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Topographic Survey and Modelling using Photogrammetry: A Comparison against Electronic Distance Measurement (EDM) Method

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Topographic surveying has been an important companion to the civil engineer in the development of human civilisation since ancient history. It is used to map terrestrial features on the ground along with its contour heights. Application of this can be seen in the establishing land boundaries and setting out construction projects. Conventional methods of surveying range from ground field methods such as the use of total station to aerial surveys such as photogrammetry or LiDAR. This study looks to assess the feasibility of aerial photogrammetry using UAVs as a replacement to the conventional EDM survey using total stations. This objective was achieved by carrying out both photogrammetric and EDM surveys on a 350m long stretch of highway. The resulting survey data were processed to produce two comparative TIN surfaces of the highway which were then superimposed together and compared for accuracy. It could be observed that on plan view, both surfaces were quite closely matched with a maximum difference of less than 0.4m and a low standard deviation. In elevation view, however, the differences were larger with maximums of 5.0m, accompanied by large standard deviations. RMS error analysis carried out also correlate with the findings.

Keywords: photogrammetry; topographical survey; highway survey; triangular irregular networks

I. INTRODUCTION

For as long as man has been constructing buildings and infrastructure, topographical surveying and mapping have existed. As early as 3000 BC, surveying was used to re-establish farm boundaries following flooding from the River Nile (Shank, 2012). In simple terms, topographic surveying is the art and science of measuring distances and angles to establish terrestrial features. In construction, surveying serves the important function of identifying the contour and features on the ground, establishing boundaries, determining quantities to be cut or filled, as well as setting out the correct position prior to construction of buildings and infrastructure.

Topographic surveying has come a long way since the ancient methods of using ropes and pegs on the ground to measure distances and angles to the use of modern total station or LIDAR for complex mapping. These advancements have made surveying more accurate and less tedious but some challenges still remain. For example, the conventional method of total station survey still relies on multiple surveyors to physically trek across the site, quite often knee deep through uncharted forests. This is often a labour intensive, time-consuming and expensive affair (Shank, 2012).

Currently, the most widely adopted method of topographical surveying is through means of electronic distance measurement (EDM). This method typically involves the use of theodolites or total stations. Compared to a conventional theodolite which measures only angles between points, a total station has the ability to measure both angles and distances to give coordinates on plan as well as elevation data. The on-board computer processes and

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saves the coordinates based on surveyed information and also averages multiple observations. As with a theodolite, a total station requires at least two persons to carry out, one to operate the station itself and another to position the target pole. However, accuracy of a total station survey is highly dependent on position of the sun for digital levellers and the distance to, angles and colour of reflected surface for reflector-less total stations (Beshr & Elnaga, 2011).

On the other hand, photogrammetry (PS) is the art and science of converting 2D image stills or photographs into a 3D geometric model. In essence, it involves taking sufficient photos of the subject matter such that it is fully enveloped by a sphere of photographs without any gaps. It is also important to ensure that all photographs overlap with each successive ones on all directions as this enables them to be aligned. A photogrammetric processing software is then used to generate a representative 3D model by stitching together the photos based on common features in a sequence of images and interpret it into spatial digital points. The resolution and accuracy of the model depends on a multitude of factors such as lighting condition, distances, pixel density of the images, the algorithm of the processing software and so on. It also requires direct line of sight to map accurately. Single-lens reflex (SLR) cameras with prime lenses are preferred over zoom lenses to prevent systematic errors and texture-less surfaces such as glass or painted walls may be difficult to process (Bhatla *et al.*, 2012). Photogrammetry has been used to scan anything from small object such as a child's toy to a building to mapping an entire town or city and makes photogrammetry a very cost-effective alternative to laser scanning (El Meouche *et al.*, 2016). There are two basic categories of photogrammetry: terrestrial where images are taken on or near ground level and aerial where images are taken from an aircraft. Aerial photogrammetry has already been adopted in the industry to monitor progress of construction on site (Memon *et al.*, 2013), as well for modelling preserved heritage structures such as the Tholos in Greece (Hatzopoulos *et al.*, 2017). This is in spite of some research still sceptical about the accuracy of the method to re-produce models as there are still significant errors in the region of +2% and -5% (Dai *et al.*, 2012). To scan a large expanse such as a topographic landscape, similar methodology applies with the obvious exception that the photos would form a blanket over the extents rather than a globe. Such forms of photogrammetry are more typically conducted using some form of aerial photography techniques on-board aircraft or more popularly these days, by unmanned aerial vehicles (UAVs). Topographic survey and mapping using photogrammetry has been gaining popularity due to its competitiveness; fast result, low cost and high accessibility (Eisenbeiss, 2011).

