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Accuracy assessment of vertical and horizontal coordinates derived from Unmanned Aerial Vehicles over District Six in Cape Town

Thabani Thuse[1], Kevin Musungu[1], Patroba Achola Odera[2]

[1]Department of Civil Engineering and Geomatics, Cape Peninsula University of Technology, Cape Town, South Africa, thuset@cput.ac.za
[2]Division of Geomatics, School of Architecture, Planning and Geomatics, University of Cape Town, Cape Town, South Africa

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Abstract

Unmanned aerial vehicles (UAVs) are now an alternative for geospatial data collection for a variety of applications. One such application is terrain mapping, particularly digital elevation model (DEM) and digital surface model (DSM) products, but questions remain about its accuracy and efficiency, especially when compared to traditional ground survey methods. Thus, the purpose of this paper is to compare the traditional surveying methods for topographical mapping through datasets obtained through Total Station (Trimble M3) and a camera mounted on a quadcopter (DJI Phantom 4 Pro UAV). We obtained both datasets in the same location at the District 6 open field area in the City of Cape Town, with undulating terrain. We compared the resultant horizontal coordinates (x and y) and orthometric height (H) at 159 check points (CPs). The drone-based elevations were derived using UAV drone computer vision techniques. In using the UAV drone, the reconstructed camera positions and terrain features were used to derive ultra-high-resolution point clouds, ortho-photos, and digital surface models from the multi-view UAV camera photos taken at 120 m above mean sea level. The root-mean-square-errors (RMSEs) for the differences between the Total Station and UAV coordinates at 159 CPs are ±0.046, ±0.038 and ±0.079 m for x, y, and H coordinates, respectively. Comparisons over slope ranges show that the highest orthometric height error (±0.090 m) is at a slope steepness of >15°, while the least orthometric height error (±0.073 m) is at a slope steepness of 5 - 10°. The results also show that the highest errors in x (±0.070 m) and y (±0.074 m) occur at a slope steepness of >15° and the least errors in x (±0.035 m) and y (±0.029 m) at a 5 – 10° slope steepness. Similar comparisons on elevation ranges show that the highest orthometric height error (±0.098 m) is at an elevation range of 60 – 100 m, while the least orthometric height error (±0.052 m) is at a 40 – 60 m elevation range. The highest errors in x (±0.051 m) and y (±0.061m) occur at elevation ranges of 40 – 60 m and 0 – 20 m, respectively, while the least errors in x (±0.040 m) and y (±0.025 m) occur at elevation ranges of 80 – 100 m and 40 – 60 m, respectively. These results indicate that horizontal positions (x, y) and orthometric heights (H) obtained from UAV are accurate enough for most mapping applications.

Keywords: *unmanned aerial vehicles, digital elevation model, coordinates, accuracy assessment, District Six*

1. Introduction

The introduction of Unmanned Aerial Vehicles (UAVs) and attempts to use them as topographical information-gathering devices has initiated discussions about the quality of derivative products and their potential for further use in geomatics applications. One desired result is a Digital Elevation Model (DEM) representing the ground surface. DEMs are important topographical products and essential requirements for many geospatial applications. However, in land surveying, traditional methods for creating DEMs take up much field time and are, therefore, expensive (Aguilar et al., 2005). Over time, photogrammetry has become one of the most important methods for creating DEMs (Henrico, 2016). The basic elevation data that DEMs contain are the reason for their widespread use and for the importance that they have assumed in many instances. Slope, aspect, and visibility are among the useful data they include that can be calculated from the elevation model (Cukrov, 2013). Recently, Airborne Light Detection and Ranging (LiDAR) systems have emerged as a powerful method for creating DEMs (Polat et al., 2015). This is because LiDAR can collect 3D information very effectively over a large area and over time, and with precision (Uysal et al., 2015). However, a major drawback of manned airborne platforms such as airplanes is that they are expensive, especially in small research areas (Vallet et al, 2011).

Since 1979, UAV applications have become common in the field of geomatics. This has largely to do with the low-cost UAV platforms in combination with digital cameras. These low-cost UAVs have high precision navigation from Global Navigation Satellite Systems (GNSS) and Inertial Navigation Systems (INS). Some UAVs are limited by their size and cannot carry a large payload. This means that these smaller UAVs will not be able to carry high quality Inertial Measurement Unit (IMU) devices (Ullrich et al., 2008). The most inexpensive UAV systems are the simple or hand-launched UAVs which are autonomously operated with a GPS-driven autopilot and an IMU sensor. Although smaller UAVs might be unstable in windy areas (Remondino et al., 2011), they can collect data faster than conventional photogrammetric methods. Other advantages include the lower cost of using a UAV. It is much less than conventional photogrammetric methods and there is also a much lower risk factor when it flies over harsh terrain. There is also the advantage that a rotary UAV can take off and land vertically and has a hovering capability (Heaphy et al., 2017).

Most of the obvious advantages of UAVs in general mapping include the relatively low hardware costs, the high level of automation of the photographic survey and the very low operating costs (Gonçalves and Henriques, 2015). The term, UAV, is often used in computer science and artificial intelligence. However, terms such as Remotely Piloted Vehicle (RPV), Remotely Operated Aircraft (ROA), Unmanned Vehicle system (UVS), and model helicopter are often used (Eisenbeiss, 2004). The Unmanned Vehicle Systems International Associations clearly define Remote Controlled (RC) and model helicopters as small, short, and medium-range UAVs, depending on size, durability, range, and flight altitude (Eisenbeiss, 2004). UAVs are widely used in land surveying (geomatics) to acquire DEMs and other information regarding the earth's surface (El Meouche et al., 2016). A DEM comprises inherent errors resulting from the primary data collecting techniques and processing methods for specific terrain and land cover types (Mukherjee et al., 2013). The accuracy of these datasets is frequently uncertain and inconsistent within each dataset. In South Africa, UAV DEM accuracies have not been compared to the traditional ground surveying techniques and conventional aerial photogrammetric standards. A typical processing pipeline for DEM generation depends on several factors such as overlap, flight altitude, and camera resolution.

Variations in these parameters affect the resultant models and the ultimate accuracy of DEMs (Hudzietz and Saripalli, 2011). Despite the range of methods available, creating a high-resolution, high-quality digital elevation model still requires a significant investment in personnel time, hardware, and software. Therefore, UAVs are increasingly used in land surveying to obtain DEM data and other surface-related information.

This study investigates the appropriateness of UAVs for horizontal and vertical positioning in undulating terrain using a drone. This is achieved by evaluating the accuracy of the horizontal and vertical coordinates obtained by a DJI Phantom 4 professional drone at 159 check points surveyed by an M3 Total Station and UAV. Further, the study carries out analysis of the effect of slope and terrain variations on the accuracy of UAV derived coordinates.

2. Study Area

The open field in the District Six area was used as the study area (Figure 1). District Six is the sixth municipal district of Cape Town, a port city on the southern tip of Africa that nestles between the mass of Table Mountain and the indigo waters of the Atlantic Ocean. The study area (District Six) is located between Nelson Mandela Boulevard and Christian Street, in Cape Town, South Africa. The site is approximately 0.33 km^2 in size. The variation from low to high elevations is approximately 107 m above ground level. The site has a steady slope clothed in different land cover types. This open space field has a morphologically dissected surface and undulating terrain and is thus suitable for assessing the use of UAV photogrammetry to capture intricate details on the topographical surface. The variation in slope and terrain makes the study site appropriate for validating UAV data.

