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Validating Uav-Sfm Photogrammetry Heights for Highway Topographic Surveying in Tanzania

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Abstract

The demand for accurate topographic surveying data to support ever-growing infrastructural development such as highway construction is huge. Topographic surveying defines a point with X, Y, and Z relative values to create a 3D earth surface model. The Z values represent the vertical height of a point from the benchmark. Vertical heights can be obtained from conventional levelling and Digital Elevations Models (DEMs), as in the case of heights from unmanned aerial vehicle structures from motion photogrammetry (SfM-P) and global navigation satellite systems (GNSSs).

GNSS-Real Time Kinematics (RTK) is the most common method used but is sometimes outscored because of limitations in terms of time consumption and physically inaccessible surfaces. Recently, SfM-P surveys appear to have been quick and effective in accessing areas that would not have been possible when applying GNSS RTK methods. SfM-P surveys have recently been reorganized through cheap, rapid and elementary methods, but few research findings have been documented. Therefore, the study for validating SfM-P surveys in topographic surveys of highways in Tanzania has proved to be most opportune.

In this study, an evaluation was performed by comparing SfM-P survey method heights to GNSS RTK method heights for an area with 3km wide and 19 km long. A total of 39 ground control points was used. The standard deviation between the SfM-P method heights and the GNSS RTK method heights was ±1.4 cm. The samples of elevation data for the preliminary surveying of highways were determined at an 80% accuracy level. However, among the respective heights, only 20% produced a +/- two-centimetre (2 cm) relative precision ─- an extremely high precision level and most satisfactory for detailed topographic surveys. This study confirms that the SfM-P survey can be most helpful in preliminary highway surveys in Tanzania and in surveys of those areas, such as the Dodoma region, with a sparser vegetation cover. However, the SfM-P survey method cannot guarantee good performance to comply with the detailed highway topographic survey height requirements of Tanzania.

Keywords: UAV SfM-P, GNSS RTK, Heights, Topographic Surveying

1. Introduction

Highway topographic survey data play a key role in geometric designs for highways. They are the base for terrain surface modelling and engineering judgments. A 3D earth surface model is produced by a topographic surveying object point made up of X, Y, and Z relative values. From a known point, the Z values represent vertical heights. These values have been the most sensitive parameters to the cost of building highways and to their safety aspects; therefore, critical analysis is emphasized.

The urgency and difficulty in obtaining elevation data in highway design and construction projects outperform conventional surveying methods. The conventional surveying techniques for this study include all methods that use equipment that produces discrete data (one-point position per observation) such as GNSS receivers, total stations, theodolites, and optical levels. These methods require physical access to the object points which is sometimes impossible or demands much time, poses many risks, and collects relatively few points of data to represent the real-world surface. Breakthroughs in science and technology have led to different alternatives to determine vertical heights, as in the case of the unmanned aerial vehicle structures from motion photogrammetry (SfM-P) surveying procedures using unmanned aerial vehicles (UAV)/drones. These new means derive vertical heights from digital elevation models (SfM-DEMs) for different engineering applications.

Over two decades, DEMs have been the most freely available resource for accessing vertical data for various infrastructural projects in Tanzania. The potential application of DEMs has far-reaching applications, with a wide range of practical and analytical utilities. Global digital elevation models (GDEMs) are the most freely available of all the models but do not cover some locations, thus omitting information out and sometimes resulting in large vertical errors (Schumann & Bates, 2018a). Hence, the need to develop accurate production methods in the case of DEMs is vital.

Recently, development has deployed SfM-P surveys, addressing costs, the urgency of the undertaking, and orchestrating the physical accessibility of the site areas. Such an approach has been beneficial under circumstances where ground-based surveys are difficult to undertake and time-consuming, and where some of the significant elements of the landscape are missing (Rayburg et al., 2009). These surveys have helped in the rapid determination of SfM-DEM outputs in areas where there is no GDEM coverage. However, there are few research findings and the associated documentation that have demonstrated the reliability of these surveys in producing accurate vertical data. The SfM-P automation sense requires investigation as most of the activities performed in conventional photogrammetry, such as orientation, control of overlaps, and speed, are all automated. Giles et al. (2020) noted that the changing landscape of geoscience, which is impacted by technology at every turn, needs to be acknowledged. Therefore, these diverse methods used in the determination of heights make such assessments essential as they have a direct impact on the fields of application in question (Alganci, 2018).

