Agronomy Research **21**(X), xxx–ccc, 2023
https://doi.org/10.15159/AR.23.065

Accuracy of waste stockpile volume calculations based on UAV Photogrammetry

R. Künnapuu[1,*], K. Kokamägi[2] and N. Liba[3]

[1]Ministry of the Environment, Environmental Management Department, Paldiski rd 96, EE13522 Tallinn, Estonia
[2]Estonian University of Life Sciences, Institute of Agricultural and Environmental Sciences, Chair of Environmental Protection and Landscape Management, Kreutzwaldi 5, EE51006 Tartu, Estonia
[3]Estonian University of Life Sciences, Institute of Forestry and Rural Engineering, Chair of Forest and Land Management and Forest Industry, Kreutzwaldi 5, EE51006 Tartu, Estonia
[*]Correspondence: raunokunnapuu@gmail.com

Received: February 1st, 2023; Accepted: June 3rd, 2023; Published: July 6th, 2023

Abstract. In environmental supervision, it is necessary to measure waste piles volume to determine whether the activities of the waste manager comply with the established requirements. The aim of this research is to determine whether the model, formed from images collected with low-priced unmanned aerial vehicle (UAV) - not with Real Time Kinematic Global Navigation Satellite System (RTK GNSS) capability - is sufficiently accurate to carry out waste-related surveying. Data collection took place in spring 2021 at the Aardlapalu transhipment station in Tartu County. The objects of the research were an unscreened composting pile and a covered composting pile. In the fieldwork, terrestrial laser scanning and photogrammetric flight were carried out. The reference value was the volume of the model formed from the data of laser scan. The volumes of all models formed by the photogrammetric method were within the permissible difference of 10% provided by law. The most accurate results were obtained from the covered composting pile with an overlap of 70% × 70% and 21 ground control points (GCPs). Using these parameters, the absolute error of the model was 1.48 m³ and the relative error was 0.65%. The most inaccurate results were obtained from the unscreened composting pile with an overlap of 80% × 80% and 21 GCP-s. The research confirmed the hypothesis that sufficient accuracy to calculate waste piles volumes can also be achieved by using a cheaper UAV and camera and with software not specially designed for photogrammetry, design, and drawing.

Key words: 3D modelling, digital image, ground control point, mean square error, photogrammetry.

INTRODUCTION

The use of Unmanned Aerial Vehicles (UAVs) in remote sensing is becoming increasingly common. This is mainly due to the rapid development of the technology and its affordability for the general user, which in turn has led to the mass production of UAVs. More and more authorities, including public authorities, are using UAV for data collection, or for monitoring purposes. Through UAV photogrammetry, UAVs are also increasingly being used in geodesy, where their advantages are particularly evident in surveying inaccessible or large areas. This saves time, labour, and transport costs. In 2019, the Unmanned Aerial Vehicle Association conducted a study on the industrial use of UAVs in Germany. According to the survey, the systems are mainly used in a geodetic context (Becker & Klonowski, 2023). The measurement with UAV is non-contact which means that they can also be used to measure objects where contact measurement could be dangerous. In the environmental supervision, it is necessary to measure the volume of waste piles to determine whether the activities of the waste manager comply with the established requirements. So far, the environmental supervision in Estonia has used UAVs to measure waste piles, but it is not known whether the model formed from images collected using this method is sufficiently accurate to carry out surveying activities. This can lead to decisions being overturned in court.

The aim of this research was to determine whether the model, formed from images collected with low-priced UAV - not with Real Time Kinematic Global Navigation Satellite System (RTK GNSS) capability - is sufficiently accurate to carry out waste-related surveying and complies with the requirements established in the current legislation. Both in Estonia and elsewhere in the world, the accuracy of the volume of a mineral stockpile model formed from images taken with UAV has been assessed. For example, Elkhrachy (2021) investigated the absolute accuracy of digital surface models, and Kokamägi (2020), Ajayi and Ajulo (2021) investigated the accuracy of volumes of the mineral stockpile model formed from images collected with UAV. Rämman (2021) compared the differences between the volume of construction-demolition piles models generated from images collected with UAV and the data provided by the company (waste quantities in tonnes).

Kokamägi (2020) assessed the accuracy of the volume of the mineral stockpile model formed from images collected with UAV and its compliance with the law. The objects of the research were a regular shaped peat stockpile and an irregularly shaped crushed gravel stockpile. The measurements were carried out with a terrestrial laser scanner, a GNSS device and two different UAVs. The relative error in the volumes of the models formed by the photogrammetric method compared to the volume of the model formed from laser scanning data were less than 4%. The study concluded that even the use of cheaper UAV in the determination of volumes provides sufficient accuracy (Kokamägi, 2020).

