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Substantiation of the determining accuracy of bulk material volumes using semi-professional UAVs

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Abstract. Over the last decade of information and technological progress, the use of drones in various segments of military, industrial, and social activities, has become promising and relevant. The use of unmanned aerial vehicles (UAVs) in surveying and geodesy has demonstrated their efficiency on conditions where they can be used: weather conditions, terrain or urban infrastructure. The accuracy of surveying depends on the technical specifications for performing geodetic work, the characteristics of the UAV, and the correct design of the flight task in compliance with safety rules. Therefore, depending on the surveying tasks, their area and complexity, and the required measurement accuracy, it is necessary to choose the available devices: semi-professional, professional, or geodetic UAVs. The paper presents the results of the surveying and geodetic use of a semi-professional Xiaomi X8 2022 quadcopter to determine the volume of a small sand storage area. Additionally, the volume of the deposit was determined using GNSS surveying and an electronic tacheometer. The errors of each surveying method were determined. An analysis of the possibilities of using various surveying methods, in particular with the use of UAVs, and a comparison of the accuracy of the methods studied were performed.

1. Introduction

One of the monthly tasks during mineral extraction is to determine the volumes in warehouses, bunkers, and dumps. With complex topography of the site, the use of outdated methods of surveying requires considerable time to perform field and office work. The use of modern equipment to solve these tasks significantly reduces the labor intensity of their implementation to a certain extent.

Innovative technologies for the use of unmanned aerial vehicles (UAVs) have their advantages and disadvantages compared to traditional methods of topographic surveying. First, surveying planning should be carried out taking into account meteorological data, which does not always correspond to the terms of their implementation. The second factor is the complexity of field work in areas with high vegetation, mountainous terrain, and high-rise buildings.

Over the past decade, the use of UAVs in various industries has become much more widespread. The main areas of scientific research on this topic are as follows:

- technical features of UAV design and their analysis;
- possibilities of using UAVs to solve specific tasks;
- analysis of optical photography systems in terms of the quality of the images obtained;
- use of drones in geodetic/surveying measurements of extraction surfaces (quarries, dumps,



deposits of useful substances);

- methodology for performing aerial photography;
- processing of survey results using UAVs;
- analysis of the accuracy of planimetric and altimetric surveys.

Article [2] discusses the design of unmanned aerial vehicles and ways to improve the control systems of such vehicles to expand their areas of use. Their use in civil, military, and special purposes is presented. Issues of flight altitude measurement and control, UAV stabilization in space, and the use of electronic control systems are considered. The information presented is an overview without conclusions on the elimination/correction of design flaws in unmanned aerial vehicles (aircraft).

The possibilities for the use of unmanned aerial vehicles are considered in publication [3], namely: the prospects for the use of methods and technologies for solving Earth remote sensing (ERS) tasks; an overview of photographic, photogrammetric, thermal, and radar imaging. According to [3], aerial photography of the terrain is used for various purposes, the most important of which are the compilation and correction of topographic maps, geological research, and the solution of various satellite monitoring tasks.

Based on the results of analytical studies, the authors note that filming with UAVs (drones) has certain disadvantages. For example, one disadvantage of using drones is their short flight time, which depends on the size and capacity of their batteries. In addition, aerial drones do not fully meet the requirements for topographic accuracy when compiling large-scale topographic maps due to the inaccurate positioning of UAVs relative to the terrain. At the same time, the article does not consider modern methods of using RTK (Real Time Kinematic) technologies and RTK-supported remote laser scanning methods (used in UAV technological designs), which increase the accuracy of surveying and geodetic work.

Article [4] presents a methodology for selecting the characteristics of the optical system of unmanned aerial vehicles, the main stages of the digital image processing process, and considers the possibility of using UAVs for terrain monitoring. The article examines the features and offers recommendations for the process of processing digital images using specialized software packages and decrypting survey results, and outlines the prospects for the development of unmanned aerial vehicle applications. A 12 MP camera (4000x3000 pixels) with a focal length of 135 mm (10x zoom) was selected as the basis for the research. The list of analyzed optical devices (digital cameras) weighing from 3 to 26 kg cannot be used on professional and semi-professional unmanned vertical take-off aircraft.