This paper evaluated the heights determined through the SfM-DEM models in terms of their fitness for highway topographic surveys as per the Tanzanian Highway Geometric Design Manual, which regulates the topographic surveying practices pertaining to highways (United Republic of Tanzania, 2011). This manual presents a range of up to 1.4 cm that is allowed in leveling misclosures for detailed topographic surveying and 20 cm for preliminary topographic surveying. The suitability or fitness of the SfM-P heights was considered in association with the suitability /fitness of the heights of the points established using the GNSS RTK method.

SfM-P surveys have been used for a wide range of community development projects. The validated findings relating to the heights derived from the SfM-P surveys will be vital to the users of these height data. These findings will improve decision-making in the use of the technology in various infrastructural projects. As such, these surveys need to be researched further (Models, D. E., & Viewing, 2007).

2. Description of the Study Area

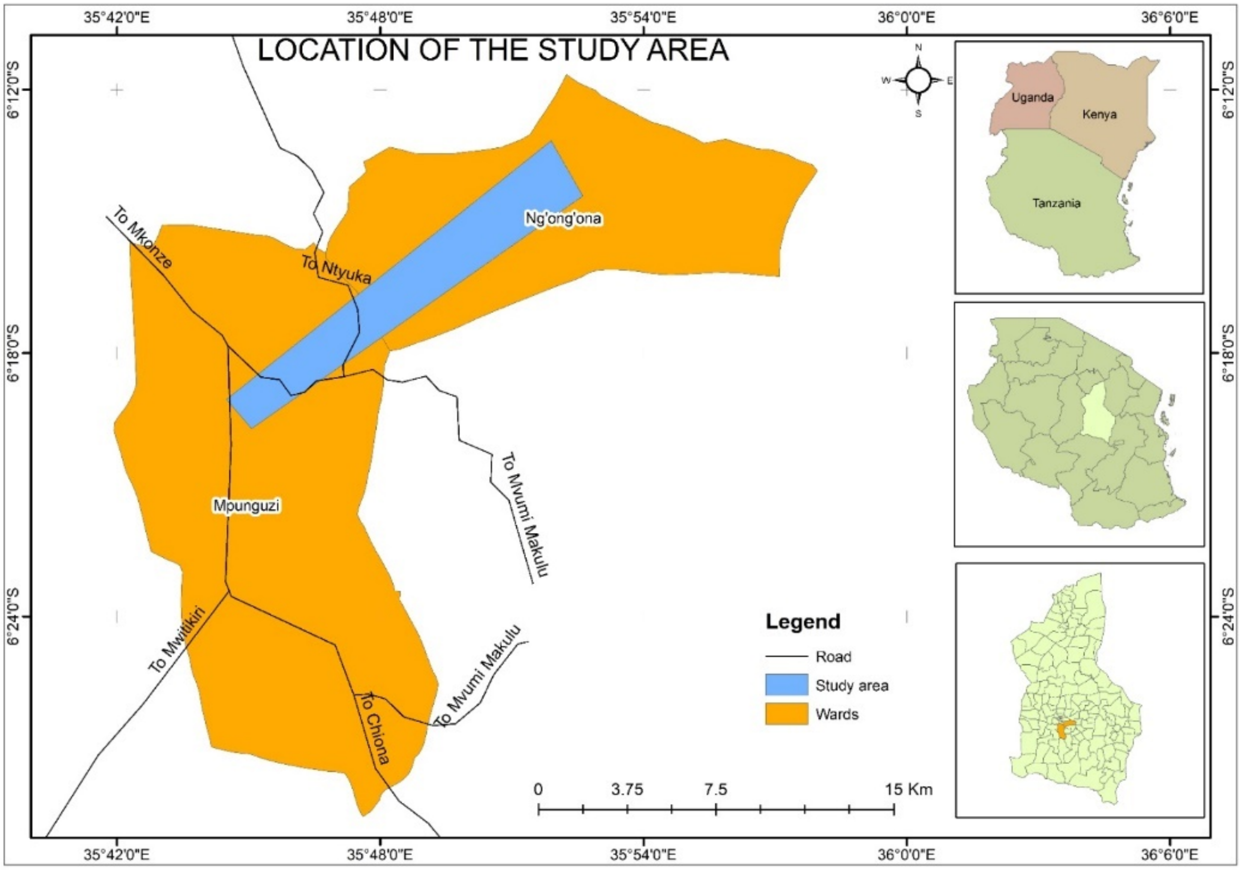

Figure 1. Location of the study area

Dodoma City is the designated national capital of Tanzania. A fresh decree promulgated in 2016 to reinforce the decision to place the government headquarters in Dodoma has attracted several infrastructural projects to the city. These projects need accurate vertical heights data; thus, this article is timely.

