EVALUATION OF UAV PHOTOGRAMMETRIC ACCURACY FOR MAPPING AND EARTHWORKS COMPUTATIONS

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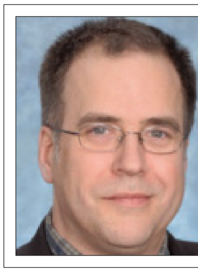
This study quantifies the accuracies achieved and tests the validity of an in-house developed Unmanned Aerial Vehicle (UAV) system employed in a stockpile volumetric survey. UAV photogrammetric results are compared with conventional GNSS survey results. To test the repeatability of the UAV system, multiple flights were flown over the same stockpile using different GNSS ground control, at different times and weather conditions. Positional accuracies of UAV photogrammetric results were found to be very similar to those from GNSS RTK survey, at the scale of photography flown. UAV stockpile volume results agreed with those from GNSS within 3 755 m^3 (0.7%) on a 530 255 m^3 pile. Stockpile volume comparisons between subsequent UAV surface models agreed within 877 m^3 (0.2%) on the same pile. Geometric analysis of independent UAV photogrammetric models over the same area indicated that they could be considered the same at a 95% confidence level. We conclude that the UAV photogrammetric approach is, at the very least, equivalent in accuracy to GNSS RTK surveys at the scale of photography observed. The accuracy of the UAV photogrammetric surveys were sufficient for 1:200 scale mapping and 0.145 m contours. The UAV photogrammetric approach also provided greater detail, resulting in more representative models of the measured surfaces.

Cet article quantifie les précisions obtenues et vérifie la validité d'un système de véhicules aériens sans pilote (UAV) développé à l'interne et utilisé lors d'un relevé volumétrique d'une aire de stockage. Les résultats photogrammétriques du système d'UAV sont comparés à des résultats de relevés du GNSS conventionnels. Pour vérifier la reproductibilité du système d'UAV, de nombreux vols ont été effectués au-dessus de la même aire de stockage en utilisant différents contrôles au sol du GNSS, à différents moments et dans diverses conditions météorologiques. Les précisions positionnelles des résultats photogrammétriques du système d'UAV se sont révélées très similaires à celles des relevés cinématiques en temps réel du GNSS à l'échelle des photographies réalisées. Les résultats du volume de l'aire de stockage du système d'UAV concordent avec ceux du GNSS avec un écart de l'ordre de 3 755 m^3 (0,7 %) pour une aire de stockage de 530 255 m^3. Les comparaisons du volume de l'aire de stockage entre les modèles de surface du système d'UAV subséquents concordaient avec un écart de l'ordre de 877 m^3 (0,2 %) pour la même aire. Les analyses géométriques de modèles photogrammétriques indépendants du système d'UAV pour la même aire indiquaient qu'ils pourraient être considérés comme étant les mêmes avec un degré de confiance de 95 p. cent. Nous concluons que l'approche photogrammétrique du système d'UAV est, à tout le moins, équivalente sur le plan de la précision aux relevés cinématiques en temps réel du GNSS à l'échelle des photographies observées. La précision des relevés photogrammétriques du système d'UAV était suffisante pour une échelle cartographique de 1/200 et des courbes de niveau de 0,145 m. L'approche photogrammétrique du système d'UAV a également fourni de meilleurs détails, permettant ainsi d'obtenir des modèles plus représentatifs des surfaces mesurées.



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Introduction

An Unmanned Aerial Vehicle (UAV), equipped with a digital camera, can be a cost-effective platform for large scale aerial mapping. Its suitability to the task is dependent on a number of factors, including the extent of the area to be mapped, required accuracy and regulatory constraints. Regulations dictate the maximum weight and flying height of the UAV. Weight and aversion to risk limits the "at-risk" payload. Consequently, small UAVs such as the one described in this paper are, by their very nature, a compromise.

In this paper, we compare the accuracy of UAV photogrammetry with conventional ground survey methods on a large stockpile. We also compare the

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Figure 1: The study UAV.