Modern capabilities of unmanned aerial vehicles are being implemented to perform everyday tasks of surveying services of open-pit mining enterprises (sometimes underground mining within the scope of reclamation, removal of waste dumps, and ground storage of minerals).

Source [5] provides a list of possible applications of unmanned quadcopters in construction and surveying.

Based on the results of collecting and analyzing images obtained using UAVs, the team of authors [6] determined the accuracy of topographic plans. The plan accuracy root mean square error RMSE (xy) and elevation RMSE (z) were analyzed separately. According to the authors, the accuracy of a digital model can be assessed based on the analysis of the root mean square error of determining the coordinates of points in cartographic images or as the average deviation of coordinates of landmarks in areas of triple overlap of images. The factors affecting the accuracy of the digital model are considered, namely: shooting height, matrix resolution, number of reference points and the quality of determining their coordinates, terrain relief, the presence of a built-in GNSS receiver, the method of post-processing cartographic material, the technical capabilities of UAVs, etc. The paper presents correlation dependencies of the root mean square error of determining the planimetric and altimetric coordinates of points depending on the flight altitude (30-500 m).

The issue of accuracy of surveying using UAVs is also addressed in publications [7,8,9]. In [8], the authors suggest using cameras with a fixed focal length and increasing the number of features to two per image to improve accuracy. The article discusses in detail the advantages and disadvantages of using UAVs for surveying compared to other types of surveying.

Based on the analysis of the results of a photogrammetric project, the authors of article [9] obtained a mean square accuracy of 32 mm for planimetric coordinates and 31 mm for altimetric coordinates, which is a fairly high indicator of the quality of surveying using UAVs.

Publications [11-19] are devoted to the legal and technical aspects of using UAVs to solve various tasks in the field of geodesy and surveying, as well as the processing and analysis of survey results and their digitization.

The scientific publication by Atamanenko Yu.Yu. [20] is also devoted to the study of the accuracy of aerial photography using UAVs. The work presents a mathematical processing of the results of double inaccurate measurements of distances between marks on the experimental site. The analysis of the research results is based on a comparison of the lengths of fixed intervals between survey points obtained using:

- ground-based geodetic surveying with GNSS positioning;
- aerial photography using UAVs and subsequent processing of the results in the DELTA DIGITALS software package.

The research has established that the absolute linear error in determining the lengths between fixed survey points is 10 mm and does not exceed the relative error of 1:2000.

The results of the analysis of literary sources on the selected topic indicate sufficient coverage of the topics of UAV application and topographic survey accuracy. The scientific works considered have a certain range of publication dates, during which the survey methodology, technical means, and means of processing the results changed. Thus, the issue of the accuracy of topographic work in modern conditions is constantly subject to refinement. This is indicated by a significant discrepancy in the errors of the position of aerial photography points, which may be the result of various factors.

An analysis of publications indicates the diverse use of UAVs to address issues of ground surveying of the Earth's surface and objects located on it. The vast majority of studies by authors are aimed at assessing the accuracy of point positions in a selected coordinate system.

The main objective of the presented studies is to establish the accuracy of determining the volumes of bulk material in mineral deposits using the latest technologies of photogrammetric surveys at low altitudes with the use of semi-professional unmanned aerial vehicles.

2. Methods

Innovative technologies for using UAVs have their advantages and disadvantages compared to traditional methods of topographic surveying. First, surveying planning should be carried out taking into account meteorological data, which does not always correspond to the terms of their implementation. The second factor is the complexity of performing field (in this context, flight) work in areas with high vegetation, mountainous terrain, and high-rise buildings.

Another disadvantage is the high possibility of losing equipment (UAVs) due to unforeseen factors.