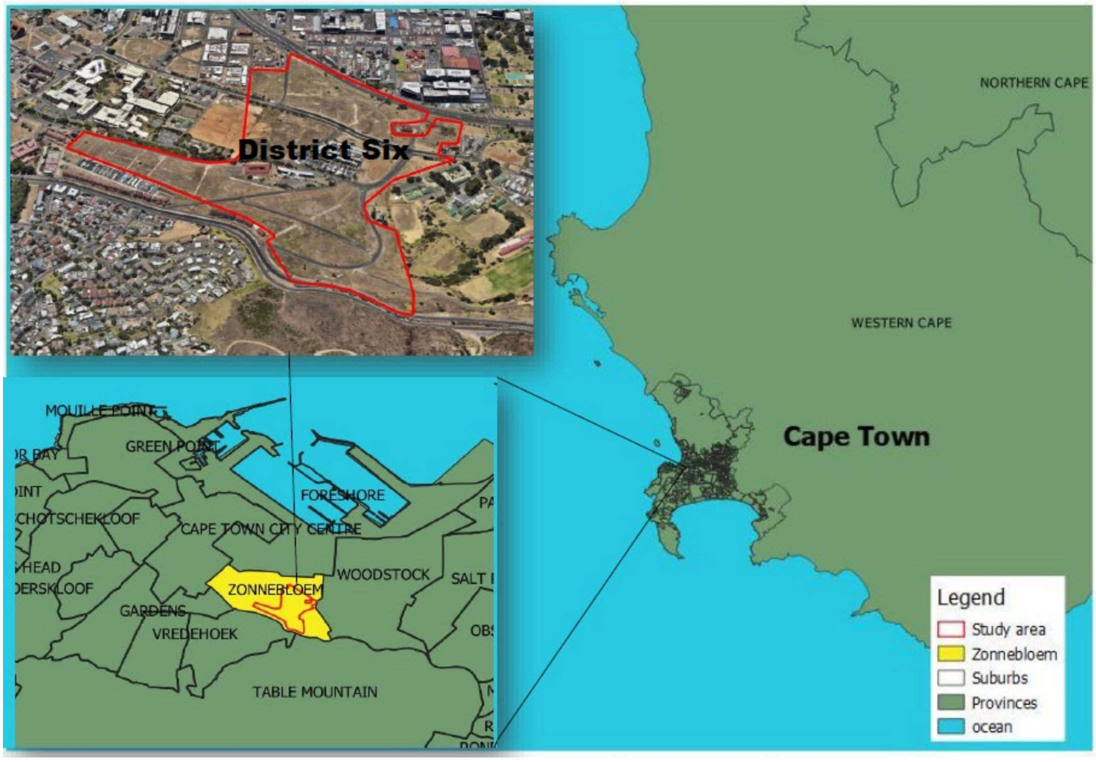

Figure 1: Test site location

3. Material and Methods

3.1. Data Collection

The primary datasets consisted of aerial photographs captured using UAV and traditional ground survey data by means of a Total Station. The steps followed are described below:

(a) Firstly, 18 ground control points (GCPs) were surveyed and located across the study area using a Total Station (M3 Trimble), as shown in Figure 2. The number of GCPs and their distribution within the study area were considered very important for investigating the geospatial accuracy of the UAV photogrammetry (Elkhrachy, 2021). Using black and white targets of size 29.7 by 42 cm, which distinguished them from the ground features, these artificial GCPs were marked just prior to the flight. They were distributed widely and uniformly throughout the whole block, particularly towards the periphery (Shahbazi et al., 2015). For RTK observations, the points were measured using the Trimble GPS base and rover 5700 and 5800 series. Each GCP was measured with a 10-second data logging rate. To obtain reliable results, measurements were conducted with a time interval during various satellite configurations. This area of Cape Town, South Africa, uses Hartebeeshoek 94 (based on WGS84) as the official geodetic datum. The GCPs were also surveyed with a Trimble M3 Total Station, which is considered more accurate than the GPS. The purpose was primarily to determine how the GPS coordinates compare to the Total Station coordinates. Comparing the two datasets, the horizontal (y, x) and vertical (H) positions of the measured points gave mean errors of 0.022, 0.012 and 0.051 m for x, y, and H, respectively. Standard deviations (SD) of ±0.029, ±0.028 and ±0.047 m were obtained for the *x*, *y*, and *H* coordinates, respectively. These results were found to be satisfactory and acceptable for this study.

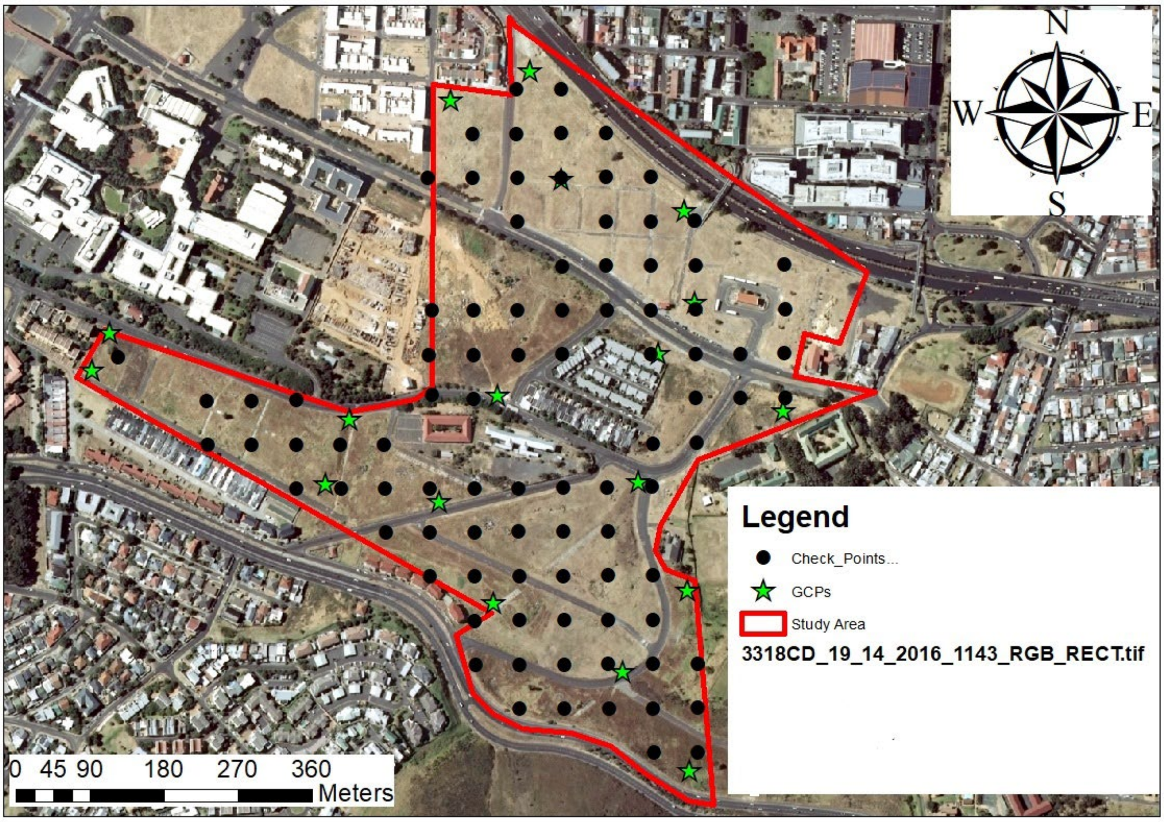

Figure 2. Distribution of ground control and check points across the study area

(b) A total of 159 equidistant pre-marked check (verification) points were measured over the 0.33 km^2 test site. The reason for pre-marking the check points before flying the drone was to ensure the visibility of the points on the image after the flight. The spatial distribution of the check points was created as a "grid" to ensure that there were sufficient points on different slopes and elevation ranges for statistical purposes (see Figure 2).