Rämman (2021) found that the use of UAV for environmental monitoring, including the measuring of waste piles, is feasible and possible (Rämman, 2021). Elkhrachy (2021) found during his research that the non-use of ground control points (GCP's) in the creation of digital surface models gives low absolute accuracy. Using GCP's, a vertical root mean square error (RMSE) of 0.06 m and horizontal RMSE of 0.038 m and 0.05 m were obtained. Such precision would be sufficient for infrastructure projects. planning and development (Elkhrachy, 2021). The aim of the research, carried out by Ali Ulvi in 2021, was to identify the number and placement of GCP's needed to achieve a high absolute accuracy result. The best z–coordinate accuracy (RMSE 0.048 m) was obtained when GCP's were evenly distributed over the entire survey area. As the number of GCP's increased, accuracy improved (Ulvi, 2021).

Before flying with an UAV, it is necessary to mark and measure GCP's because UAVs usually don't have RTK GNSS capability (Yang et al., 2020). GCP's with fixed geodetic coordinates are essential for high accuracy sensing of the environment (Nex & Remondino, 2014). Measurements where high accuracy is required, have relied on the use of GCP's for improving product geolocation with respect to real-world coordinates (Kalacska et al., 2020). Most researchers expect that the higher the number of GCP's, the better the general accuracy. By increasing the number of GCP's from 8 to 20, the accuracy of the model increases significantly but continued to raise the number of GCP's the trend of accuracy improvement slowed. Finally, the planimetric accuracy of the RMSE gradually approach two times the Ground Sample Distance (GSD), and the elevation accuracy of the RMSE approach three times the GSD (Yang et al., 2022).

Oscar Rahu and Karmo Siim (2019) determined in their bachelor's thesis that the best results are achieved when images are taken at altitudes of 50 m to 70 m, airspeeds of 4 m s^{-1} to 5 m s^{-1} and an overlap of 70% × 70% (RMSE X-0.012 m; RMSE Y-0.012 m; RMSE Z-0.019 m) or 80% × 80% (RMSE X-0.012 m; RMSE Y-0.012 m; RMSE Z-0.021 m). The work also showed that the data collected with UAV provide sufficient accuracy (Rahu & Siim, 2019). Ajayi and Ajulo (2021) concluded in their research that the main advantages of an UAV are the speed of measurement in the fieldwork, the high density and integrity of the resulting point cloud, and the low cost of the UAV. Higher hardware requirements and longer post-processing time were identified as the main disadvantages (Ajayi & Ajulo, 2021).

A master's thesis was prepared and defended at the Estonian University of Life Science in the spring of 2022 based on the data presented in the article (Künnapuu, 2022). The use of an UAV to determine the accuracy of the volumes of the models of the waste piles took place in South Estonia in June 2021. This paper describes the technique and methodology used to conduct the research, the data collection and the modelling, volume estimation and data analysis. The research provides the knowledge that it is possible to determine the volume of waste piles with a low-cost UAV that meets the established requirements. In addition, it shows that regulatory compliant results can be obtained without GCP's. In the future, this will help avoid litigation. This study also provides an opportunity to reduce the time needed for the work. If we know the smaller parameters that will give us results that comply with the regulations, we can reduce the time needed for fieldwork and data processing. In total, we performed only two flights with a frontal and side overlap of 70% × 70% and 80% × 80% and flight height was 50 m. To get a better overview, it would be necessary to extend the parameters used (overlap, height, different UAVs). The objects studied in this research are also relatively simple in their characteristics and shape. The next step is to investigate the accuracy of calculating the volumes of more complex waste piles use different UAV-s. It is also possible to investigate whether the accuracy of the model is affected by the type of waste. In addition, it will investigate whether reduce the flight overlap, changing the altitude, or using different UAVs will have an impact on the accuracy of the model and analyse the amount of time spent for the different variants.

MATERIALS AND METHODS

The research was carried out in cooperation with the employees of the Estonian University of Life Sciences, a postgraduate student, and the geodetic surveying company 3D PUNKT OÜ. The aim of the research was to find out whether the model formed from aerial photographs collected by a low-cost UAV - not equipped with RTK GNSS capability - is sufficiently accurate for waste pile surveying and meets the requirements of the current legislation. In this study we used a low-cost UAV, that has a built-in low-resolution camera and lacks RTK GNSS capability. There are no specific requirements in Estonia on the accuracy of measurements at landfills and waste piles. Requirements have been established for the accuracy of measurements and the documentation of measurement results when extracting mineral resources. The difference between the values of the two measurements shall not exceed 10% when the stockpile volume is less than 20,000 m³ (Markšeiderimõõdistuse täpsustatud nõuded ja kord, 2019).

Objects of the research

The objects of the research were two waste piles located in the territory of the Aardlapalu transhipment station in South Estonia. The area of the surveyed area was estimated to be 7,000 m^2. The Aardlapalu transhipment station is administratively located on the cadastral parcel of the Aardlapalu prügila in Uhti village, Kambja municipality (Fig. 1). The transhipment station is located at an estimated distance of 5 km from the city of Tartu.