An overall pros and cons comparison between the two surveying methods is summarised in Table 1.

Table 1. Comparison between photogrammetry vs. electronic distance measurement surveys

	Photogrammetry (PS) Survey	**Electronic Distance Measurement (EDM) Survey**
Speed	✓ Fast	✗ Slow
Manpower	✓ Low demand (1 semi-skilled person)	✗ High demand (minimum 2 skilled persons)
Coverage & Accessibility	✗ Poor (limited by terrain, obstacles)	✗ Poor (limited by terrain, obstacles)
Cost	✓ Low	✗ High

Source: (Bryant, 2018)

The resultant data generated from most modern surveys methods can be converted to a 3D point cloud data file. The point cloud data can be imported into any one of the 3D modelling software such as Autodesk Revit, Civil 3D or Bentley Microstation to form TIN (triangular irregular networks) surfaces or DTMs (digital terrain model). TIN surfaces are a series of faceted triangles that join up the point clouds to represent the topography being modelled. Resolution of TINs tend to be higher for variable terrain than flatter, featureless ones. The more amount of points the better, and a denser cloud is more reliable as it provides better observation points and higher accuracy (Canada, 2016). TINs are extensively used in the GIS (geographic information system) community and also for engineering applications where higher precision is required for calculating land areas and volumes. It is suitable for modelling small areas in great detail but less so for large areas as the high amount of nodes require excessive computing power.

II. RESEARCH OBJECTIVES

The objective of this research exercise is to assess the suitability of using photogrammetry in replacing the conventional practice of carrying out EDM topographical survey using total stations for 3D mapping and modelling of existing highway profiles. In order to achieve this objective, the accuracy of photogrammetry survey was determined by comparing its resultant 3D contour model against that from an EDM total station survey.

III. METHODOLOGY

The experimental programme involved performing two iterations of survey activity of a pre-determined site: first an aerial survey using a UAV followed by an EDM survey using a total station. The point data from each set of survey were used to develop 3D TIN surfaces of the terrain which were then superimposed to compare accuracy. Figure 1 summarises the activities in the different phases of the experimental programme.

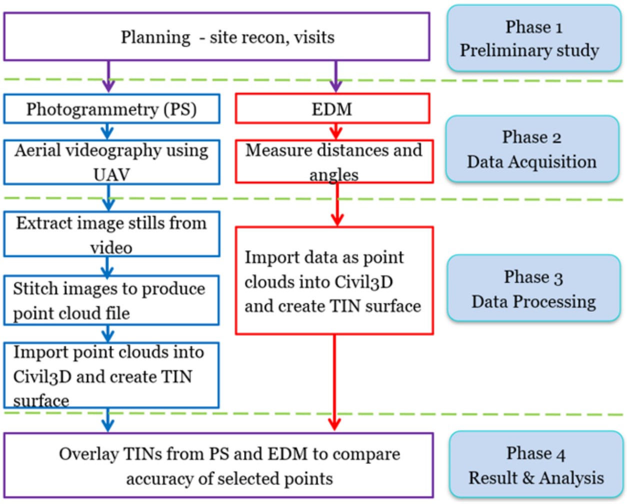

Figure 1. Flow chart of methodology

A. Surveyed Location

Based on past research, the site selected for the PS survey should ideally meet the following criteria:

- Contains an existing highway on rolling terrain,
- Be free of large building structures.
- Contains areas with and without foliage cover (Eisenbeiss, 2011).

The site selected is a 350m x 50m stretch of road centred at coordinates 6°01'56.5"N, 116°06'59.4"E (Figure 2). The road name is Jalan Samudera and is located within the confines of Universiti Malaysia Sabah, a public university in the city of Kota Kinabalu, Malaysia. Jalan Samudera is one of the main roads in the university premises, linking the main library, recital hall, and several of faculty buildings. It is a 2 km long single carriageway road that is street-lighted and has kerbed pedestrian walkway. The road segment selected for modelling is approximately 350m in front of the main library. This site contains a good mix of foliaged and clear terrain, with minimal built-up obstructions. The terrain in this region is considered rolling terrain but the extent under investigation is a gentle and linear slope of less than 8 % gradient.