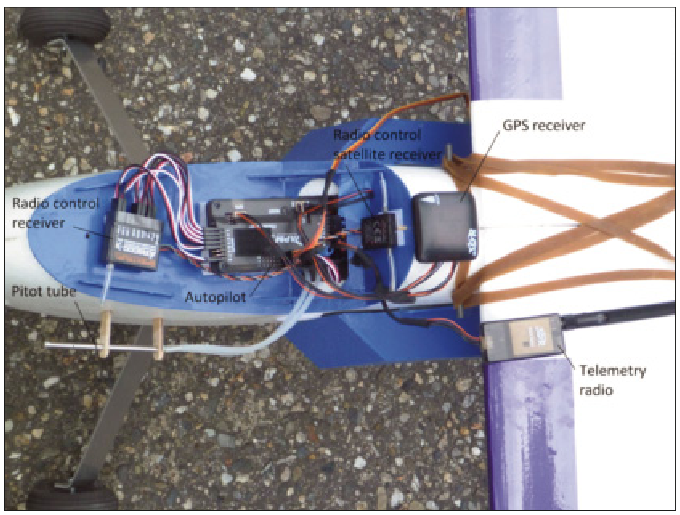

Figure 2: UAV autopilot, sensor, and radio packages.

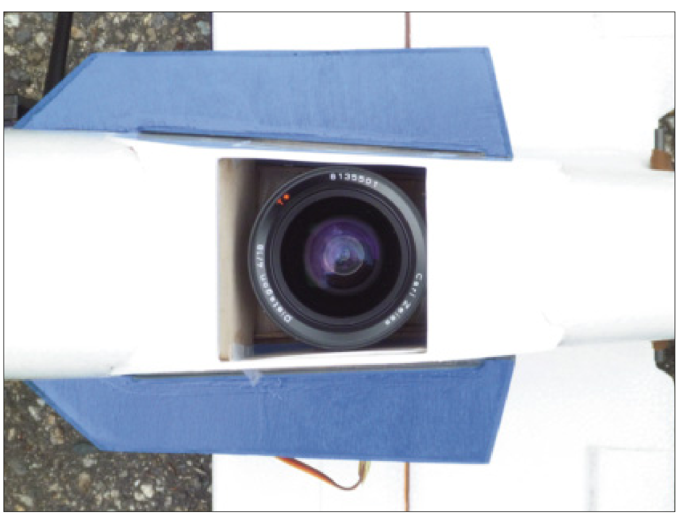

Figure 3: UAV payload—Samsung NX1000 with Carl Zeiss 18mm lens.

repeatability of UAV photogrammetric surveys over the same area. The UAV used in this study was developed in-house and had a non-metric consumer camera as its payload.

Review of Literature

This study is not the first to look at the accuracy of UAV photogrammetric mapping employing a non-metric camera. With the advent of commercial UAVs and highly automated bundle adjustment software, the push to prove the platform for aerial mapping applications has been relentless. *Draeyer et al.* [2014] and *Strecha* [2014] compared non-metric UAV photogrammetry with GNSS RTK and terrestrial LiDAR for stockpile volumes. Their tests employed a 16 megapixel Canon IXUS consumer camera in a small fixed-wing UAV. Volume comparisons with the UAV survey, for 16 000 m^3 stockpiles, were found to be within 2–3% for GNSS, and 0.1% for terrestrial LiDAR. Comparison of the surfaces was done in elevation only. At a Ground Sample Distance (GSD) of 5 cm, elevation differences between the tested methods of 2–4 cm with standard deviations of 7–17 cm were observed. *Wang et.al.* [2014] utilized a Canon 5D Mark II, 21 megapixel DSLR consumer camera in a multi-rotor UAV for their similar comparisons. They determined the mean square errors of 12 GNSS Ground Control Points (GCPs) with UAV mapped positions to be $\sigma_x = 7$ cm, $\sigma_y = 8$ cm, $\sigma_z = 2$ cm. Comparison of UAV photogrammetry and terrestrial LiDAR point clouds was done on 5 cm resampled Triangulated Irregular Networks (TINs). Maximum deviations were stated to lie from –1.0 to 0.98 m, with most deviations being within 0.4 m. The large deviations were attributed to surface movement. The estimated accuracy of volume computation was 1.55%. All of the above was at a GSD of 1 cm.