(c) A DJI Phantom 4 Professional drone, with a mounted 1 /2.3" CMOS effective pixels :12.4 camera sensor, was then used to capture aerial photographs at a height of 120 m above the ground. This camera possesses a FOV 94° 20 mm (35 mm format equivalent) f/2.8 focus lens and has a Max image size of 4864 x 3648. A total of 290 images were captured, and 75% and 70% overlaps were used for the front and side overlaps to maximise stereoscopy and avoid holes. To provide a stereoscopic picture of a scene and avoid gaps for successful photogrammetric results, at least 60% forward and 30% lateral overlaps are required (Rau et al., 2011). Factors such as flight regulations, maximum flight time, and ground pixel size were considered to determine the flight height. Our flight height, 120 m, was compatible with all aspects mentioned. It did not exceed the maximum acceptable flight height in South Africa, and the mission could be completed with one battery per flight, which provided approximately

20 minutes of flight time. It yielded 290 photos in each of the required strips to cover the entire study area (See Figure 3 for details of the flight). Furthermore, our preliminary assessment of flight heights showed that 120 m was more optimal than 100 and 140 m flight heights. Flight 120 m provided a RMSE of 0.080 m, while flights 100 and 140 m provided RMSEs of 0.338 and 0.264 m, respectively.

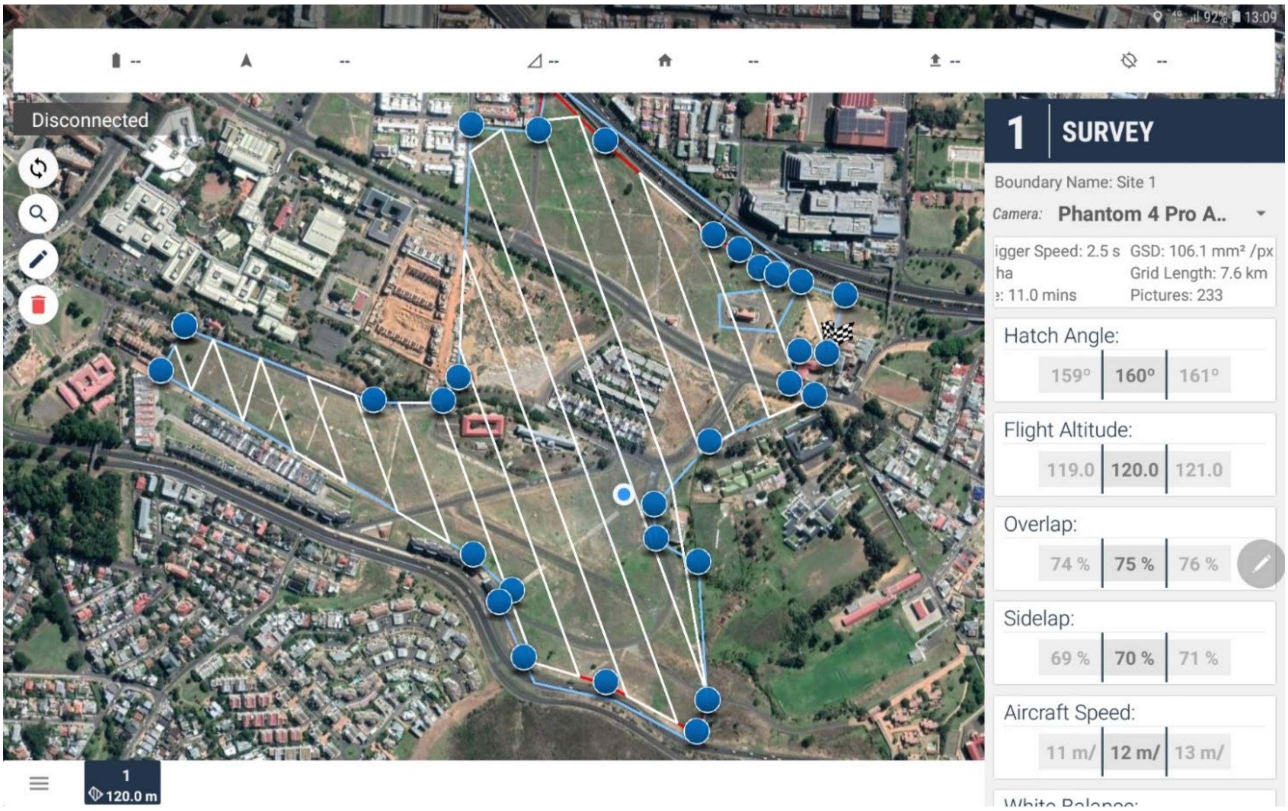

Figure 3. Flight planner results – Flight lines, Angles and Overlaps

(d) The other traditional field survey was conducted using a Trimble M3 Total Station. The horizontal and vertical positions (*x*, *y*, and *H*) were determined by means of a topographical survey (spot shots), which permitted the selection of the positions of the check points throughout the study area.

(e) The trigonometric positioning data were then recorded in the Total Station's internal data recorder, along with detailed feature coding information for each observation. This detailed feature coding allowed the survey software to draw lines between data, to place different feature types on different data layers, and to create contour and break-line information. The contour and break-line information were used to generate a triangle file required to create a digital terrain model.

3.2. Data Processing

3.2.1. *Total Station data*

The coordinates for the control points during field testing were acquired from the South African National Geo-Spatial Information (NGI), with coordinates formatted appropriately for the software to import the coordinate and point information automatically. In this instance, the file type was a 'csv' output. The data layers uploaded into the software included: Town Survey Marks and Trigonometrical Beacons and the observations from the Total Station. A physical printout of all the uploaded data in *x*, *y*, and *H* format was also made as a backup. The purpose of this backup was to provide for the unlikely event of an automatically imported csv file being corrupted and not then being used during processing. The necessary checks were done on the data, which included the selected control points. This was to ensure that the data were accurate and consistent.

The digital data from the M3 Trimble Total Station and Trimble GPS were exported onto an SD card into a csv file format. The GPS was used to locate and place the GCPs, and the Total Station was used to survey both the check points and the GCPs. (This file format is the standard file format for ArcGIS and survey software programs.) The csv file was copied from the SD card onto the computer and then imported into the program. The import process involves reducing the raw bearings and distances in the observation data into points in coordinate format. Unique point identifiers that ArcGIS software can interpret were placed in the observation data in the field in the form of an alpha-based coding system. Additional 'string' information was stored with point coding to create lines between the common points. This coding and string system also allowed ArcGIS to automatically label contourable points and break-lines for creating a three-dimensional triangle file, which was used to create contour data and a DTM within the software (see Figure 4). The DTM plans were used as a benchmark for comparison with the UAV survey results and plans. After the reduction process had been completed, the reduction report and data were manually checked for errors. No errors were found in the data, as per the report.

3.2.2. *UAV drone data*

Image processing was completed through the Pix4D software. A total of 18 ground control points (GCPs) were used for geo-referencing the ortho-rectified images taken by the UAV drone during the field survey. Ground control points were imported into the project to geo-reference the point cloud accurately. The Pix4D software contained a three-stage automatic image processing capability with each automatic processing completed, as the user prompt. The generated Digital Surface Model and Ortho-mosaic are presented in Figure 5.