Figure 2. Extent of highway surveyed *6°01'56.5"N 116°06'59.4"E*

Source: (Google Maps, 2019)

1. Photogrammetry Survey (PS)

A UAV (DJI Phantom 4) was employed exclusively for the photogrammetry survey. The Phantom 4 (Figure 3) which is a battery powered quad-copter with on-board high definition camera. The UAV flight was carried out on 13 April 2019 between 10 am and 2 pm under good meteorological conditions with clear skies and minimal wind (< 3 kts) to ensure minimal drift and image distortion. Cloudy skies and highly oblique sun positions can cast moving shadow lines on the ground and may distort the image processing results. Three personnel were involved in the survey: a drone operator, a supervisor and a safety observer. The UAV was programmed to fly an orbiting circuit track at a height of 80 m AGL along the selected highway (Figure 4) with the camera caged to look vertically downward (< 3 ° off vertical) to take true vertical air images. Forward speed was kept under 5km/h to prevent distortion.

Figure 3. DJI Phantom 4 UAV
Source: (Da-Jiang Innovations, 2019)

Figure 4. UAV track along ground
Source: (Google Maps, 2019)

The recording was initially done in video mode at 30 fps with a resolution of 1280 x 720 to ensure a good stereoscopic coverage of the survey area. One hundred image stills of the same resolution were extracted from the video using frame export function in video editing software. Preliminary research had recommended a minimum 60 % overlap in the images along the UAV track and between 20 % to 40 % lateral overlap as shown in Figure 5. Higher amounts of overlaps and coverage would reduce coverage errors arising from crab or tilt but also more images. It is also recommended that the intersection angles between adjacent images be kept in the region of 60 to 90° (Dai *et al.*, 2014). Full details of the imaging specification and mission details are summarised in Table 2.

Table 2. Photogrammetry survey specification

UAV Imaging Specification	
Sensor size	½.3 inch CMOS
Video and image width/height	1280 x 720 pixels
Sensor height x width	8 x 13.2 mm
Lense focal length	8.8 mm
Mission Details	
Flight altitude	100 m
Forward speed	< 5 km/h
Total tracked distance	~ 630 m
Flight duration	~ 5 mins
Video duration	3:58 mins
Image Details	
Image overlap (forward/side)	> 60 %/ >30 %
Total number of images extracted	100
Ground sample distance	~ 12.63 cm/pixel
Coverage per image	~ 150 m^2
Distance between exposure stations	< 10.0 m

The image stills were then aligned together and stitched using an off-the-shelf photogrammetric software, Autodesk ReCap Photo, which interprets the scanned images of objects into a 3D mesh of the terrain. The terrain mesh is then purged of unwanted elements such as unconnected points or elements and then exported into Autodesk Recap Pro to create point cloud data which contains planimetric (x, y) and elevation (z) information. The point clouds data are imported into Autodesk Civil 3D (C3D) to generate a TIN surface.

2. Electronic Distance Measurement (EDM) Survey

The EDM survey was carried out using a conventional total station unit via traversing and levelling. This was carried out between 9 am and 4 pm on 7 April 2019 by three personnel where one operates the total station whilst another two assists using the prisms. It was completed within the day. The indirect method of contouring using random spot was carried out due to proximity to a busy road. The survey point data were obtained using a mix of trigonometry and triangulation, resulting in a data represented in x, y and z Cartesian coordinate system related to the temporary bench-mark (TBM), hence referred to as the reference point 'R'. This TBM/reference point 'R' is located at the corner of one of the sets of yellow road rumble strip as shown Figure 6 below. The collected x, y, z coordinate points were processed using excel and then imported points into Autodesk Civil 3D to form a TIN surface.

B. Comparison

Both the TIN models from PS and EDM surveys were superimposed in C3D centred at the TBM/reference point marked 'R' (coordinate 0, 0, 0) and then aligned using another control point P81 which also lies along the yellow road rumble strip.

A hundred points representing features on the topography such as road markings, corners of pavement and buildings, and other permanent fixtures were pre-selected to assess the accuracy between the two TIN models (Figure 5). These feature points were compared in terms of relative location on plan (x and y-axes) together with the elevation (z-axis). The accuracy comparisons were performed using statistical methodology. Standard deviation (SD) was used to measure the spread of the differences whilst root mean square error (RMSE) was used to measure the amount of difference.

C. Limitations

The software (Autodesk Recap Photo) employed to stitch the image stills is a free to use, educational version which has a maximum processing capacity of one hundred (100) images. As such the area surveyed had to be limited. Additionally, the UAV had to be flown at greater heights at the expense of detail and image resolution to ensure full coverage of the area.