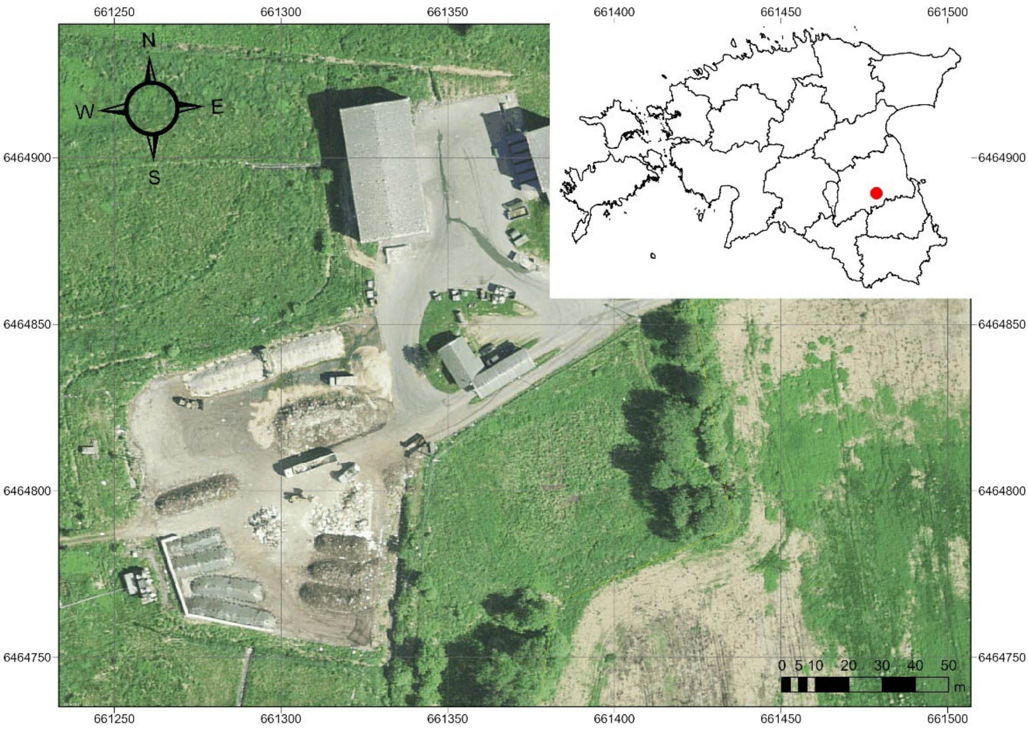

Figure 1. The location of the Aardlapalu transhipment (L–Est97 coordinates X: 6464800 m; Y: 661300 m) station is shown as a dot on the map of Estonia.

The first object was a relatively regular shaped unscreened composting pile in the south-eastern part of the transhipment station (Fig. 2, a) and the second object was a regular shaped and uniform coloured covered composting pile in the northern part of the site (Fig. 2, b).

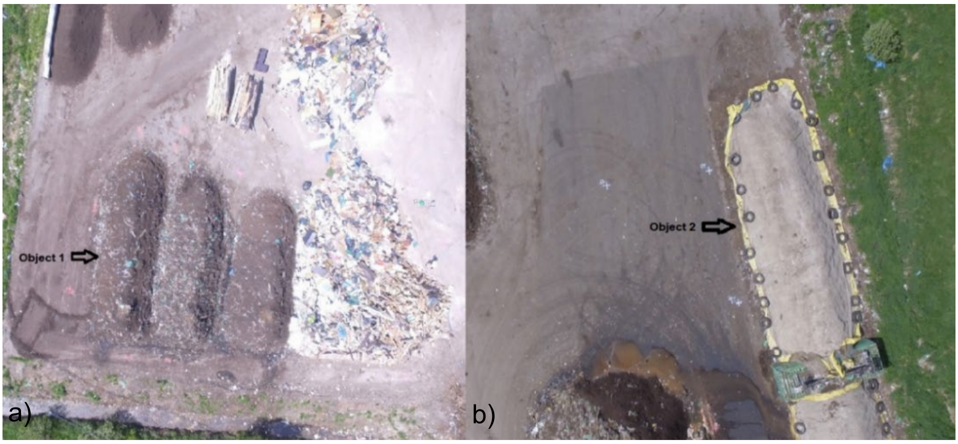

Figure 2. View of the unscreened composting pile (a) and the covered composting pile (b).

Flight planning

First we identified a date with suitable weather conditions for the flight, selected the instruments and prepared the flight plans. Flight planning took place in the office just before going to the fieldwork. Flights were planned on a tablet using DJI GS Pro application. In total, two flights were planned with a frontal and side overlap of 70% × 70% (Fig. 3, a) and 80% × 80% (Fig. 3, b).