Image processing was completed in less than five hours through the Pix4D software. A total of 290 images were obtained, with a GSR of 34.30 mm/pixel for the 120 m flight. The Pix4D software calculated a total area of 0.583 km^2 within the ortho-rectified georeferenced image. During field testing, 18 GCPs were used to geo-reference the ortho-rectified or 'tiled' images captured by the UAV. The Pix4D software computed the root mean square error (RMSE) of 0.006 m during the georectification process. The report also showed a 100% image calibration with a median of 34678 matches per calibrated image. The low RMSE for the GCPs indicates that the georeferenced UAV survey model has a high degree of three-dimensional accuracy.

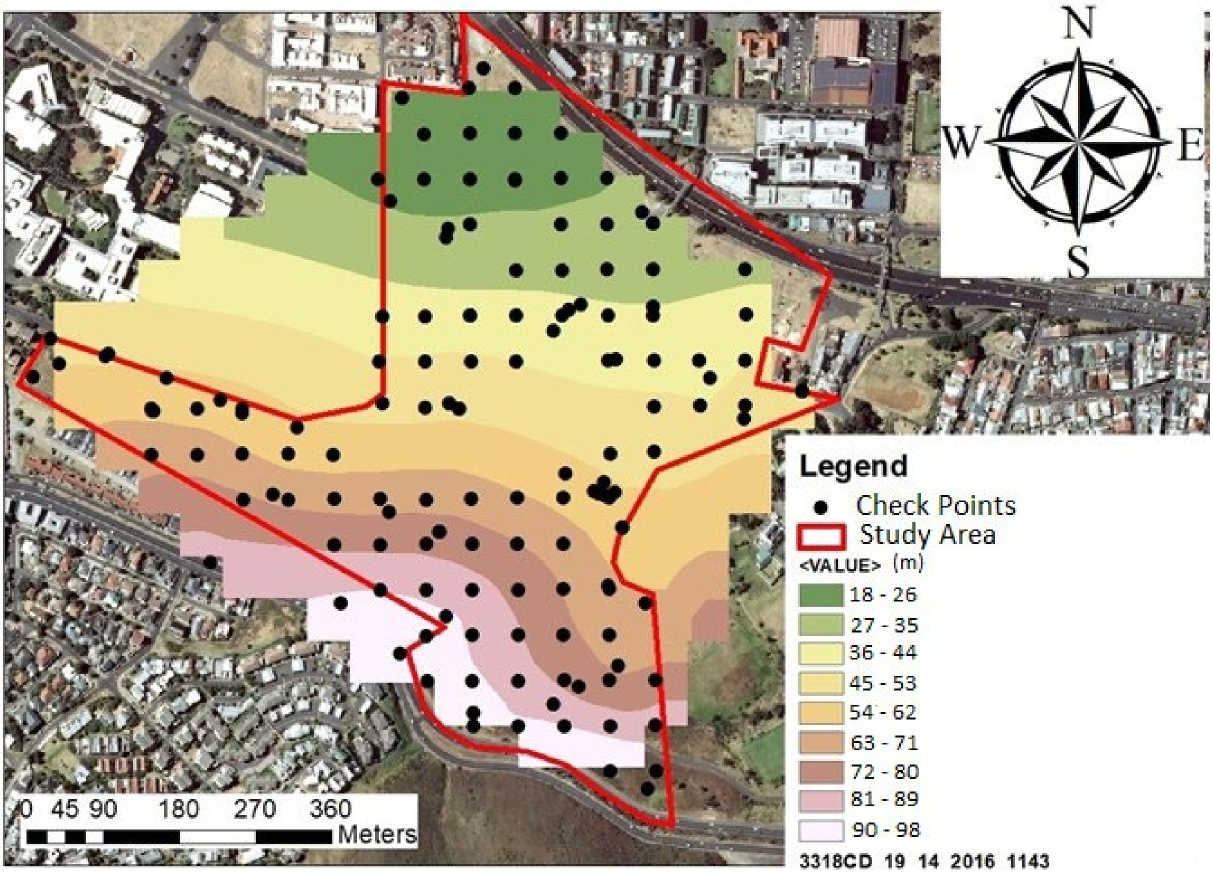

Figure 4. Digital Terrain Model from the Total Station data

The surface model for the flight exported from Pix4D was imported into the ArcGIS project. The project workspace was set to the Hartebeeshoek 94 coordinate system. The DEM generation was performed in the medium resolution mode (see Figure 6). The most important assessment of all these procedures was the independent verification of the horizontal and vertical accuracy of the DEM using check points.

An orthophoto, representing an image of the scene, was produced through the aerial triangulation process, the latter itself based on the measurement of tie points. Having successfully registered each of the overlapping image pairs of the study area, as acquired by the UAV, and ensuring that both the height and tilt distortions were removed (orthorectification) to ensure geometric correctness, accurate spatial information could then be extracted from the imaged area (from the orthophoto). Pre-marking the points on the ground before flight was necessary to ensure their visibility on the image after the flight. The points were then digitized, and their horizontal coordinates (x, y) and height (H) obtained from the georeferenced image (ortho-mosaic) and DEM. After digitising the check points, values were extracted from the UAV DEM to facilitate the validation process.

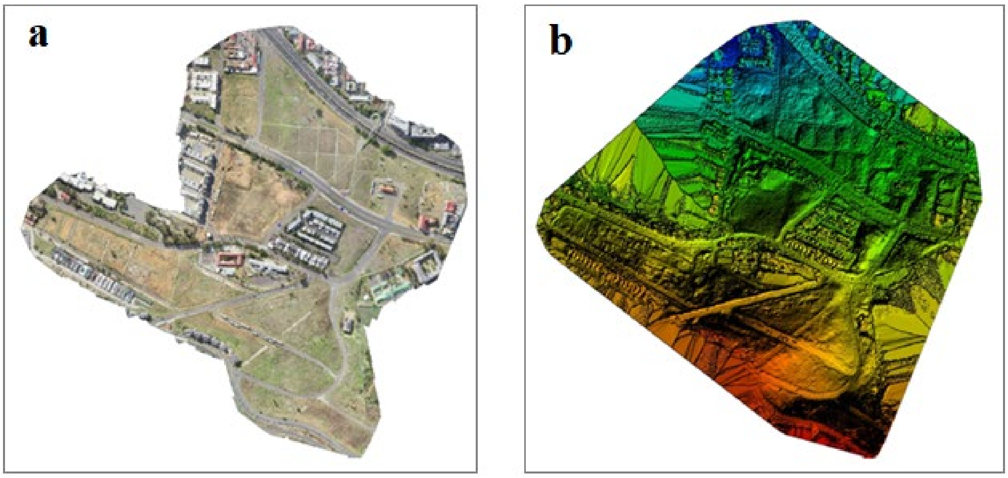

Figure 5. Screenshot of the Ortho-mosaic from UAV data (**a**) and Digital Surface Model from UAV data (**b**)