Figure 5. Survey points used for comparison
Source: (Google Maps, 2019)

IV. RESULT AND DISCUSSION

A. TIN Surfaces from Point Cloud Data

The 3D point cloud of the highway topography from the stitched images can be seen in Figure 6. The model was visually inspected to ensure sufficiently dense and well-connected mesh as well as for problems such as duplicated contours or overlapping points. The highway itself and main features surrounding it were well-aligned with but some artefacts and distortion were evident. Furthermore, there are large areas of voids such as the underside of trees where no images were available.

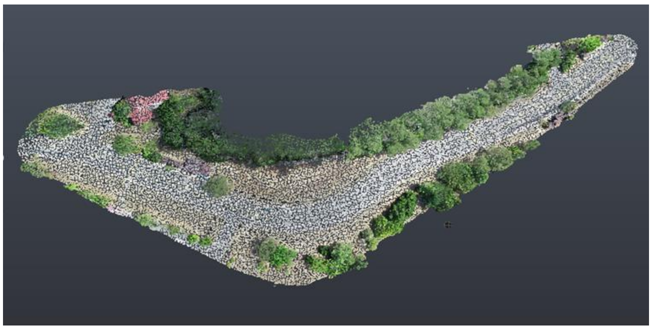

Figure 6. Point cloud from Autodesk ReCap

From the point cloud data, 3D mesh model (Figure 7) was generated and imported into Autodesk Civil 3D to produce the final TIN surface for comparison purposes. The TIN surface (Figure 8) shows the series of triangle vertices joining up to form the surface contour. Quite evident is the detail and amount of triangulation between the left-hand side of the surface which is the lower and flatter part of the terrain and the right-hand side where the highway began to slope upward. This correlates with past researches that have indicated that flatter terrain would tend to have lower mesh resolution whilst sloping or rolling terrain would have higher resolution.

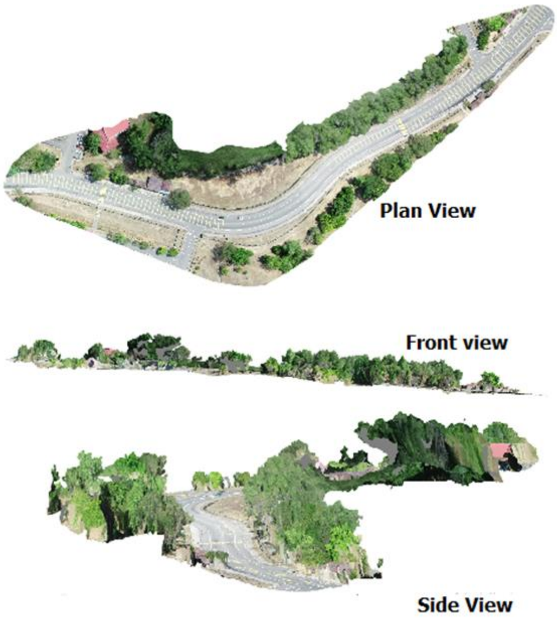

Figure 7. 3D mesh of point cloud data

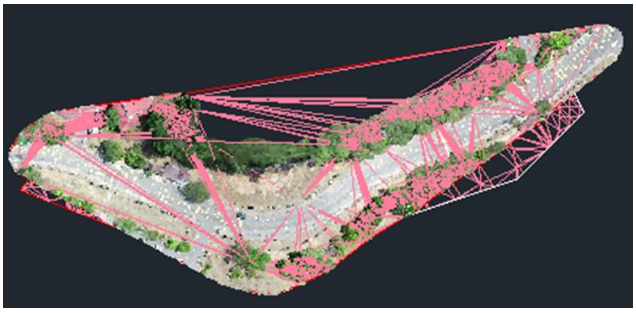

Figure 8. PS and EDM TIN surfaces superimposed

B. Summary

The x-y (plan) and z (height) coordinates of the 100 feature points from both the PS and EDM surfaces were tabulated in a spreadsheet. The difference between both datasets were compared with selected accuracy band published in the Royal Institution of Chartered Surveyor (RICS) guidance note (RICS, 2014) in terms of the maximums, minimums, the mean or average difference and the standard deviation (Table 3).

The mean plan accuracies in both x- and y- axes are very similar in magnitude, all coming in under 40 mm. The maximum difference for x and y-axes are 231 mm and 399 mm respectively. The mean value for both axes lie at 39 mm or less and has a standard deviation of 0.035 mm and 0.051 mm respectively.