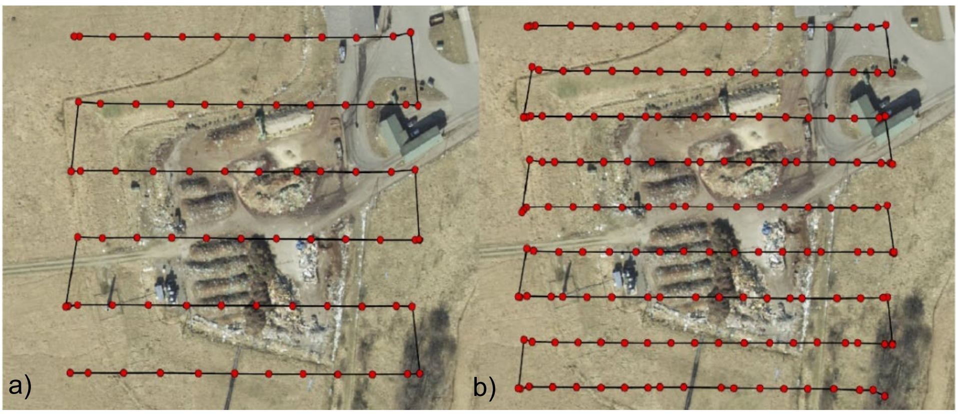

Figure 3. Flight trajectory (black line) and photo location (dot) for frontal and side overlap at 70% × 70% (a) and 80% × 80% (b).

Flights were planned with grid flight paths and the altitude was set at 50 m. Grid flight paths were chosen because it's the most common way of collecting images to volume calculations. Double grids provide a more detailed 3D image, but the increase in the number of images also increases the flight and post-processing time and hardware requirements.

Data collection

The fieldwork was carried out on June 2, 2021. During preparation, 25 GCP's were made in the vicinity of the waste piles using aerosol paint. After the GCP's were marked, the centre of the marks was measured with an RTK GNSS receiver Trimble R4-3. 20 epochs were measured on each mark. According to the report, the Position of Dilution of Precision (PDOP) of the measurements ranged from 1.1–1.7, and the horizontal accuracy of the points was within 0.8 cm and vertical accuracy was 1.3 cm. Special marks were then installed to orient the laser scanner and to link the different waypoints, which were then measured using the RTK GNSS receiver. The PDOP of the measurements ranged from 1.0–1.4, with a horizontal accuracy of 0.7 cm and a vertical accuracy of 1.1 cm. After the RTK GNSS measurements, a terrestrial laser scanning of the waste piles was performed using a Faro FocusS 70. Finally, photogrammetric flights were carried out with the UAV DJI Phantom 3 Professional (Fig. 4).

Figure 4. Carrying out a photogrammetric flight with an UAV DJI Phantom 3 Professional.

The flights were autonomous, using the DJI GS Pro application. In total, two flights were performed with a frontal and side overlap of 70% × 70% and 80% × 80%. With a frontal and side overlap of 70% × 70%, the flight duration was 5 minutes and a total of 75 photos were taken. A flight with a frontal and side overlap of 80% × 80% took 8 minutes and 170 photos were taken in total. The flight height was 50 m, and the (GSD) was 2.10 cm.

Data processing

During the research the coordinates of the points collected with the RTK GNSS receiver on the object, the point clouds obtained by laser scanning, and the JPEG images with metadata collected with UAV were used. To create point clouds using the photogrammetric method, the images were processed in ArcGIS Drone2Map software. In total, the GCP's was marked on at least four different photos. A maximum of 21 of the 25 measured GCP's were used to form the point clouds. 4 points were used as check points (CP) to control the absolute accuracy of the coordinates if it's necessary. The point clouds were created in L–Est97 coordinate system and EH2000 height system. Using the photogrammetric method, 6 different point clouds were generated (Table 1).

In total, it took an average of 8 minutes to create a point cloud from the 70% × 70% overlapping image. The same figure for 80% × 80% overlap was 44 minutes. The point cloud from the laser scanning were first processed in Autodesk Recap 2022. Models of the unscreened composting pile (Fig. 5, a) and the covered composting pile (Fig. 5, b), as well as the surface models of the base of the piles were created in Civil 3D 2021 software. The point cloud was thinned to a point spacing of 3 cm and the Triangulated Irregular Network (TIN) method was used to create the models. The heights of the models surfaces were then compared, and the volume of the waste piles was calculated.

Table 1. Different point clouds generated by the photogrammetric method

Overlap (%)	GCP's used
70% × 70%	21
70% × 70%	5
70% × 70%	0
80% × 80%	21
80% × 80%	5
80% × 80%	0

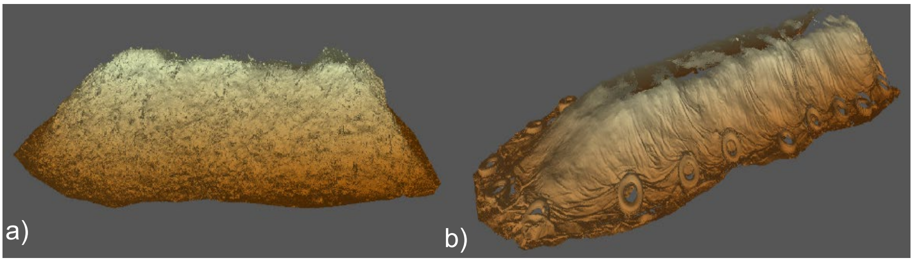

Figure 5. Model of an unscreened composting pile (a) and a covered composting pile (b) generated from the results of laser scanning in Autodesk Civil 3D 2021 software.