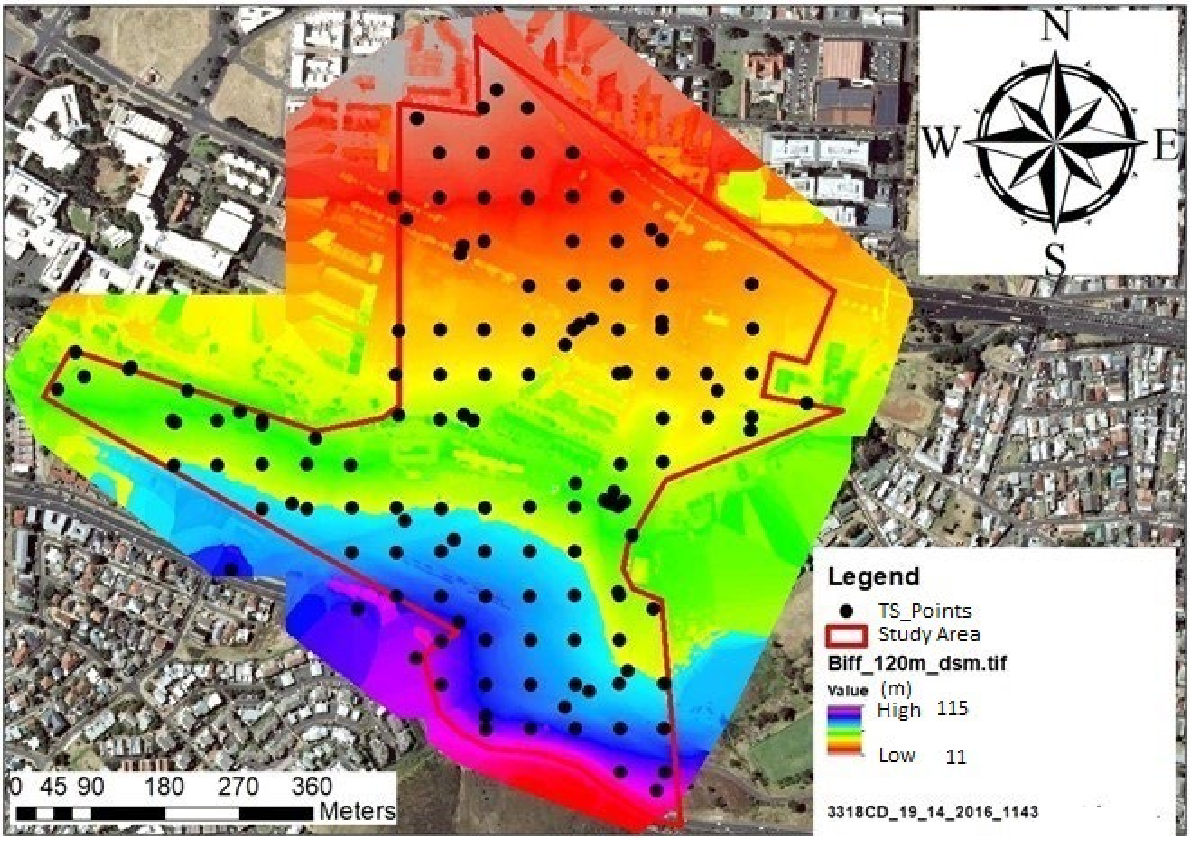

Figure 6. Digital Elevation Model from UAV data

3.3. Residual analysis and DEM accuracy

We used root mean square error (RMSE) to assess the accuracy of the vertical and horizontal coordinates derived from the UAV data covering the study area. RMSE is the mean square root of square discrepancies between the reconstructed model and the surveyed coordinates (Congalton, 2005) at 159 CPs. Errors in this case are the differences between the ground surveyed coordinates and the coordinates from the reconstructed model using UAV data. RMSE is susceptible to estimated outlier values, as large errors have a significant impact on the measure. However, it remains one of the most preferred statistics applied in most validation studies. Equations [1–3] show expressions for RMSE values for the *x*, *y*, and *H* components, respectively.

$$RMSEx = \sqrt{\frac{\sum_{i=1}^{n}(XDEM - XTS)^2}{n}} \qquad [1]$$

$$RMSEy = \sqrt{\frac{\sum_{i=1}^{n}(YDEM - YTS)^2}{n}} \qquad [2]$$

$$RMSEH = \sqrt{\frac{\sum_{i=1}^{n}(HDEM - HTS)^2}{n}} \qquad [3]$$

where:

n is the number of points observed,

XDEM, *YDEM*, and *HDEM* are the *x*, *y*, and *H* coordinates estimated by the model, and

XTSi, *YTSi*, and *HTSi* are the *x*, *y*, and *H* coordinates measured by the Total Station.

4. Results and discussion

4.1. Overall accuracy of UAV derived coordinates

The accuracy of the UAV data was achieved by comparing the Total Station and UAV DEM coordinates at the 159 check points. Table 1 presents the statistics of the differences between the DEM extracted coordinates and the Total Station acquired coordinates. The computed vertical RMSE presented in Table 1 is ±0.079 m at 120 m flying height. The horizontal RMSE is ±0.046 and ±0.038m for the *x* and *y* coordinates, respectively. The spatial distribution of the coordinate differences in *x*, *y* and *H* are shown in Figures 7, 8 and 9, respectively. The vertical coordinates obtained from the UAV DEM are relatively less accurate compared to the horizontal coordinates. The results displayed in Figures 7, 8 and 9 demonstrate the effect of terrain (see Figure 6) on the accuracy of the UAV-derived coordinates. In general, large errors occur in high elevation and steep slope areas.

Table 1. Statistics of the differences in *x*, *y* and *H* between Total Station and UAV data at 159 check points

Coordinate	Minimum (m)	Maximum (m)	Mean (m)	Standard Deviation (m)	RMSE (m)
x	-0.164	0.178	0.003	0.046	0.046
y	-0.136	0.097	-0.001	0.038	0.038
H	-0.270	0.369	-0.042	0.067	0.079