The z-axis (elevation measurement) however exhibited significantly larger differences and variation compared to those on the x-y plane. It recorded a maximum difference of 5.028 m which is 1,260 % larger compared to the largest difference in the x-y plane. Similarly, the mean difference is also comparatively larger at 1.639 m or 4,200 % larger. These findings are reflected by the relatively larger standard deviation of almost 1.5 mm.

In terms of mean accuracy for practical use, the PS model does not meet the stringent requirements of RICS Accuracy Band A for high accuracy engineering setting out. However, the plan accuracy meets the accuracy requirements for Accuracy Band E for topographic surveys or for the purposes of boundary registration or land valuation, which is the purpose of this research. In terms of the maximum deviations, though, the plan accuracy does not meet Accuracy Band E at all and is only sufficiently good low accuracy topographic surveys or urban mapping in terms of plan accuracy at Band H.

As explained earlier, the modelled elevation/height accuracy is much less compared to plan accuracy. It does not meet the basic accuracy requirement even for low accuracy topographic survey (Band H and I). The mean height deviation of 399 mm means it is only good for purposes of non-urban mapping or utility surveys whilst the maximum height deviation of 5028 mm renders it almost useless as survey data. It would appear depth perception is an issue with photogrammetry techniques as the same issue persists when modelling building structures too (Bhatla *et al.*, 2012).

Table 3. Comparison of accuracy of PS against EDM vs. RICS establised standards

	Plan accuracy		Height accuracy	RICS Accuracy Band A – high accuracy engineering setting out		RICS Accuracy Band E – topographic survey/low accuracy setting out/area registration/valuation		RICS Accuracy Band H – low accuracy topographic survey setting out/urban mapping	
	x-axis	y-axis	z-axis	Plan accuracy	Height accuracy	Plan accuracy	Height accuracy	Plan accuracy	Height accuracy
Maximum	231 mm	399 mm	5028 mm	+/- 4 mm	+/- 2 mm	+/- 50 mm	+/- 50 mm	+/- 500 mm	+/- 250 mm
Minimum	0.000 mm	0.000 mm	0.000 mm						
Mean	32 mm	39 mm	1639 mm						
Variance	0.001 mm²	0.003 mm²	2.248 mm²						
Std. Dev.	0.035 mm	0.051 mm	1.499 mm						

C. Root Mean Square Error (RSME) Analysis

Root Mean Square Error (RMSE) is a measurement of how well observed/experimental data points agree with a predicted model. It is essentially the standard deviation of residuals; of how spread out these residuals are. In this research the actual data points are the coordinates of the TIN surface from PS whilst the predicted model is the TIN surface from EDM. RMSE is best described by the Equation 1 below.

$$RMS\ Error = \sqrt{\frac{\sum_{i=1}^{n}(T_i - P_i)^2}{n}} \qquad (1)$$

where
Ti = EDM survey coordinates value
Pi = photogrammetry survey coordinates value
n = numbers of measurement

Table 4 summarises the overall RMSE for the difference in each axis. It can be seen that overall the RMS error value between the PS and EDM datasets the x and y-axes is very low at under 0.1 m, reflecting that there is a very close fit between the two and that the observed data from PS is highly accurate. In the z-axis, however, the RMS error is overwhelmingly larger at 2.205 m. This translated to an error that is 3,445 % larger than the deviations in the x and y-axes.