UAV Platform and Image Acquisition Payload

The UAV used in this study was an in-house developed 1.8 m fixed-wing, single engine, carbon fibre reinforced, EPO foam model (Figure 1). UAV auto-navigation and camera shutter triggering was accomplished with an APM 2.6 autopilot. The APM autopilot incorporates a number of sensors, including L1-code GPS receiver, flux-gate compass,

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3-axis MEMS gyros and accelerometers, barometer, and air speed sensor. Full manual flight control was provided via standard RC-transmitter, with backup and telemetry available via a secondary telemetry radio and ground tablet computer (Figure 2) [*Mah* 2014].

The payload was an uncalibrated, consumer grade Samsung NX1000 mirrorless camera with a Carl Zeiss 18 mm focal length, full frame (35 mm) lens (Figure 3). The camera sensor was a 20 megapixel CMOS APS-C format. Camera calibration was accomplished, post-mission, in the bundle adjustment software. The use of a full frame lens on a cropped sensor camera reduced the portion of the lens that is actually involved in creating the image. This resulted in a sharper image and greatly reduced vignetting. To minimize changes in the calibration of the camera during the mission, the lens was set at a fixed aperture (f 5.6), and the focus was fixed at the corresponding hyperfocal distance (2.7 m). The resulting depth of field was 1.5 m to infinity. Piezoelectric sensor cleaning was turned off. The ISO was set at 800 which, for this particular sensor, results in a minimal increase in image noise. Shutter speeds varied from 1/1000 to 1/4000 of a second [*Mah* 2014].

UAV Field Accuracy Test—Stock Pile

To test the accuracy and repeatability of the UAV aerial mapping system, a stock pile that had been surveyed previously was chosen. An updated GNSS RTK survey was performed, defining the shape of the pile utilizing a TIN, or mesh, and break-lines defining major changes in slope. This is an accepted and common method of detail topographic surveying and in this case, surveying stock piles for quantities.

Accuracy of earthwork volume determinations by this method are generally no worse than a few percent and are, in part, dependent on the pile size (height) and accuracy of the surface model [*Draeyer et al.* 2014]. On a pile of this size (530 255 m^3, surface area 71 250 m^2, average height 7 m), the accuracy of the volume determination would be expected to be better than 1% of the total. On much smaller piles, the error could reach a few percent. The method is also quite efficient as only the "rich" points needed to best define the shape of the surface are collected.

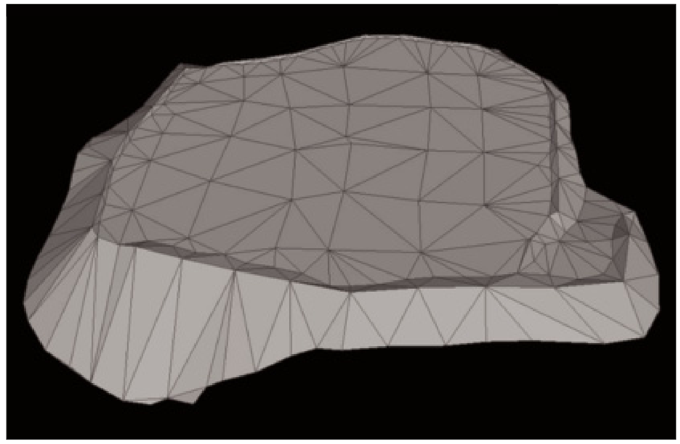

Figure 4: GNSS RTK surveyed 220 point mesh of 372 faces.

Figure 5: Portion of image showing targets 9 and 1 from a 90-m height above the top of the pile.

Figure 6: Distribution of photo targets–second flight.

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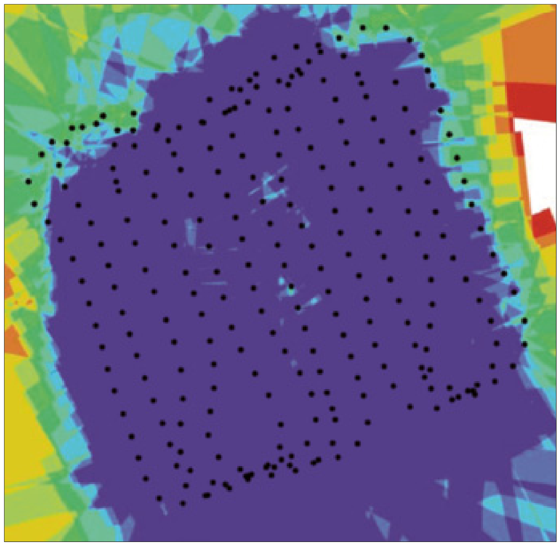

Figure 7: Flight lines with photo locations.