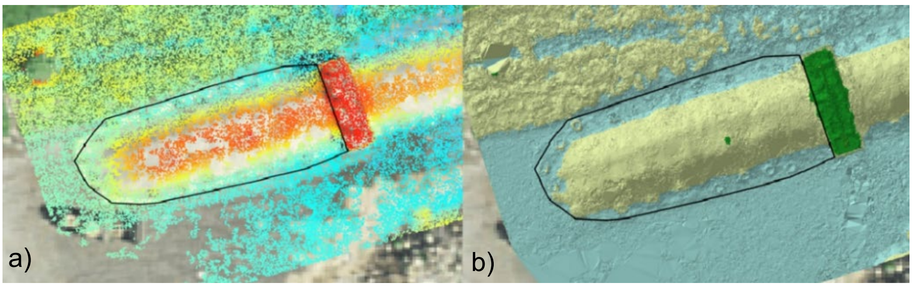

Figure 6. The point cloud and the contour (a) and the waste pile model (b) in ArcGIS PRO software.

Using the photogrammetric method, 12 models were created from the collected images with different overlaps and using different numbers of GCP's. From the point cloud (Fig. 6, a) generated by the photogrammetric method a waste pile model (Fig. 6, b) was created in ArcGIS PRO software using the TIN method. A TIN model is an elevation model created from irregularly spaced points with height values. The points are connected to each other and form a network of triangles (Siriba et al., 2015). In the TIN network, three principles must be followed when forming each triangle. Each triangle formed must be as close as possible to an isosceles triangle, the vertices forming the triangle must be the closest, and the triangle network must be unique. Only in this case can the grid be as close as possible to the actual ground surface. The most widely used is the Delaunay triangulation. The Delaunay triangle network is unique, and no other points exist within any circle passing through the triangle vertices (Yongxiao et al., 2021).

The point cloud was not thinned. After that, a model of the surface of the base of the waste pile was formed. Finally, the heights of the surface models were compared, and the volume of the waste piles was calculated. The above process was carried out 12 times. After calculating the volumes, Microsoft Excel software was used to compare the results on an object-by-object basis. The volumes of the models generated by the photogrammetric method were compared with the volume of the model generated from the data collected by terrestrial laser scanning, which was taken as a reference value.

The Gaussian RMSE formula was used to calculate the RMSE (Randjärv, 1997).

$$m = \pm\sqrt{\frac{[\Delta^2]}{n}}, \quad (1)$$

where Δ^2 is the sum of the squares of the differences between the volumes of the model generated from the laser scanning data and the volumes of the model generated from the photogrammetric data, and n is the number of different models.

RESULTS AND DISCUSSION

Volumes of the models

The volume of the model formed from the data collected during the terrestrial laser scanning of the unscreened composting pile was 189.01 m^3, and the volume of the model formed from the data of the covered composting pile was 228.58 m^3. The volumes of the models generated by the photogrammetric method are presented in Tables 2 and 3.

Table 2. Volumes of the models formed from the unscreened composting pile using the photogrammetric method

Overlap (%)	GCP's used	Volume (m^3)
70% × 70%	0	184.61
	5	197.98
	21	197.78
80% × 80%	0	186.45
	5	199.62
	21	199.89

Table 3. Volumes of the models formed from the covered composting pile using the photogrammetric method

Overlap (%)	GCP's used	Volume (m^3)
70% × 70%	0	222.17
	5	230.20
	21	230.06
80% × 80%	0	216.50
	5	232.45
	21	233.80

Assessing the accuracy

A total of 7 models were created from the unscreened composting pile, the volumes of the models were calculated and compared with the volume of the model created from the data collected during the terrestrial laser scanning. 3 different models were formed from the 70% × 70% frontal and side overlap collected images. The absolute error between the volumes of the models formed by the photogrammetric method and the model formed from the laser scanning data was as follows: without GCP -4.40 m^3, with 5 GCP 8.97 m^3 and with 21 GCP 8.77 m^3 (Fig. 7). The relative error between the volumes of the models was as follows: without GCP -2.33%, with 5 GCP 4.75% and with 21 GCP 4.64% (Fig. 8).

With an overlap of 70% × 70%, the RMSE of the volumes of the models formed from the collected images was 7.68 m^3.