Table 4. Summary of RMSE analysis

	X-axis	Y-axis	Z-axis
RMSE	0.047m	0.064	2.205

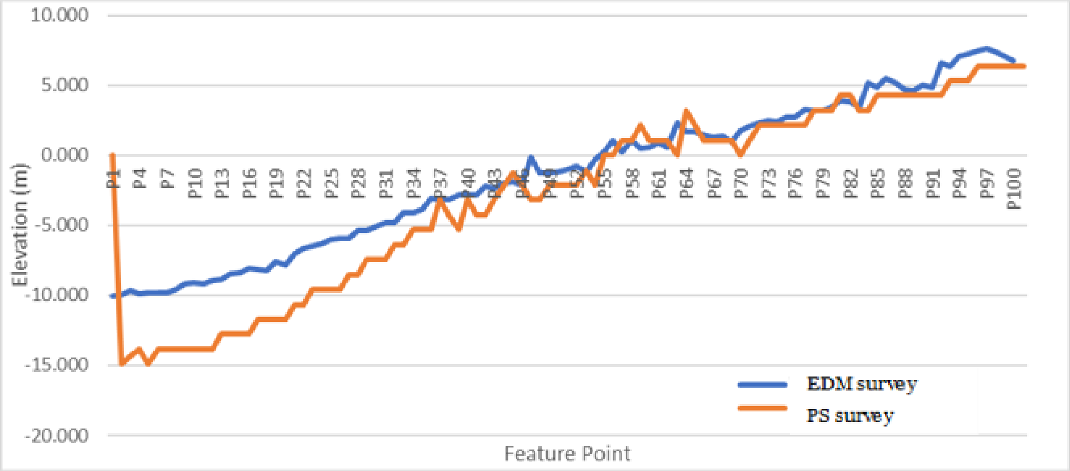

Figure 9. Variation in vertical profile

Similar comparisons were carried out by (Jalloh *et al.*, 2017) for a field utilising total station survey as well as photogrammetry with GCP and GPS information. Comparatively, the RMSE difference in this research is lower in planimetry (x and y-axes) whilst it is higher in elevation. This may be attributed to the use of GCPs in the other research. It has also been suggested that the camera be calibrated against the surveyed element using a checkerboard of known dimensions to improve accuracy of photogrammetry results (Omar *et al.*, 2018).

The deviations in the elevation (z-axis) can be better visualised from the vertical profile comparison in Figure 9.

It can be seen that the difference is largest at feature point P1 and gradually reduces toward P35. This region is also where the elevation is lower and the profile from PS here is also consistently lower than EDM up until P45. From P36 onwards the difference was more consistent.

Whilst the utmost care and preparation had been used in the execution of this research, several lessons were learnt in the course of carrying out that, in hindsight, may contribute to more representative or accurate results than ones obtained.

1. The photogrammetry TIN surface formed from the point cloud data should have been scaled based by either UAV's altitude and ground distance or by using the ratio between the camera's focal length and the UAV's altitude. However, these scale calibrations could have only been done whilst performing the UAV flight.
2. Neither surveys were linked to the national datum but instead an arbitrary reference point. There was only 1 ground control points (GCPs) used in the PS survey as well. More GCPs could increase accuracy of elevation data. Future survey work should be cross-referenced back to the national datum for commonality.
3. Consider usage of other photogrammetry meshing software such as Bentley Contextcapture or Agisoft Photoscan as different processing algorithms may produce variation in results as well. This was well demonstrated in the comparison of point clouds generated by four different software (Syring & Nylund, 2018).

V. CONCLUSION

This experiment has been designed to assess the accuracy of adapting photogrammetry techniques to map highway topography when compared against the more conventional EDM method of using a total station. It can be demonstrated that:

1. Photogrammetry techniques can be used to re-produce the planimetric data (x and y-axes) of topography surveys down to an average accuracy of 39 mm and a maximum of 399 mm. This is also reflected in the RMS error of only 0.064 m. The standard deviation is also relatively low, coming in at less than 0.04 mm which means most results are quite close to the mean average. This means it is within the allowable accuracy limits for use as topography survey data as prescribed by the RICS.
2. However, it is much less accurate in representing the height/elevation of the terrain (z-axis) where deviations up to an average of 1.64 m and maximum of 5.028 m was observed. RMS error for this axis is also higher than those for the plan view at 2.205 m. Again, the standard deviation in the z-axis is also quite high at almost 1.5 m. This means the resultant difference has a high level of spread about the mean value. Whilst the mean deviation value falls within acceptable range for low accuracy topographic survey, the maximum deviation is well outside any prescribed allowance for height deviations set by the RICS.

This research has shown that the planimetric accuracy for photogrammetry is suitable for topographic mapping (RICS Accuracy Band E) but not so for anything that requires higher precision than B and E accuracy. As for the elevation accuracy, the mean value fell within acceptable limits for non-urban/utility mapping, but further research would have to be carried out to improve its maximum values for it to be of any use as survey data.

Further research will be required to develop this method into one that is feasible and practical for use in the industry:

1. Identifying the factors affecting low accuracy of the height/elevation measurement (z-axis) and how to mitigate this. One method may be to include oblique angled images.
2. Assess warping effect in the TIN surfaces as the effect of perspective on the camera lenses tend to cause distortion in the images.
3. Consider carrying our similar comparison research on more variable terrain such as a rolling terrain (slopes ranging from 8 to 15 %).
4. Investigate effect of ground cover such as foliage or buildings on accuracy of results.

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