Figure 8: UAV photogrammetric 1.5 million point textured mesh with 3 million faces.

Table 1: Ground control point residuals—first flight.

GCP:	X(m)	Y(m)	Z(m)	3D(m)	Photos
1	0.022	0.000	-0.030	0.037	8
10	-0.001	-0.031	0.024	0.039	28
11	0.025	-0.027	-0.005	0.037	22
12	-0.055	-0.030	0.039	0.074	12
2	0.005	0.015	-0.065	0.067	17
3	-0.018	0.017	-0.042	0.049	15
5	-0.012	-0.002	0.008	0.015	13
6	0.013	0.013	0.022	0.029	15
7	-0.032	0.033	0.035	0.057	20
8	0.018	0.021	0.003	0.028	16
9	0.034	-0.008	0.009	0.036	18
Std. Dev:	**0.026**	**0.021**	**0.031**	**0.046**	
RMSE:	**0.033**		**0.031**		

The GNSS receivers utilized for this survey were Trimble R8s. For RTK measurements, these dual-frequency geodetic instruments have a manufacturer's stated accuracy specification of ±1 cm + 1 ppm RMS horizontal, and ±2 cm + 1 ppm RMS vertical. In-house testing [*Mason* 2013] confirmed that this specification is reasonable for the methods employed in this paper.

Figure 4 shows the result of the GNSS survey. The triangulated surface model contains 372 faces derived from 220 GNSS points. The point density of the model on the surface of the pile was 0.003 points/m^2. This is quite sparse but adequate to model the surface for volume computations when "rich" points are used.

Targeted Ground Control Points (GCP) were established to control the UAV aerial photography. Two sets of 11 targets were established around the perimeter and on top of the pile. Targets were a 60 cm square checkerboard pattern, spiked to the ground at the centre (Figure 5). GNSS RTK was utilized to position the targets. Figure 6 shows the distribution of control points around the pile.

Photo and line spacing were selected to obtain a 75% forward and side overlap of the images. Average flying height was 118 m above the ground. Flight-line direction was chosen to be perpendicular to the prevailing winds. Flying speed was 50 km/h. Two independent flights were flown. Each flight had its own set of 11 GNSS control points. As there was quite a period of time between the two flights, only the second flight imaged both sets of control. Flying time was 6 min per flight. Figure 7 shows the distribution of the 266 photos over the pile in the second flight. Blue (the darker area) indicates that each point on the ground is imaged in nine or more photos. The average pixel on the ground (GSD) was 25 mm.

Photogrammetric bundle adjustments and Dense Surface Model (DSM) computations of the images were done in an automated manner employing Agisoft PhotoScan Professional (version 1.0.4). Figure 8 shows a perspective view of a 1.5 million point textured mesh of the pile derived from a 9.8 million point DSM from PhotoScan. Point density on the surface of the pile was 140 points/m^2, or about 45 000 times more points than the GNSS RTK survey. At this level of detail, the definition of break lines is largely unnecessary.

The fit of the GPS surveyed ground control targets is shown in Table 1. The standard deviations indicate that the UAV photo survey is of a similar accuracy as the GNSS RTK survey at this scale. The horizontal and vertical RMSEs were

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approximately equal to 1.3 times the GSD. The "3D" column denotes the Euclidian distance derived from the Cartesian XYZ point residuals. The "Photos" column indicates the number of photos that imaged a particular GCP.

Comparison of GPS Pile Survey with UAV Photo

To test the GNSS and UAV photo models against each other, we utilized CloudCompare. This software uses a distance measurement between point clouds, or meshes, based on a Hausdorff distance (distance based on nearest neighbour) [*Giradeau-Montaut et al.* 2004]. In the CloudCompare implementation, it is a Euclidean distance. The Hausdorff distance indicates how far two subsets of a metric space are from one another. It can be defined as the greatest distance from a point in one set to the closest point in the other. Sampled at every point on a surface (point cloud or mesh), it is a generalized approach that is easily automated. This makes it particularly suited to determining the similarity of three dimensional objects, such as those described in this paper.