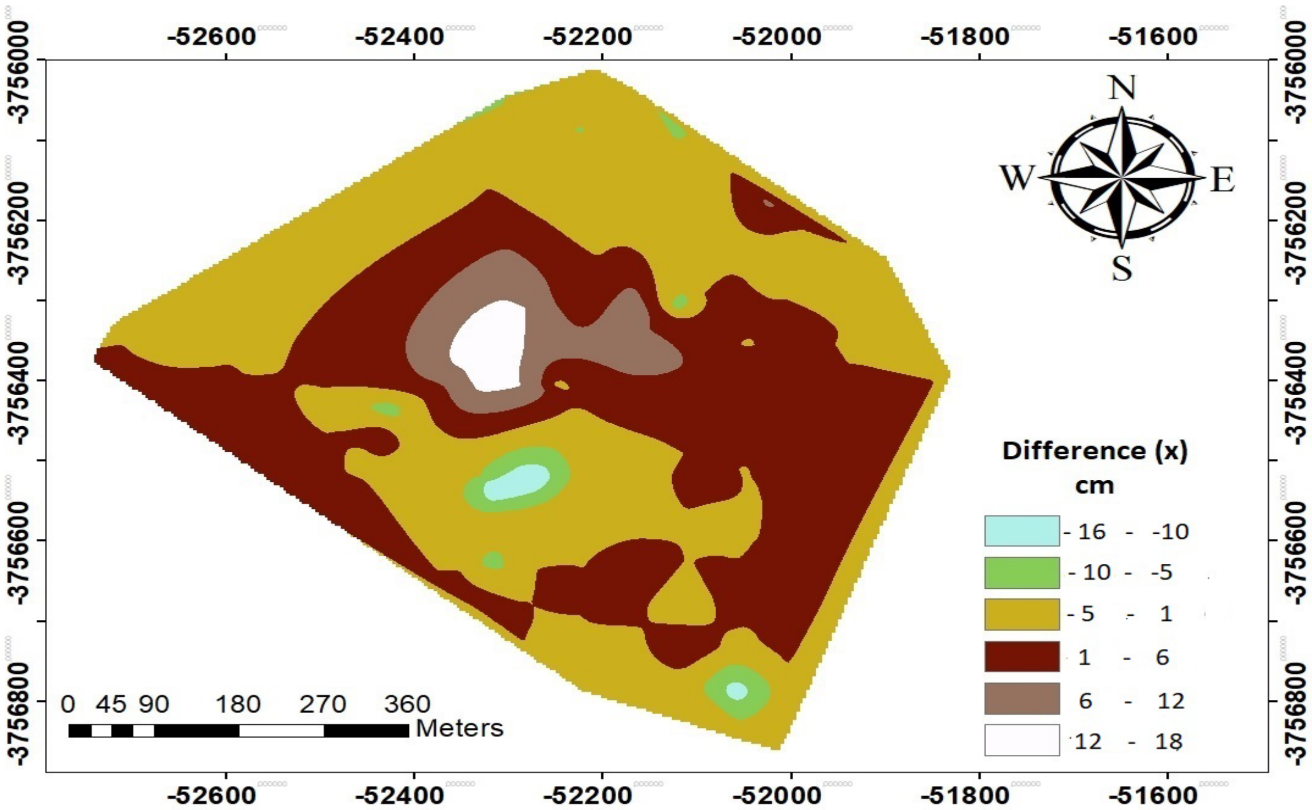

Figure 7. Coordinate difference between Total Station and UAV in the *x* position

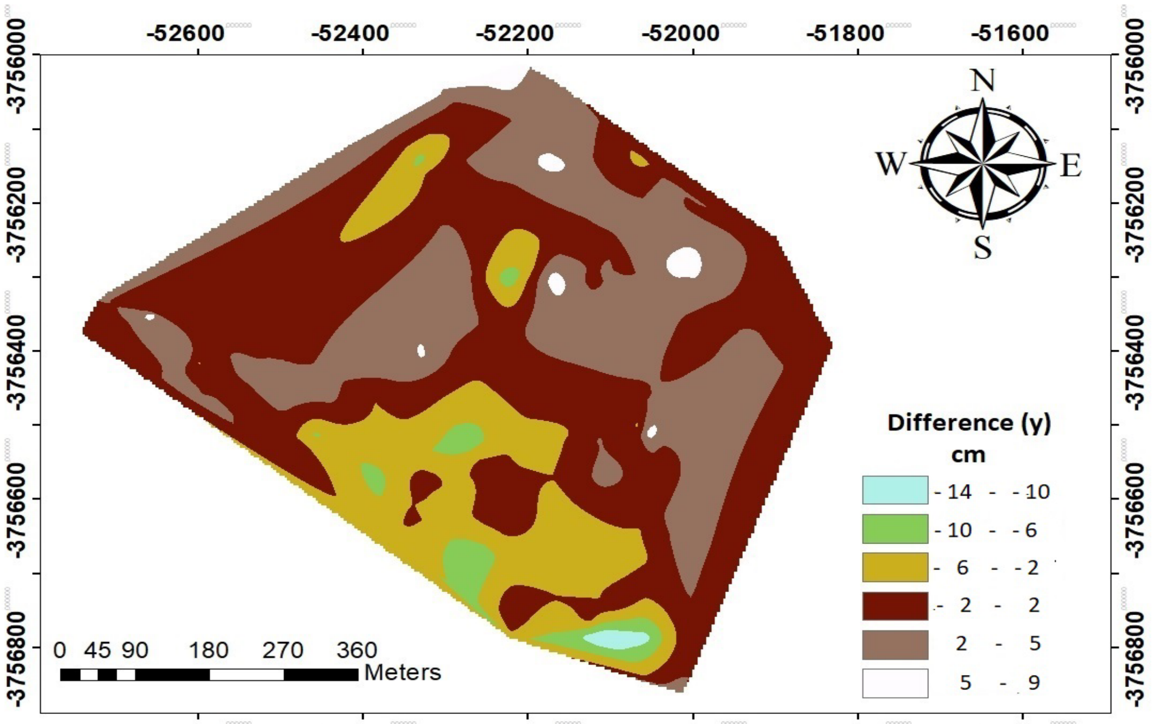

Figure 8. Coordinate difference between Total Station and UAV in the *y* position

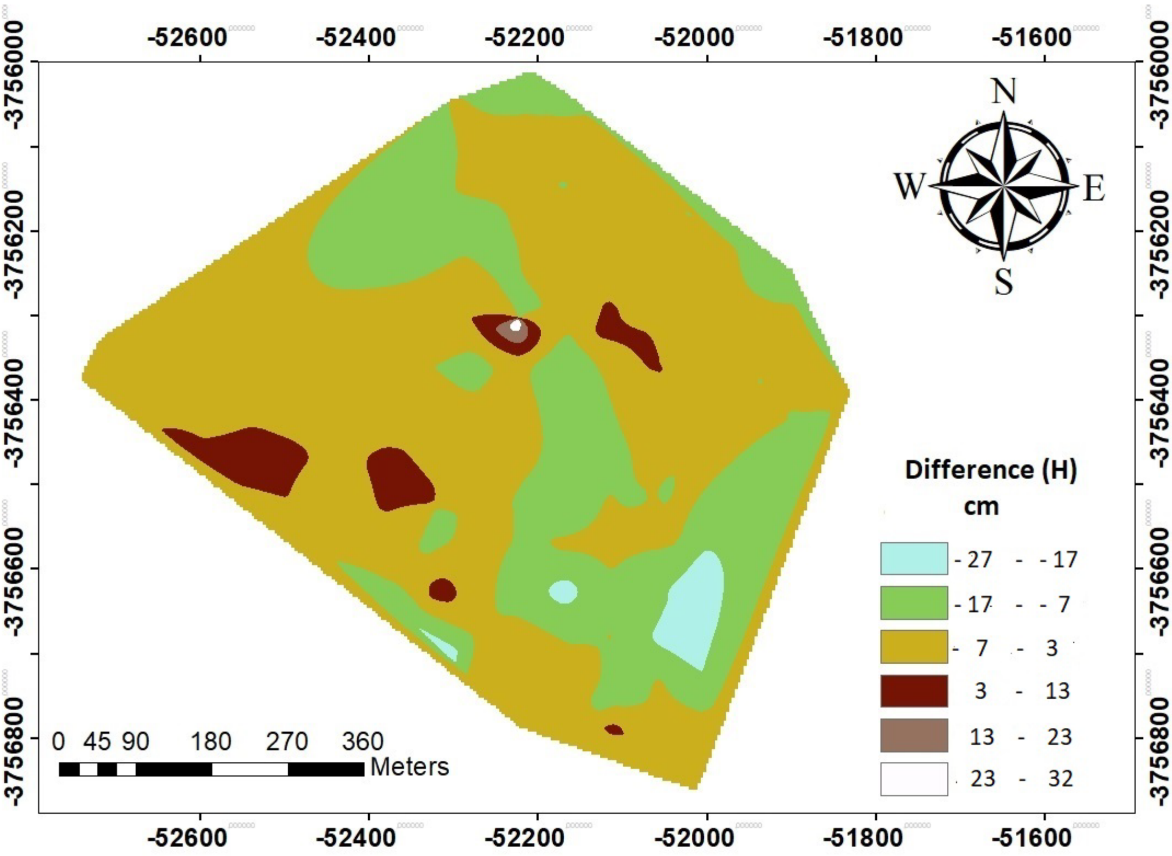

Figure 9. Coordinate difference between Total Station and UAV in the *H* position