The terrain is flat and bare, and, therefore, presents an ideal environment for the application of an SfM-P survey. The study area links the two major trunk roads, namely that of Dar-es-Salaam Road to Iringa Road, which are both part of the city outer ring road. This study area covers a block of 19 km by three kilometres (3 km) and extends from the Mpunguzi to the Ng'ong'ona peri-urban ward in Dodoma city, Tanzania.

3. DEM, SfM-P Surveying, and GNSS -RTK Highway Topographic Surveying

3.1. DEM and SfM-P Surveying

A Digital Elevation Model (DEM) is a 3D computer graphical representation of elevations of the bare ground (bare land) surface of the Earth, excluding trees, buildings, and any other surface objects. There are commercial and free online DEMs to supplement the availability of height data in areas where topographic data may be needed. The available global DEMs cover a large part of the world,but are unfortunately lacking in precision and accuracy and have left some areas uncovered. As researchers in developing countries do not have their own models, they have been conducting research into assessing the precision of the available GDEMs on a global scale (Ulotu, 2017a). However, the GDEMs assessed by these researchers have been shown to have a relatively lower vertical precision (up to 1m) and are technically Digital Surface Models (DSMs) rather than DEMs, while many of the users are uninformed in their deployment of them (Ulotu, 2017b). The recent decade has witnessed the growth of SfM-P surveys that allow for the creation of SfM-DEMs from SfM-points cloud generated from images collected by SfM-P drones.

Drones have the ability to access data of higher spatial and temporal resolutions (Kinghan & Surveyors., 2019). They can be customized depending on user preference; are flexible, rapid in image capture and processing, have a high spatial resolution and are hence successful in effecting good model reconstructions (Rusli et al., 2019).

3.2. GNSS RTK Highway Topographic Surveying in Tanzania

GNSS RTK is the method most used for collecting orthometric height data for topographic surveys (Series, 2019). Those orthometric heights computed through GNSS RTK are considered accurate enough for topographic surveys and in the georeferencing of DEMs (ESRI, 2017) (Batakanwa & Lipecki, 2020).

A preliminary topographic survey collects all the physical information which may affect a proposed highway alignment. It produces maps, consisting of all the surface geometric details in which the preliminary alignment is plotted at a scale of 1:2000. At this scale, this means that the minimum detectable linear distance is 20 cm. From this map, and based on this preliminary alignment, a detailed topographic survey can then be conducted. Height accuracies related to topographic surveys of highways in Tanzania are expressed as the measure of allowable misclosure between two vertical control points (United Republic of Tanzania, 2011). This measure expresses the precision of the standard height closure, as expressed in equation 1:

$$C = \pm\sqrt{K}\ \text{Cm} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{equation 1}$$

where C = maximum closure in centimetres and K is the distance between two control points (in km).

4. Methodology

The resources used for data collection in this study were relatively cost-saving in terms of number of days in the field and the number of sets of equipment, as compared to any conventional topographic surveying project for the size of the area. (Refer to Table 1. and Table 2.)

Table 1. Resources used

Resource	Quantity	Time (Days)
Professional Surveyor	1	10
Survey Technicians	2	10
Unskilled Labor	2	6
Four-Wheeled Car	1	12
UAV Surveying Drone	1	7
Set of GNSS Receivers	1	3
Bag of Cement	1	7
Bag of lime	1	7
Laptop Computer	1	10

Table 2. Data Collection Method

Data Set	Method of acquisition	Software Used
Primary Control Points	Static GNSS	TBC
Ground Control Points (GCP)	GNSS RTK	EG Star
Vertical heights	GNSS RTK	EG Star
UAV Drone Images	UAV Surveying Drone	Agisoft Metashape
	DHJI Mavic 2 Pro	Drone Deploy

A DJI Mavic 2 Pro platform with a 20 Megapixel 1″ CMOS Sensor was used. It has a fish-eye Hasselblad camera in-built, so camera calibration is automated.