Figure 9 shows the histogram, mean and standard deviation of the distance between the 220-point GNSS surveyed surface of Figure 4 and the 9.8 million-point UAV DSM used to derive the mesh shown in Figure 8.

While the mean distance of 0.067 m separating the two surfaces seems somewhat reasonable, the standard deviation of 0.427 m seems quite large given the expected accuracies of the methods employed.

In Figure 10, the XY distribution of these separations can be seen. Visually, the largest differences (1–3 m) occur on the side slopes of the pile, between GNSS points. The same is true for the top of the pile, but to a much lesser extent (up to 30 cm) between the GNSS surveyed points. It would appear that the differences may have more to do with the sparsity of points on the GNSS surveyed surface and the subsequent interpolation errors resulting from this, as opposed to the accuracy of the UAV photo surface. A visual inspection of some of the areas in question confirmed that interpolating between GNSS points at the top and toe of the side slope could produce errors of several metres in some locations. To further clarify this situation, we interpolated elevations on the UAV photo mesh at the GPS surveyed elevation locations on the top of the pile.

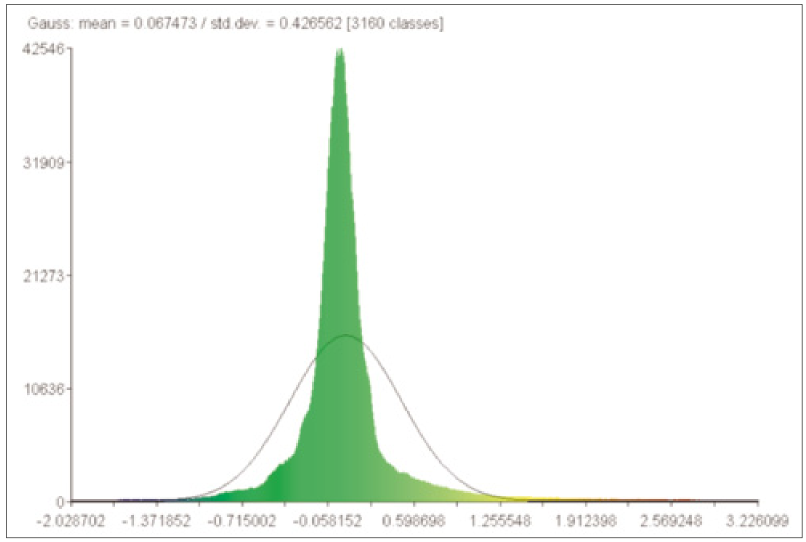

Figure 9: C2M distances–UAV DSM point cloud vs. GNSS mesh.

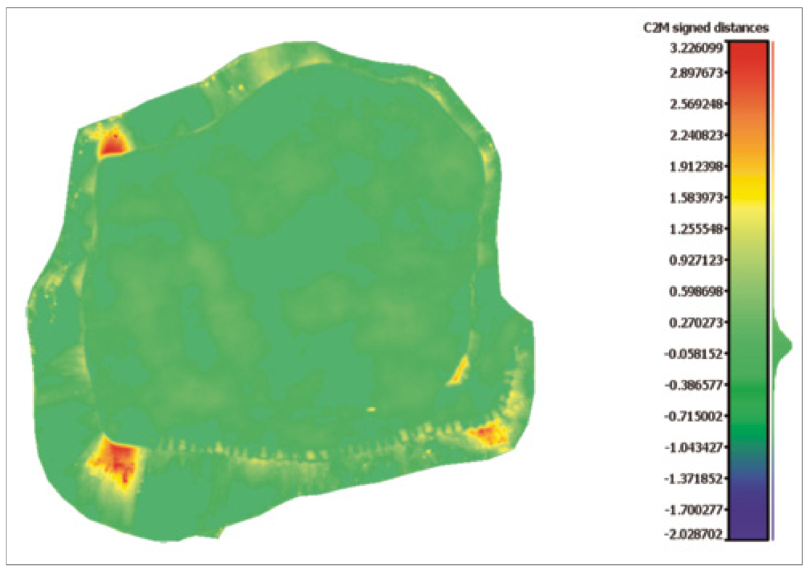

Figure 10: C2M signed distances–UAV DSM vs. GNSS survey.