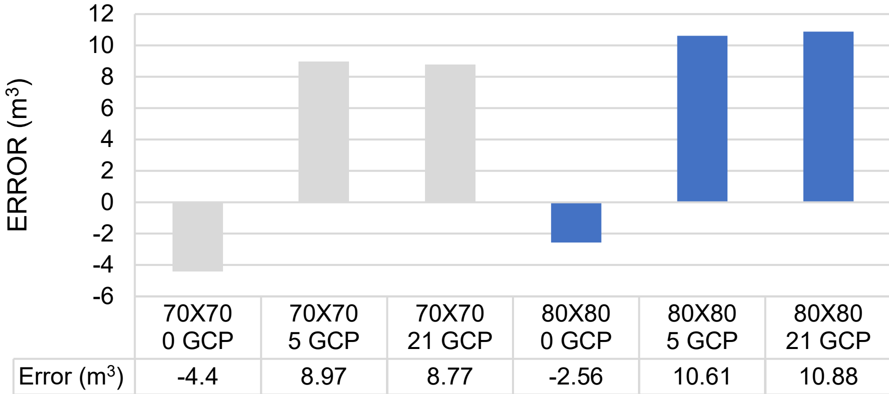

Figure 7. Absolute error (m^3) between models generated from an unscreened composting pile and a model generated from laser scanning data.

3 different models were also formed from the 80% × 80% frontal and side overlap collected images. The absolute error between the volumes of the models formed by the photogrammetric method and the model formed from the laser scanning data was as follows: without GCP -2.56 m^3, with 5 GCP 10.61 m^3 and with 21 GCP 10.88 m^3 (Fig. 7). The relative error between the volumes of the models was as follows: without GCP -1.35%, with 5 GCP 5.61% and with 21 GCP 5.76% (Fig. 8). The RMSE of the volumes of the models formed from the collected images was 8.90 m^3.

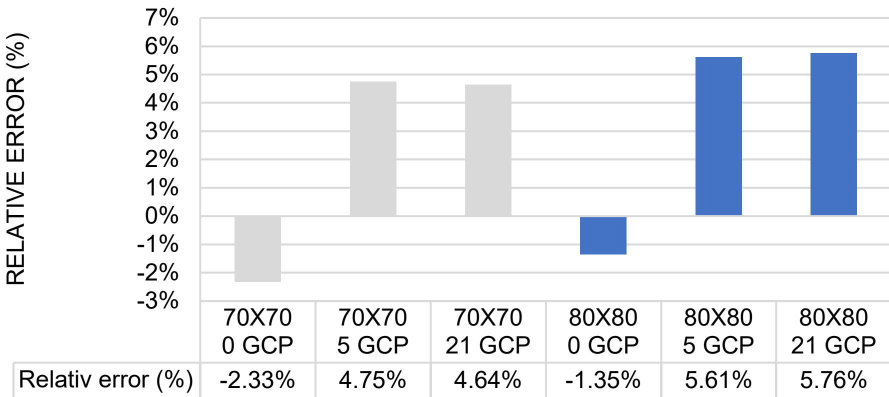

Figure 8. Relative error (%) between models generated from an unscreened composting pile and a model generated from laser scanning data.

The same workflow was repeated for the covered composting pile. 3 different models were formed from the 70% × 70% frontal and side overlap collected images. The absolute error between the volumes of the models formed by the photogrammetric method and the model formed from the laser scanning data was as follows: without

GCP -6.41 m^3, 5 CGP 1.62 m^3 and 21 GCP 1.48 m^3 (Fig. 9). The relative error in volumes between the models was as follows: -2.80% for no GCP 0.71% for 5 GCP and 0.65% for 21 GCP (Fig. 10). With an overlap of 70% × 70%, the RMSE of the models formed from the images collected was 3.91 m^3.

3 different models were also formed from the 80% × 80% frontal and side overlap collected images. The absolute error between the volumes of the models formed by the photogrammetric method and the model formed from the laser scanning data was as follows: without GCP -12.08 m^3, with 5 GCP 3.87 m^3 and with 21 GCP 5.22 m^3 (Fig. 9).

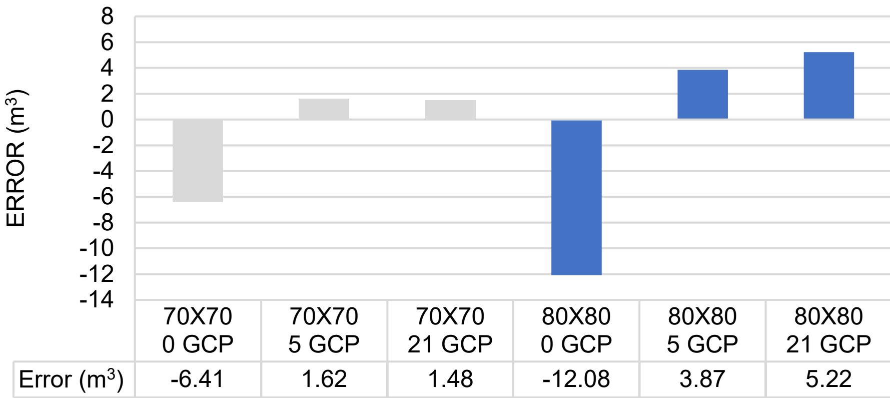

Figure 9. Absolute error (m^3) between models generated from a covered composting pile and a model generated from laser scanning data.