4.1. SfM-P Surveying

The procedures set for the execution of the project data collection process are discussed below.

4.1.1. Drone flight planning

The flight planning started by identifying the boundary of the area of interest (AOI). Google Earth Pro software was used to visualise the AOI and to demarcate the boundary line of the AOI. Later, the boundary line was saved in a kmz data format for further flight mission planning.

The flight plan mission for the UAV drone was performed using drone deploy software to obtain the required precision. A high proportion of image overlap, both forward and lateral, was selected to ensure drone resilience against wind gusts. Overlap is vital in performing image matching and was determined by finding the corresponding points on several photos in the automated software.

The parameters used in the flight plan design for UAV drone image acquisition were as follows: a flight altitude of 190m, a front overlap of 70%, a lateral overlap of 65%, a speed of 10 metres per second, and an image resolution of 0.045cm.

4.1.2. Static control points extension and ground control points (GCPs) planning and placement

Control points extension: A network of control points was designed to extend the second-order points within the study area. Three control points, namely, TDO55, TDO56 and TDO57, were established from TDO37 (Geological Survey of Tanzania) and T237 (Ng'ong'ona Primary School Station) as a baseline of observation through the GNSS static method (Refer to figure 2.) They were established to tie the project to the national coordinate system.

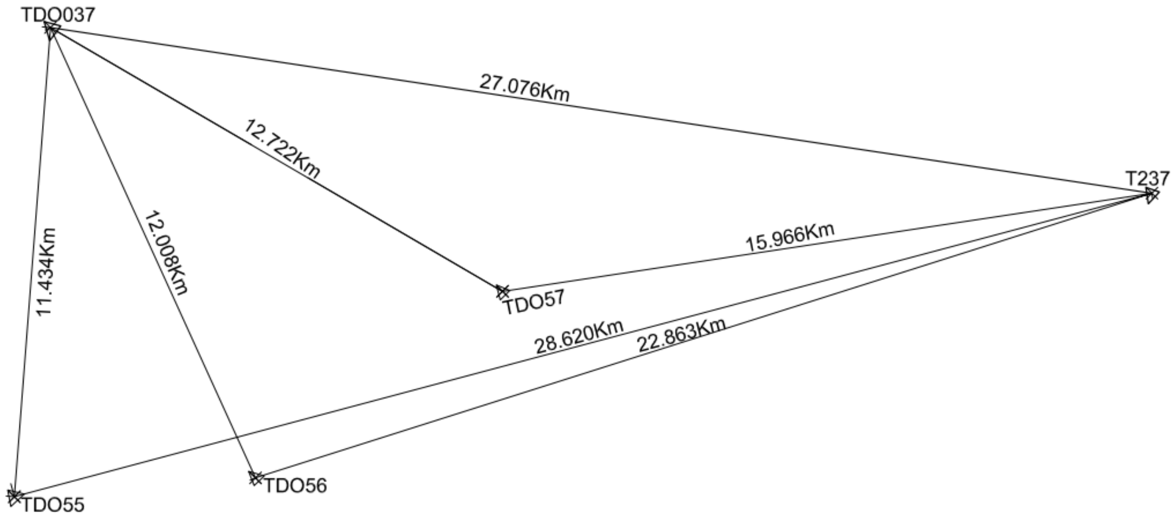

Figure 1. Static control points surveying network

GCP planning and placement followed after the control point extension to assist in the alignment and registration of the obtained images relative to the coordinate system. A total of 42 GCPs were established on the ground. All the GCPs were named by means of the letters, GCP, followed by numerical values (e.g.,GCP1 to GCP42). These GCPs were coordinated by means of the GNSS-DGPS RTK technique. The designed network ensured that the base-rover distance was kept to a maximum distance of approximately two kilometres to ensure that the RTK corrections were relevant every time. Base stations, B1, B2, B3, and B4, were coordinated to determine an approximate closer location for the landing and taking-off of the drone to save power and to catch up on the starting position of a new flight line, as demonstrated in Figure 3. All the GCPs were marked with a one-metre white cross, as seen on the images for georeferencing, alignment and image analysis.