As can be seen in Table 2, the average elevation difference between GNSS surveyed and UAV mapped points is 1 cm ± 4 cm. There is no statistically significant difference between the surfaces at these measured points, and the accuracy of the differences is consistent with the observation that the GNSS and the UAV photo errors appear to contribute equally to this result at this scale of photography.

This result supports the theory that the large deviations seen in Figures 9 and 10 are most probably the result of the sparsity of the GNSS surveyed model. There is little that could be done to improve this situation using the GNSS RTK survey method. The side slopes where the greatest errors ocurred

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Table 2: Pile top vertical check points. Elevation differences GNSS Survey—UAV Photo.

RTK Point	GNSS RTK Elev(m)	UAV Photo Elev(m)	RTK-UAV (m)
9105	490.33	490.35	-0.02
9107	492.62	492.60	0.02
9108	493.68	493.73	-0.05
9109	493.66	493.72	-0.06
9110	492.65	492.64	0.01
9111	491.58	491.57	0.01
9112	490.30	490.29	0.01
9113	489.26	489.26	0.00
9114	488.92	488.90	0.02
9115	490.38	490.36	0.02
9116	491.75	491.72	0.03
9117	492.76	492.72	0.04
9118	493.89	493.92	-0.03
9119	493.73	493.75	-0.02
9120	492.62	492.63	-0.01
9121	491.56	491.53	0.03
9122	490.05	490.04	0.01
9123	489.02	488.96	0.06
9124	489.32	489.33	-0.01
9125	490.61	490.65	-0.04
9126	491.99	491.95	0.04
9127	493.04	493.03	0.01
9128	493.67	493.63	0.04
9129	493.27	493.36	-0.09
9130	492.71	492.78	-0.07
9131	491.26	491.33	-0.07
9132	489.88	489.97	-0.09
		Average:	**-0.01**
		Std Dev/ RMSEz:	**0.04**

Table 3: Ground control point residuals—second flight.

GCP	X(m)	Y(m)	Z(m)	3D(m)	Photos
31	-0.001	0.022	-0.027	0.034	14
32	-0.001	0.022	-0.048	0.053	12
33	0.003	-0.031	-0.021	0.038	15
34	0.030	0.033	-0.017	0.048	15
35	0.033	-0.002	0.048	0.058	16
36	-0.020	0.030	0.000	0.036	19
37	-0.073	-0.013	0.011	0.075	22
38	0.012	-0.002	-0.001	0.012	12
39	0.010	-0.009	0.049	0.051	17
40	-0.005	-0.054	-0.019	0.057	16
41	0.012	0.003	0.028	0.030	9
Std.Dev:	**0.027**	**0.025**	**0.030**	**0.048**	
RMSE:	**0.039**		**0.030**		

Table 4: Ground check point residuals—second flight.

GCP:	X(m)	Y(m)	Z(m)	3D(m)	Photos
1	0.042	0.015	-0.043	0.062	10
10	-0.048	-0.052	0.031	0.077	22
11	-0.022	-0.010	0.041	0.048	20
12	0.009	-0.005	0.055	0.056	14
2	0.019	0.037	-0.073	0.084	13
3	0.015	0.019	-0.039	0.046	15
5	0.023	0.032	0.026	0.047	15
6	0.006	-0.029	0.088	0.093	12
7	-0.023	-0.011	0.042	0.049	17
8	0.035	-0.009	0.039	0.053	15
9	-0.025	0.024	0.013	0.037	13
Std.Dev:	**0.027**	**0.026**	**0.049**	**0.062**	
RMSE:	**0.039**		**0.049**		

were also unsafe to access, and had been "bermed off" from the top for safety. These berms were also difficult to model in the GNSS survey, owing to their excessive detail and loose nature. Many of the sloped areas can only be safely surveyed via remote means (i.e. photogrammetry, laser scanning, reflectorless total station, etc.).

