.7	49.5
	CP	5	4.3	2.6	3.9	-9.1	16.3	18.5	16.9	7.9	14.2	-52.7	76.3	28	27.3	6.6	16.9	-169	51.1
	CHTS	4.9	4.4	2.5	3.8	-13.4	16.3	18.5	16.7	8.2	14.6	-44.4	76.3	19.8	16.4	11.1	15.1	-82	53.8

The results show that the CRC and CHTS algorithms are more successful in representing the topography, compared to the CP algorithm. The produced orthophoto was draped over the results of the CRC, CP and CHTS interpolation algorithms and given in Figures 2, 3 and 4, respectively.



Figure 2. The result of the CRC algorithm



Figure 3. The result of the CP algorithm



Figure 4. The result of the CHTS algorithm

4. Conclusions

UAS images provide high-resolution base maps for a wide variety of forestry applications. DTMs produced with UAS images are favourable when extracting morphological features such as crown diameter, tree heights etc. Deformation monitoring in forest roads, generating base products for forest management plans, inventory collection in small or large-scaled areas, gathering information for topographic plans and forestation are only a few of the application areas in which UAS-based DTMs can be used effectively. Compared to LiDAR data and satellite imagery, acquisition and processing of UAS images is cheaper, which makes the use of UAS-based point clouds more prevalent (Akgül et al., 2016). In this study, the filtered UAS-based point cloud was interpolated with Multiquadric functions. Accuracy evaluation results indicated that the CRC algorithm represented the study area best. The main conclusion drawn from the evaluation results is that UAS-based DTMs can be used in the applications requiring high 3D accuracy.

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