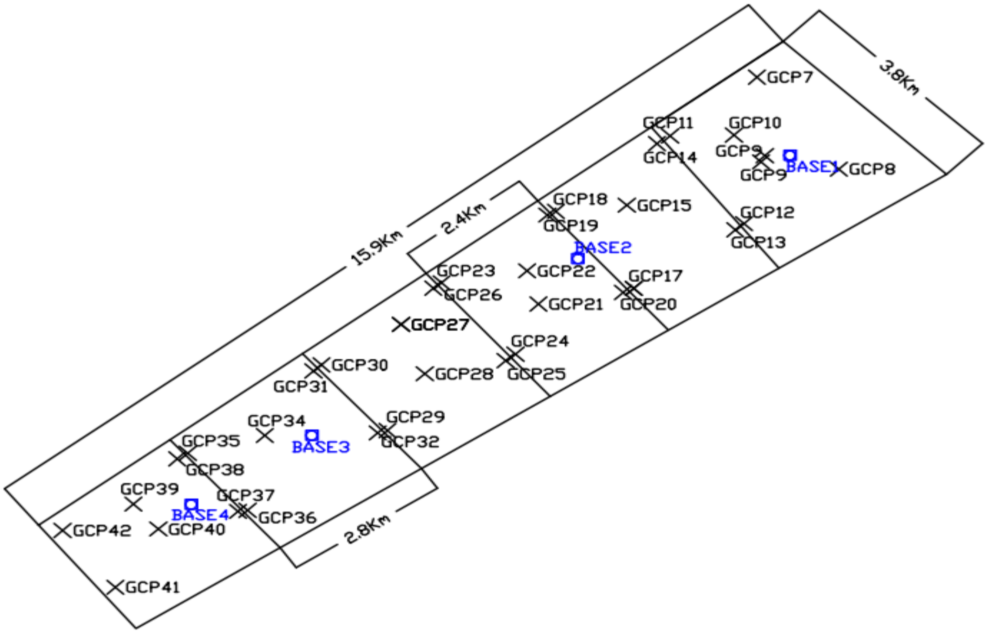

Figure 2. GCP distribution sketch and chunks strategy for image acquisition

4.1.3. Image acquisition

Image data involved very large storage devices and high transfer speeds. The whole study area was divided into seven missions to ensure good data management. SfM-P survey data, such as images, points cloud and SfM-DEM were retained as chunks. Each chunk was made up of more than 1 000 images and covered an area of approximately two kilometres by two kilometres (2km x 2km). Owing to the large size of the image (37GB) and the SfM-DEM (200GB), the piecewise processing techniques were used to avoid running out of storage space, to optimize power management, and to reduce possible computing complications. GCPs were introduced much closer to facilitate chunk stitching along the overlapping portions of the chunks.

4.2. Quality Assessment of SfM-P Heights

The quality of an SfM-P survey is an essential requirement for many applications. The SfM-P surveying method accumulates errors at different stages (e.g., during image capture, the interpolation procedure for resampling, and in determining the land cover in respect of the terrain slope formations (Kinghan & Surveyors., 2019b). The quality of the SfM-P survey was assessed by measuring its vertical height precision against the heights established through GNSS RTK. The SfM heights were derived from SfM-DEMs. Thus, height precision can be defined as the level of uncertainty in the height of a pixel/point from a referenced height datum (Schumann & Bates, 2018); (Böer et al., 2018). However, the quality of the assessment is subjective and relies upon the user's requirements for a particular application (Polidori & Hage, 2020). For this study, quality was quantified in the proposed classes of precision and expressed as a height error, as provided for in the requirements for standard scales to drawings and maps in the Tanzanian Road Geometric Design Manual, as presented in table 3 (United Republic of Tanzania, 2011).

Table 3. Proposed Precision for SfM-DEM expressed as a Vertical Error

Characteristics	Height error (cm)
Very High Precision	≤ 1.5 cm
High Precision	From 1.6 cm - 20 cm
Low Precision	>20 cm

In Tanzania, like most other countries in the world, most of the topographic surveying projects for highways are being executed by applying the GNSS RTK method (Gura et al., 2021). This practical experience in the preliminary topographic surveying of highways in Tanzania has prompted this study to use GNSS RTK data as standardized for comparing the GNSS RTK method to the SfM-P method. Height differences between the GNSS RTK and SfM-P methods were computed and evaluated by means of statistical measures of precision in terms of mean error (ME) and standard deviation (SD). In a nutshell, the smaller the SD, the higher the precision of a dataset. The SD measures the reliability of the values of the SfM-P survey elevations as against their corresponding values as presented in the GNSS RTK survey dataset.