GNSS Volume Comparison

Despite the differences between UAV photo and GNSS surveyed surfaces, the volumes compared quite favourably. The volume difference for the entire pile, computed between the first UAV flight and the GNSS survey, was computed to be 3 755 m^3, or 0.7% of the total pile volume, or a 5 cm thickness over the pile surface area.

Comparison of Successive Photo Models

The purpose of this test was to determine the repeatability of successive photo missions on the same site. Two flights were made of the pile. Each flight had its own ground control points (11 per

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flight). The second flight imaged both sets of control, providing a means of checking the aerial triangulation against the first flight's control. The GCP residual standard deviations for the second flight were virtually identical to the first (Table 3).

The ground control points from the first flight were used as check points for the second flight. Table 4 show that the horizontal errors are much the same as in previous summaries (1.5 times GSD). Vertical errors were larger (2 times GSD). There was some time between the placement and survey of the two sets of targets. It is possible that a couple of targets had moved as they were only held down by a single spike, some of which were noticed to be loose. None of the differences would be considered significant at a 95% confidence level.

The DSMs from the first and second flights were processed with CloudCompare to determine the cloud to cloud (C2C) separation. The mean absolute C2C distance between the two DSMs was 0.032 m ± 0.024 m (Figure 11). This difference is not significant at the 95% confidence level. This test confirms the two surfaces can be considered the same and the UAV surveys repeatable.

Table 5 summarizes the differences in the two surfaces expressed as X, Y and Z components. Much like the comparison with the GNSS surface, this comparison shows weakness on the side slopes of the pile, but at a much reduced magnitude. Most of the outliers fall in this region (although they represent less than 0.4% of the total points). Most of the side slope outliers occur where there are very abrupt changes in elevations (ie. erratic rocks) and in areas of dark shadow.

A patch of the top surface of the pile also has outliers (see green (lighter patches) on top of pile in Figure 12). We do not have a definitive reason for this occurrence. We observe that this area corresponds well with an area of poor photo overlap in the first flight. Conditions were windy for this particular flight, and the autopilot tuning had not yet been optimized, which could have led to poor image geometry. Overall, the UAV flight comparison is orders of magnitude better in representation and accuracy when compared to the GNSS comparison.

UAV Volume Comparison

The volume difference for the entire pile, computed between the first and second UAV flights, can be expressed as 877 m^3, or 0.2% of the total pile volume, or a 1 cm thickness over the pile surface.

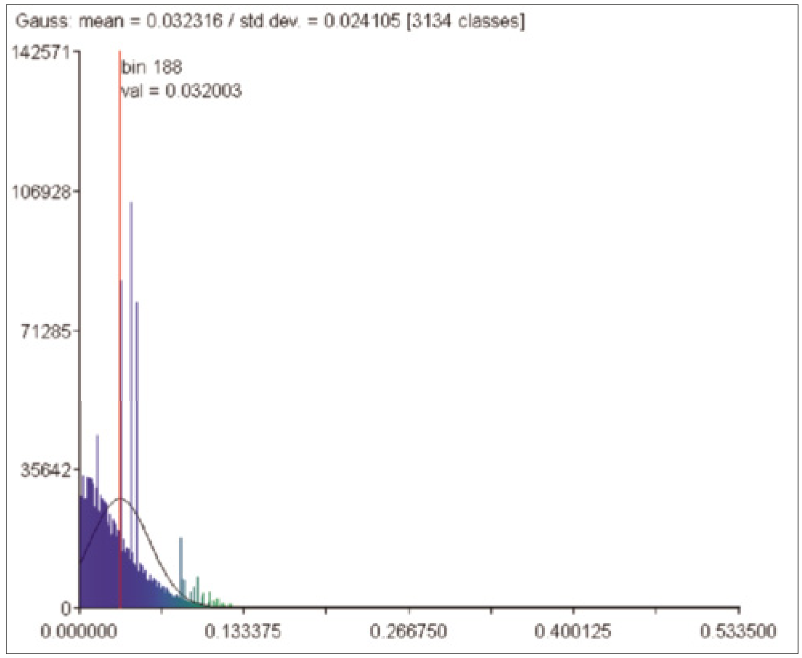

Figure 11: Cloud to cloud absolute distances for 9.8 million distances between flight 1 and 2 surfaces.