4.2. Accuracy of UAV data over a varying slope

Slope measures the rate of change of elevation at a surface location. The slope for an area unit (i.e., a cell or triangle) is measured by the quantity and direction of tilt of the unit's vector: It is a directed line perpendicular to the unit. A cross-section of a selected area is used to determine the points, together with the terrain profiles of each area. These slope profiles are determined according to their respective axes (vertical and horizontal) since both axes give different terrain profiles for each slope. Table 2 shows the statistics of the coordinate differences between Total Station and UAV DEM data at varying slopes, while Figure 10 shows trends in the variation of RMSE across varying slope ranges. The highest error (0.090 m) for vertical position is at a slope of above 15°, and the least error (0.073 m) at a 5–10° slope steepness. For the vertical position, larger errors are more likely to occur over steep-slope areas (>15°) than low-slope areas (5–10°). This means that drone surveys can map gentle slopes and flat surfaces with high precision and efficiency. These results are consistent with those of Talib et al. (2020). Results for horizontal position comparisons show that the largest errors (0.070 and 0.074 m for *x* and *y*, respectively) occur over steep-slope areas (>15°), while smallest errors (0.035 and 0.029 m for *x* and *y*, respectively) occur over low-slope areas (5–10°). In general, as shown in Figure 10, the accuracy of UAV DEM data decrease with increase in slope. It is worth noting that the varying numbers of test points across slope ranges affect rigorous comparisons. It is, however, possible to deduce that slope affects the accuracy of UAV DEM data.

Table 2. Statistics of the differences between Total Station and UAV-derived coordinates at varying slopes

Slope (°)	**Points**	**Coordinate**	**Min. (m)**	**Max. (m)**	**Mean (m)**	**SD (m)**	**RMSE (m)**
0 – 5	74	*X*	-0.164	0.178	0.005	0.055	0.055
		y	-0.112	0.097	0.007	0.038	0.038
		H	-0.233	0.369	-0.039	0.074	0.083
5 – 10	50	*x*	-0.088	0.107	0.007	0.034	0.035
		y	-0.092	0.074	-0.002	0.029	0.029
		H	-0.270	0.120	-0.039	0.063	0.073
10 – 15	26	*x*	-0.044	0.051	-0.002	0.025	0.025
		y	-0.078	0.070	-0.010	0.040	0.040
		H	-0.215	0.006	-0.057	0.052	0.077
>15	6	*x*	-0.164	0.021	-0.032	0.068	0.070
		y	-0.136	0.015	-0.057	0.052	0.074
		H	-0.156	0.050	-0.041	0.087	0.090

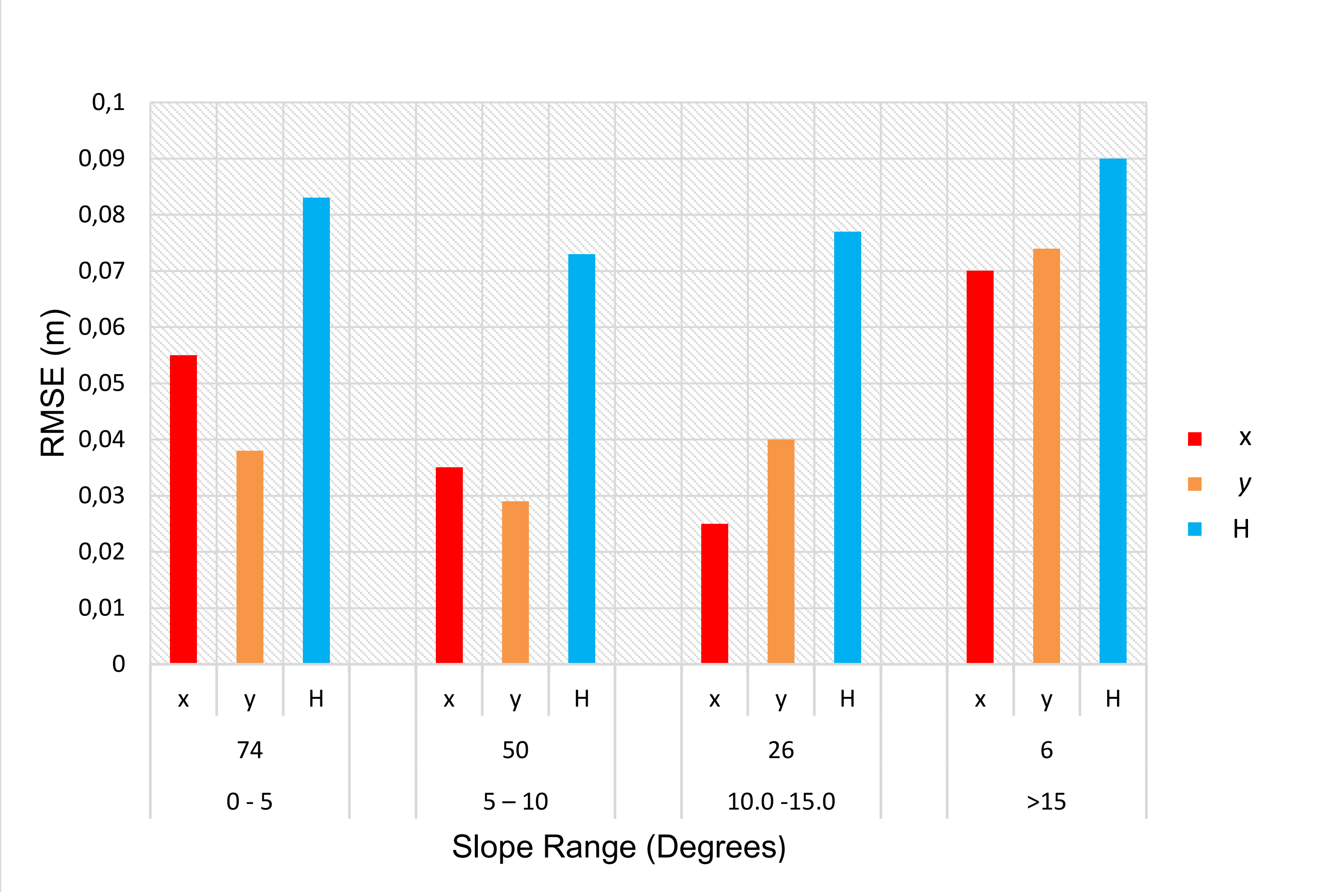

Figure 10. RMSE of the differences between Total Station and UAV-derived coordinates at varying slopes

4.3. Accuracy of UAV data over varying elevation

Table 3 shows the statistics of the coordinate differences between Total Station and UAV DEM data at varying elevations, while Figure 11 shows trends in the variation of RMSE across elevation ranges (0 – 20, 20 – 40, 40 – 60, 60 – 80 and 80 – 100 m). Root mean square error (RMSE) is calculated for each class to analyse the effect of different elevation ranges on the horizontal and vertical accuracy of UAV DEM. The results show that the highest error (0.098 m) for a vertical position is at the elevation range of 60 – 100 m, and the least error (0.052 m) is at the 40 – 60 m elevation range. The highest errors of 0.051 m and 0.061 m for *x* and *y* are at the elevation ranges of 40 – 60 and 0 – 20 m, respectively. The least errors of 0.040 m and 0.025 m for *x* and *y* are at 80 – 100 and 40 – 60 m elevation ranges, respectively. In conclusion, elevation variations influence the horizontal and vertical accuracy of a DEM captured by UAV.