The reliability of the results obtained from the comparison of the two datasets was computed as equations 2 and 3:

$$ME = \frac{1}{n}\sum_{i=1}^{n}(z^{*} - z) \text{ ……………………………………equation 2}$$

$$STD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(z^{*} - z)^{2}} \text{ ……………………………………………. equation 3}$$

where $Z*$ = GNSS RTK elevation; Z = SfM-DEM elevation; and $n =$ the number of values for both equations 2 and 3.

5. Results and Discussion

5.1. Static Observations

The primary data on which all the subsequent results were based were established by applying the static GNSS method. The static control points established were observed for at least 30 minutes. The observation base points were in the Tanzanian reference frame epoch 2011 (TAREF 11) reference frame, which implies that all the data obtained were in WGS 84 EGM 96, and projected to UTM in zone 36S. Table 6 shows the established static control points, TDO55, TDO56, and TDO57, as based on T237 and TDO37.

Table 4. Static control points coordinate list.

ID	Easting (Metres)	Northing (Metres)	Elevation (Metres)
T237	830982.451	9311336.583	1046.261
TDO37	804206.897	9315361.947	1144.436
TDO55	803328.117	9303961.570	1181.896
TDO56	809190.585	9304419.255	1265.054
TDO37	815195.895	9308949.837	1206.704

These are the results from two successful adjustment iterations. A chi-square test with a precision confidence level of 95% at 12 degrees of freedom was obtained. Using Trimble Business Centre software, the post-processed redundancy number was established as 12 and the aprior factor as 2.97.

5.2. Establishment of Ground Control Points (GCPs)

A total of 42 GCPs were established on the ground by applying the GNSS RTK method. Three of the GCPs were not included in the analysis as their images were cropped to remove the premises of the University of Dodoma. The SfM-DEM was produced from more than 10 000 photos, the full mosaic was aligned, and the chunks stitched (Refer to figure 4.)