Table 5: Summary of XYZ absolute distance statistics.

N=9,820,909 points	X(m)	Y(m)	Z(m)	3D(m)
C2C absolute dist.	0.021	0.021	0.029	0.042
Standard Deviation:	0.015	0.016	0.023	0.032
RMSE:	0.022		0.023	

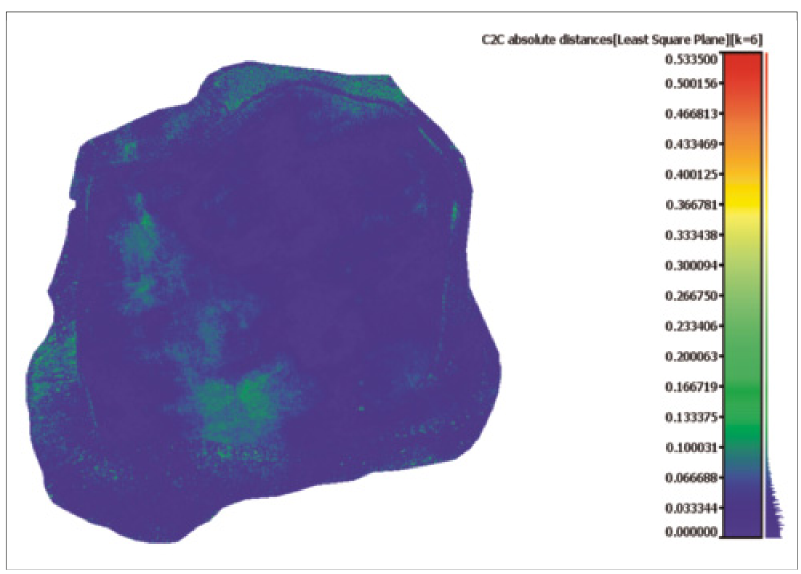

Figure 12: Cloud to cloud absolute distances between flight 1 and 2 surfaces.

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Conclusions

In this paper, we sought to determine the accuracy of UAV photogrammetry relative to GNSS RTK survey for stockpile surveys, at an average photo scale of 1:6 600. Vertical accuracy of the UAV photogrammetry with respect to the GNSS RTK survey (combining the results from Tables 2 and 4) was found to be RSMEz = 0.044 m. According to the US National Map Accuracy Standards (NMAS), the equivalent contour interval would be 0.145 m [*SBCD* 1998]. Horizontal accuracy of the UAV aerial mapping with respect to the GNSS RTK survey (Table 4) was found to be RSMEr = 0.039 m. According to ASPRS standards, this is sufficient for mapping at a scale of 1:200. Traditionally, this scale was considered to be beyond the practical limit of aerial mapping, being more appropriate for ground survey methods [*ASPRS* 1988].

Volumes were computed for the GNSS surface and the two UAV photogrammetric surfaces. The UAV surface agreed with the GNSS surface to 0.7%, and the two UAV surfaces agreed within 0.2% of total pile volume (530 255 m^3). It is interesting to note that the volume difference between the two UAV surfaces only amounted to a 1-cm difference over the surface area of the pile–an almost trivial amount given the accuracies observed.

We also looked at the repeatability of UAV photogrammetric surveys by comparing DSMs from two flights with different ground control. The mean absolute C2C distance between the two DSMs was 0.032 m ± 0.024 m (for 9.8 million points). This indicates that at a 95% confidence level, the two DSMs can be considered the same surface.

The results of this paper support the findings of others with respect to the accuracy and mapping suitability of UAV photogrammetry [*Draeyer et al.* 2014; *Savoy* 2013; *Strecha* 2014; *Wang et al.* 2014]. The accuracies achieved are not the highest the in-house developed UAV system described in this paper should be able to attain. The described UAV system [*Mah* 2014] can easily fly at half the height above ground observed in this paper and still maintain 75% forward and side overlap in images. It is not unreasonable to estimate that accuracies could approach half of those stated above. At this level, extremely accurate ground control would be required.

It is our opinion that the results support the use of UAV aerial photography for the accurate survey of stockpiles and earthworks. The UAV aerial photogrammetric approach is accurate, efficient, and can provide increased safety over conventional terrestrial survey methods.

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