The relative error between the volumes of the models was as follows: without GCP -5.28%, with 5 GCP 1.69% and with 21 GCP 2.28% (Fig. 10). The RMSE of the volumes of the models formed from the collected images was 7.92 m^3.

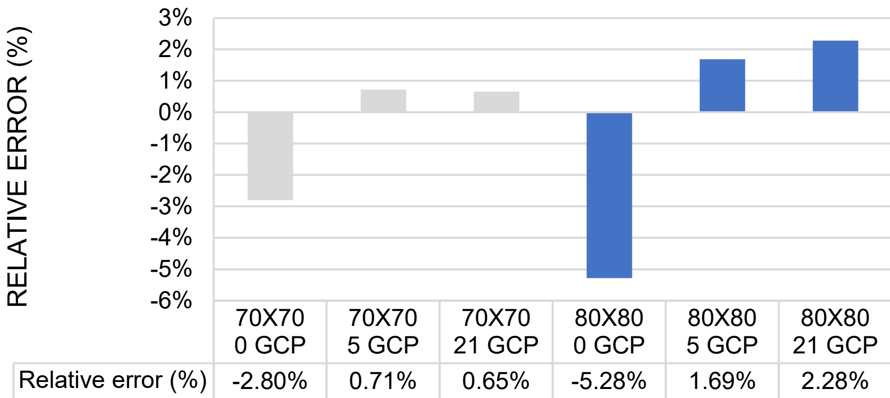

Figure 10. Relative error (m^3) between models generated from a covered composting pile and a model generated from laser scanning data.

Kokamägi (2020) used the same methodology in his research to assess the accuracy of the volume of the mineral stockpile model formed from images collected with UAV and its compliance with the law. The objects of the research were the regular shaped peat stockpile and an irregularly shaped crushed gravel stockpile. During the research RTK GNSS receiver Trimble R4-3, laser scanner Trimble SX10 and two different UAVs (DJI Phantom 4 Pro and Aibotix Aibot X6) were used. The relative error in the volumes of the models formed by the photogrammetric method compared to the volume of the model formed from laser scanning data were less than 4%. The most inaccurate results were obtained from the gravel stockpile without GCP's, where the relative error was 3.7%, use UAV DJI Phantom 4 PRO. The most accurate results were obtained from the peat stockpile with all GCP's, use UAV Aibotix X6. Using these parameters, the relative error was 0.70% (Kokamägi, 2020). Both studies concluded that even the use of cheaper UAV in the determination of volumes provides sufficient accuracy.

CONCLUSIONS

The environmental supervision in Estonia uses UAVs to measure the volume of waste pile, but it is not known whether this method is accurate enough to carry out surveys. The aim of this research was to find out whether the model formed from aerial photographs collected by a low-cost UAV is sufficiently accurate for waste pile surveying and meets the requirements of the current legislation. The volume of the model generated from the data collected during the terrestrial laser scanning of the unscreened composting pile was 189.01 m^3. With an overlap of 70% × 70%, the RMSE of the models formed from the collected images was 7.68 m^3. The same figure with 80% × 80% overlap was 8.90 m^3. The volume of the model generated from the data collected during the terrestrial laser scanning of the covered composting pile was 228.58 m^3. With an overlap of 70% × 70%, the RMSE of the models formed from the collected photos was 3.91 m^3. The same figure with 80% × 80% overlap was 7.92 m^3.

The volumes of all models were within the permissible difference of 10% provided by law. The most accurate results were obtained from the covered composting pile with an overlap of 70% × 70% and use 21 GCP's. Using these parameters, the absolute error of the model was 1.48 m^3 and the relative error was 0.65%. The most inaccurate results were obtained from the unscreened composting pile with an overlap of 80% × 80% and use 21 GCP's, where the absolute error was 10.88 m^3 and relative error was 5,76%. During the research found that a model formed from images collected with a frontal and side overlap of 70% × 70% gives better results in measuring volumes than an overlap of 80% × 80%. Oskar Rahu and Karmo Siim also came to the same conclusion in their bachelor thesis defended in 2019 at the Estonian University of Life Sciences, who found that the best result was obtained with 70% × 70% overlap. In some cases, models without GCP's were more accurate than those with GCP's. The reason that better model accuracy was obtained without GCP's may have been due to the fact, that the waste pile contour was drawn on the model linked to the GCP's in the data processing, and there may have been a slight inaccuracy when the model without GCP's was later inserted into the contour. However, the use of GCP's helped to improve the results in most cases.