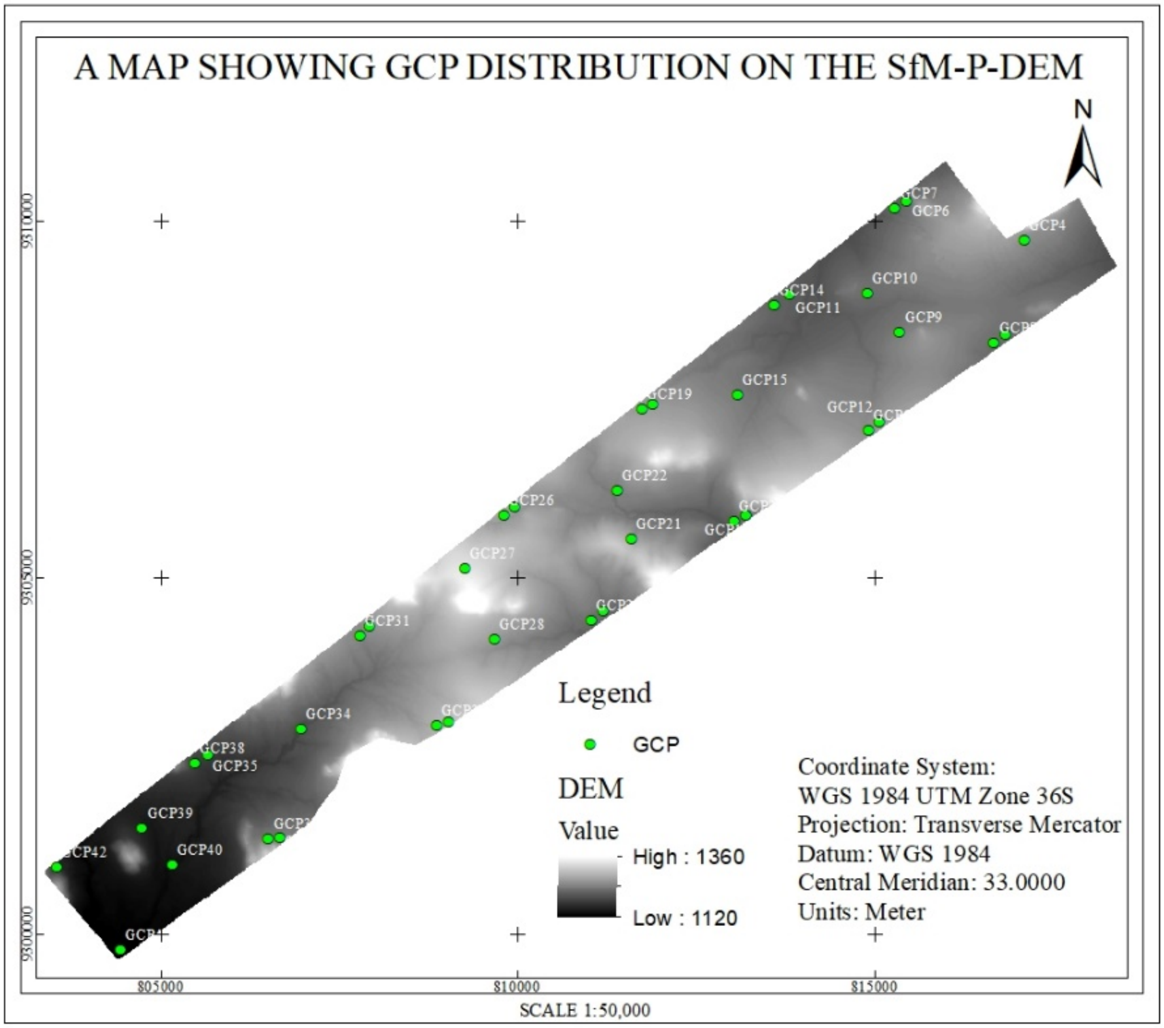

Figure 3.GCP distribution on the SfM-P-DEM

Subsequent to the comparison heights of the GCPs extracted from the SfM-DEM to the heights extracted from the GNSS RTK method, the results were tabulated, as in table 5.