It is worth noting that our results, presented in Figures 10 and 12, do not show clear trends as to the effects of elevation and slope on the UAV-derived coordinates, probably owing to the varying numbers of points used in the validation. However, individual differences indicate less accurate coordinates from UAV in high elevation and steep slope areas. Talib et al (2020) conducted a similar study using a multi-rotor UAV on an area of 0.256 km^2, and their results prove that relatively larger errors occur in high elevation and high slope areas than in low elevation and low slope areas.

Table 3. Statistics of the differences between Total Station and UAV-derived coordinates at varying elevations

Elevation (m)	Points	Coordinate	Min. (m)	Max. (m)	Mean (m)	SD (m)	RMSE (m)
0 – 20	4	*x*	-0.052	-0.029	-0.042	0.010	0.043
		y	0.036	0.070	0.060	0.016	0.061
		H	-0.123	-0.052	-0.082	0.030	0.086
20 – 40	38	*x*	-0.114	0.115	-0.001	0.042	0.042
		y	-0.090	0.097	0.012	0.039	0.040
		H	-0.162	0.369	-0.029	0.085	0.088
40 – 60	55	*x*	-0.074	0.178	0.029	0.048	0.051
		y	-0.028	0.072	0.011	0.021	0.025
		H	-0.163	0.048	-0.041	0.043	0.052
60 – 80	39	*x*	-0.164	0.056	-0.003	0.040	0.046
		y	-0.090	0.031	-0.014	0.024	0.033
		H	-0.270	-0.011	-0.087	0.064	0.098
80 – 100	22	*x*	-0.139	0.006	-0.017	0.040	0.040
		y	-0.136	0.052	-0.029	0.055	0.057
		H	-0.065	0.049	-0.030	0.030	0.077

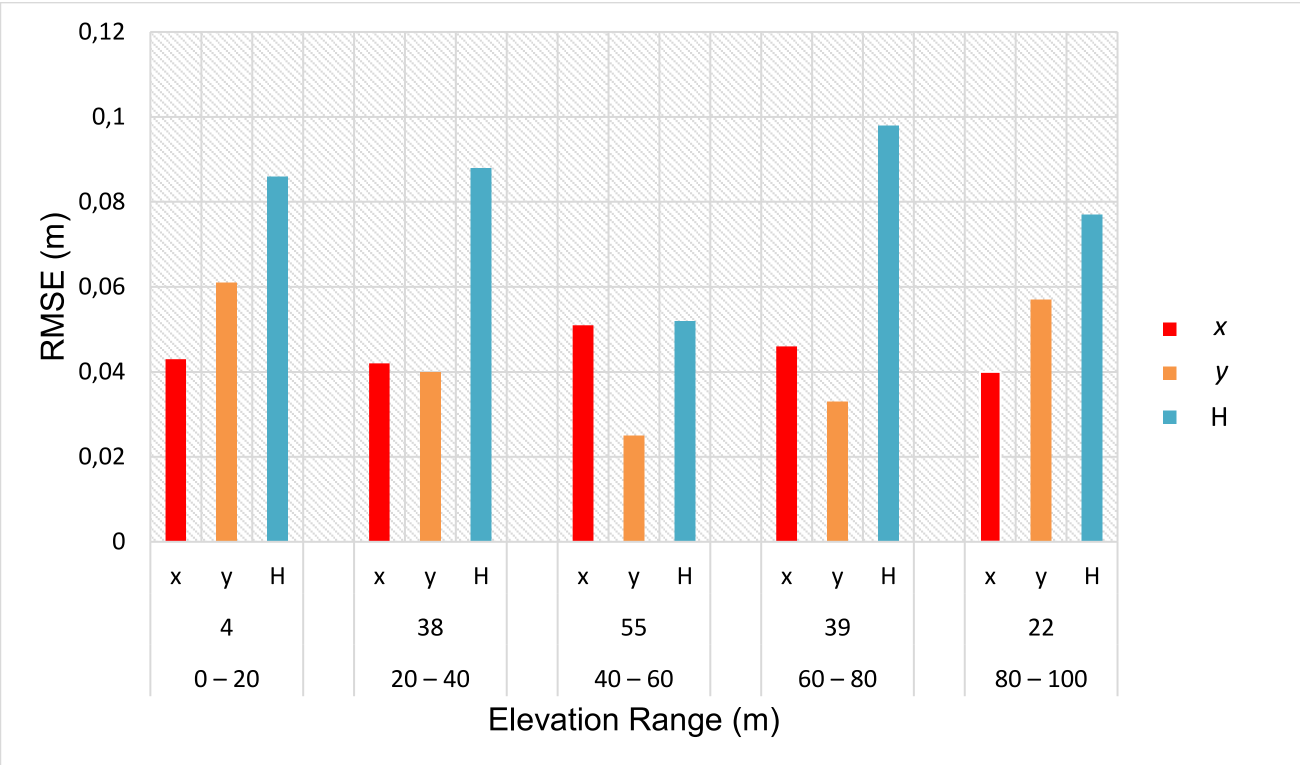

Figure 11. RMSE of the differences between Total Station and UAV-derived coordinates at varying elevations

5. Conclusion

The horizontal and vertical coordinates acquired from Total Station and derived from UAV DEMs in District 6 have been compared in this study. The drone-based elevations were derived using UAV drone computer vision techniques. Using the UAV drone, the re-constructed camera positions and terrain features were used to derive ultra-high-resolution point clouds, ortho-photos, and elevation models from the multi-view UAV camera photos. Coordinates of 159 common points were compared, and a root mean square error (RMSE) of 0.079 m was obtained for the differences between the vertical coordinates measured with the Total Station and the vertical coordinates derived from the UAV DEM. The same points gave a RMSE of 0.046 m on the *x* position and a RMSE of 0.038 m on the *y* position (horizontal coordinate differences). Issuing from a comparison of 157 of the 159 points with a 0.034 m ground sample distance, the accuracy achieved throughout the 159 checkpoints was 99% reliable. Agüera-Vega et al. (2016) found comparable outcomes when they evaluated the accuracy of DSMs and Ortho-photos from UAV photogrammetry. Our results show that *x*, *y* and *H* coordinates derived from UAV photogrammetry concur in terms of practical accuracy with those measured by a Total Station which are commonly used for cadastral, topographic, and engineering survey work. This means that UAV photogrammetry can be used as a surveying method to capture accurate spatial data faster and at a relatively lower cost compared to the conventional surveying techniques.

The UAV field measurements were obtained in less than a third of the time required to conduct field measurements over the same site using the conventional Total Station technique. This demonstrates that UAVs are significantly more efficient over expansive terrain than conventional surveying techniques. The UAV was determined to be suitable for DEM generation and topographical surveys. Owing to the required specific point accuracy and information, it was also determined that DJI Phantom 4 Pro UAV is not suitable for precise surveys requiring horizontal and vertical accuracies better than 0.05 and 0.08 m, respectively. In the coming years, owing to its low cost and relative simplicity, the use of UAV photogrammetry to generate 3D visualisations is likely to increase. Increased image overlap tends to result in greater point densities. The spatial resolution of a Total Station survey is limited to the points surveyed, whereas the UAV-derived topography is a by-product of the resultant three-dimensional point cloud, which is used to generate a high-resolution orthophoto, DEM and DSM.

The combination of field testing, results and analysis gives some clear indications of the accuracies of UAV-derived coordinates and the appropriate use of photogrammetric unmanned aerial vehicles for the purpose of survey applications. However, there are several limitations within aspects of this paper, such as the use of only one commercially available mapping UAV and the relatively small site area. The use of different field-testing sites, vastly different terrain and overall site conditions would better indicate the UAV's appropriate use as a survey application.

6. References

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