It was also found that it is possible to create accurate models from the collected images and to measure the volume of the models using software not specifically designed for photogrammetry, design, and drawing. Based on the results of the research, it can be considered that the models formed by the photogrammetric method from the images collected by an UAV are of sufficient accuracy to carry out waste pile surveying. When carrying out waste pile surveys, it is recommended to use a 70% × 70% frontal and side overlap when carrying out a photogrammetric flight. Unofficial surveys can be carried out without the use of GCP's, but in the case of official surveys, the use of GCP's is necessary to ensure better model accuracy. As the objects studied in this research are relatively simple in their characteristics and shape, the next step is to investigate the accuracy of calculating the volumes of more complex waste piles use different UAVs. In addition, it will investigate whether reduce the flight overlap, changing the altitude, or using different UAVs will have an impact on the accuracy of the model and analyse the amount of time spent for the different variants.

ACKNOWLEDGEMENTS. We would like to thank Martin Sirk from the company 3D PUNKT who helped us with terrestrial laser scanning.

REFERENCES

Ajayi, O.G. & Ajulo, J. 2021. Investigating the Applicability of Unmanned Aerial Vehicles (UAV) Photogrammetry for the Estimation of the Volume of Stockpiles. *Quaestiones Geographicae* **40**(1), 25–38. https://www.sciendo.com/article/10.2478/quageo-2021-0002

Becker, D. & Klonowski, J. 2023. Object Recognition of a GCP Design in UAS Imagery Using Deep Learning and Image Processing—Proof of Concept Study. *Drones* **7**(2), 94. https://doi.org/10.3390/drones7020094

Elkhrachy, I. 2021. Accuracy Assessment of Low-Cost Unmanned Aerial Vehicle (UAV) Photogrammetry. *Alexandria Engineering Journal* **60**(6), 5579–5590. https://doi.org/10.1016/j.aej.2021.04.011

Kalacska, M., Lucanus, O., Arroyo–Mora, J.P., Laliberte, E., Elmer, K., Leblanc, G. & Groves, A. 2020. Accuracy of 3D Landscape Reconstruction without Ground Control Points Using Different UAS Platforms. *Drones* **4**(2), 13. https://doi.org/10.3390/drones4020013

Kokamägi, K., Türk, K. & Liba, N. 2020. UAV photogrammetry for volume calculations. *Agronomy Research* **18**(3), 2087–2102. https://doi.org/10.15159/ar.20.213

Künnapuu, R. 2022. *Accuracy of waste stockpile volume calculations based on UAV photogrammetry*. Master's Thesis, Estonian University of Life Sciences, Tartu, Estonia, 88 pp. (in Estonian).

Markšeiderimõõdistuse täpsustatud nõuded ja kord. 2019. Riigi Teataja. Estonian legislation. https://www.riigiteataja.ee/akt/124052022010?leiaKehtiv (in Estonian).

Nex, F. & Remondino, F. 2014. UAV for 3D mapping applications: A review. *Applied Geomatics* **6**, 1–15.

Rahu, O. & Siim, K. 2019. *Factors affecting the accuracy of orthomosaics and 3D point clouds collected from unmanned aerial vehicle.* Bachelor's Thesis, Estonian University of Life Sciences, Tartu, Estonia, 120 pp. (in Estonian).

Randjärv, J. 1997. *Geodesy I*. Tartu, Estonia, 360 pp. (in Estonian).

Rämman, K. 2021. *Analysis of the volume of construction waste with drones*. Master's Thesis, Estonian University of Life Sciences, Tartu, Estonia, 112 pp. (in Estonian).

Siriba, D.N., Matara, S.M. & Musyoka, S.M. 2015. Improvement of volume estimation of stockpile of earthworks using a concave hull–footprint. *Micro, Macro & Mezzo Geo Information* **5**. https://www.researchgate.net/publication/287196050_Improvement_of_volume_estimation_of_stockpile_of_earthworks_using_a_concave_hull-footprint

Ulvi, A. 2021. The Effect of the Distribution and Numbers of Ground Control Points on the Precision of Producing Orthophoto Maps with an Unmanned Aerial Vehicle. *Journal of Asian Architecture and Building Engineering* **20**(6), 806–817. https://doi.org/10.1080/13467581.2021.1973479

Yang, H., Li, H., Gong, Z., Dai, W. & Lu, S. 2020. Relations between the Number of GCPs and Accuracy of UAV Photogrammetry in the Foreshore of the Sandy Beach. *Journal of Coastal Research* **95**(1), 1372–1376. https://doi.org/10.2112/SI95-263.1

Yang, J., Li, X., Luo, L., Zhao, L., Wei, J. & Ma, T. 2022. New Supplementary Photography Methods after the Anomalous of Ground Control Points in UAV Structure-from-Motion Photogrammetry. *Drones* **6**(5), 105. https://doi.org/10.3390/drones6050105

Yongxiao, W., Xitun, Y., Xiongfei, Y., Hang, Z. & Qi, H. 2021. Research on Earthwork Calculation Based on TIN Model. In: *3rd International Conference on Civil Architecture and Energy Science (CAES 2021).* Hangzhou, China, pp 1–4. https://doi.org/10.1051/e3sconf/202124803001