Table 5. Comparison of Heights between GNSS RTK and SfM-DEMs

P.No.	North (m)	East (m)	GNSS RTK Heights(m)	SfM-P Heights(m)	Differences in Height (m)	Point Description	**Vertical Accuracy**	**Land Cover**
1	9310276.598	815448.823	1203.348	1203.607	0.259	GCP6	Low	Bushes
2	9310164.265	815290.318	1200.244	1200.225	-0.019	GCP7	Very High	Bushes
3	9309399.484	818247.381	1188.142	1188.133	-0.009	GCP1	Very High	Bushes
4	9309724.485	817095.471	1229.914	1229.937	0.023	GCP4	High	Bushes
5	9308409.888	816838.259	1205.709	1205.697	-0.012	GCP5	Very High	Bushes
6	9308294.753	816675.994	1206.007	1206.018	0.011	GCP8	Very High	Bareland
7	9308985.063	814899.494	1206.219	1206.246	0.027	GCP10	High	Grapes Farmland
8	9308443.483	815356.866	1216.14	1216.174	0.034	GCP9	Considerable	Grapes Farmland
9	9307184.104	815071.671	1234.908	1234.953	0.045	GCP12	Considerable	Bushes
10	9307059.743	814925.494	1234.624	1234.594	-0.03	GCP13	High	Bushes
11	9308969.215	813820.297	1195.377	1195.415	0.038	GCP11	Considerable	Grapes Farmland
12	9308812.588	813597.351	1199.171	1199.187	0.016	GCP14	Very High	Bareland
13	9307558.643	813089.524	1214.608	1214.568	-0.04	GCP15	Considerable	Grapes Farmland
14	9307433.93	811889.937	1234.533	1234.509	-0.024	GCP18	High	Bushes
15	9307357.893	811746.679	1237.985	1237.984	-0.001	GCP19	Very High	Bareland
16	9305867.893	813204.843	1214.598	1214.626	0.028	GCP17	High	Bareland
17	9305867.905	813204.829	1214.996	1214.626	-0.37	GCP18	Low	Bushes
18	9305784.619	813028.071	1200.508	1200.419	-0.089	GCP20	Considerable	Grapes Farmland
19	9305550.463	811595.797	1236.631	1236.668	0.037	GCP21	Considerable	Grapes Farmland
20	9304532.364	811206.357	1203.759	1203.793	0.034	GCP24	Considerable	Bareland
21	9304399.201	811040.406	1206.335	1206.177	-0.158	GCP25	Low	Bareland
22	9306224.561	811402.87	1220.62	1220.633	0.013	GCP22	Very High	Bushes
23	9305982.686	809953.164	1239.79	1239.844	0.054	GCP23	Considerable	Bushes
24	9305874.459	809815.493	1241.603	1241.612	0.009	GCP26	Very High	Grapes Farmland
25	9305135.257	809270.615	1286.844	1286.691	-0.153	GCP27	Low	Bushes
26	9304133.533	809672.195	1236.391	1236.421	0.03	GCP28	Considerable	Bareland
27	9302980.723	809040.987	1262.023	1262.038	0.015	GCP29	High	Bareland
28	9302930.869	808874.268	1253.873	1253.825	-0.048	GCP32	Considerable	Bareland
29	9302879.355	806964.513	1189.014	1188.954	-0.06	GCP34	Considerable	Grapes Farmland
30	9304314.341	807926.34	1230.239	1231.066	0.827	GCP30	Low	Bareland
31	9304192.441	807788.428	1223.682	1223.706	0.024	GCP31	High	Bareland
32	9302516.803	805662.701	1173.94	1173.975	0.035	GCP35	Considerable	Bareland
33	9302402.433	805481.271	1175.073	1175.085	0.012	GCP38	Very High	Bareland
34	9301359.144	806672.569	1220.241	1219.775	-0.466	GCP36	Low	Grapes Farmland
35	9301336.658	806512.484	1219.992	1219.496	-0.496	GCP37	Low	Bareland
36	9300975.975	805164.99	1144.621	1144.681	0.06	GCP40	Considerable	Bareland
37	9301485.044	804743.287	1153.961	1153.915	-0.046	GCP39	Considerable	Bareland
38	9300947.286	803545.305	1166.269	1166.118	-0.151	GCP42	Low	Bareland
39	9299792.944	804436.878	1128.534	1128.547	0.013	GCP41	Very High	Bareland
					Mean Deviation = 0.014m			

5.3. Analysis of Deviations

From table 7, the values with negative deviation signify that the modelled height is below ground surface height and the positive value signifies that the modelled height is above ground height. The vertical precision ranges are referred to in Table 3. The mean deviation of 1.4cm and the standard deviation of 0.196, mean that when the data were computed at a 95% confidence level, the Z value was 1.96 and therefore, produced a confidence interval of 1.4 ± 0.01 cm. Among the heights from the SfM-DEM, only 20% of the heights presented with a very high precision range, as suggested in the Tanzanian Geometric Design Manual(United Republic of Tanzania, 2011). The manual set a standard closure precision of ±1.40 cm to ±2.00 cm, to be attained between GNSS RTK and SfM-P heights, with control points/benchmarks at two to four kilometres (2 - 4 km) respectively.

Table 7 also shows the different levels of precision for different land covers, as classified. However, the analysis depicts no precision trend related to the land cover in question. The image resolution captured was set to 0.045 cm. This high resolution ensured accurate triangulated irregular network (TIN) modelling for height interpolations, minimizing the possibility of encroachments between the neighbouring classes, irrespective of the landcover class within.

6. Conclusion and Recommendations

6.1. Conclusion

The results obtained from this study clearly show that the heights derived from the SfM-P survey can be used for preliminary topographic surveys of highways, but are not reliable for detailed topographic surveys of highways in Tanzania. The misclosures were within acceptable standards as far as the Tanzanian Highway Geometric Design Manual is concerned (United Republic of Tanzania, 2011). The high resolution of the images and the strategic distribution of GCPs also positively impacted the precision of the SfM-P survey heights.

6.2. Recommendations

To save on time and costs, the author recommends the application of SfM-P technologies for the preliminary topographic surveying of highways. Such surveys also serve to improve the methods associated with model reconstruction and the visualization of a 3-D surface model and, hence, simplify and enhance the associated decision-making processes.

The study also recommends further research to check the suitability/fitness of SfM-P surveying heights *versus* spirit levelling to deduce the geoidal model effects emanating from SfM-P surveying errors.

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