The advantages of using unmanned aerial vehicles are:

- speed of surveying in field conditions, which is limited only by the technical characteristics of the UAV and external shooting conditions;
- the ability to quickly process the results of the survey;
- obtaining a three-dimensional model of the surveyed surface with the possibility of performing its spatial analysis.

When using UAVs to survey surfaces of warehouses that lack vegetation, high efficiency and speed of field work with sufficient accuracy are achieved. The purpose of the research is to evaluate the accuracy of determining the volume of bulk material using various surveying methods, in particular unmanned aerial vehicles.

Experimental studies were conducted to determine the volume of sand in a private enterprise in the village of Sotnytske, Dnipropetrovsk region. The surface of the storage facility was measured using a Leica TS06 electronic tachymeter, a Sokkia GSX3 GNSS receiver, and a Xiaomi FIMI X8 SE2022 unmanned aerial vehicle in accordance with the instructions [21]. To ensure the accuracy of the survey results, markers were used, the spatial coordinates of which were determined using RTK satellite

positioning and 1st order polygonometry. The survey points obtained with the GNSS receiver and the electronic total station coincide in space, which ensures high-quality analysis of the results. Errors in determining the coordinates of the starting points do not affect the result of the volume determination, since they are used simultaneously for three survey options.

To determine the volume of the warehouse, the following initial information is required:

- the initial topographic surface within its design boundaries;
- spatial coordinate reference of the survey contour in local or regional systems.

The spatial position of the survey points of the warehouse surface was determined from the reference points of the geodetic base, the diagram of which is shown in figure 1. The coordinates of the geodetic base points were determined from the starting points of the local system. The survey surface contour is the lower edge of the embankment within the boundaries specified by the customer. The distance between the survey points when determining the topographic surface of the warehouse was 2-10 m.



Figure 1. Diagram showing the location of starting points (red) and the geodetic control network (blue) for topographic surveying.

The points of the geodetic control network were fixed in the form of 1.2 m long driven benchmarks. The benchmarks were made of steel rods with a diameter of 20 mm. The points on the surface of the warehouse were coordinated using an electronic tacheometer with a reflector installed on a stake with a verticality control of ± 5 mm. Using this method, the spatial position of the survey points was simultaneously determined using GNSS receiver. The heights from the surface of the warehouse were fixed for both survey options. Thus, the planimetric and altimetric positions of the survey points coincided, which improved the quality of the experiment.

The spatial coordinates of the geodetic base were determined by laying an open polygonometric traverse of the 1st order between the starting points. Horizontal angles were measured with an electronic tachymeter in one complete measurement with a root mean square error of 7". The absolute accuracy of length measurements was 2 mm, and the relative accuracy did not exceed 1/50000. The work includes a simplified adjustment of the coordinates of the polygonometric traverse. The angular discrepancy was 8", the relative linear discrepancy was 1/42000, which is significantly less than the permissible values.

After completing the cycle of ground surveys with the above-mentioned geodetic instruments, a

flight task of photographing the terrain was performed using a Xiaomi FIMI X8 SE2022 quadcopter.

The calculation of the main flight parameters of the UAV, which ensures the relationship between the GSD (Ground Sample Distance) size and the shooting height, is determined by the formula: $GSD = (Sw \cdot H \cdot 100) / (Fr \cdot imW)$, where GSD – pixel size in projection onto the earth's surface, cm/pixel; Sw – camera sensor width, mm; Fr – focal length, mm; H – shooting (flight) height, m; imW – frame (image) width, pixels.

Depending on the required accuracy of shooting and the scale of the plan/map, the GSD parameter is determined (table 1).

Table 1. Recommended GSD values for different survey scales.

Scale of the plan	GSD, cm/pixel
1:500	3.5
1:1000	7
1:2000	14
1:5000	35

To determine the volume of the warehouse, it is necessary to perform a topographic survey corresponding to a scale of 1:1000. The height of the flight task should be (for conditions of use of the Xiaomi FIMI X8 UAV):

$$H = (GSD \cdot Fr \cdot imW) / (Sw \cdot 100) = (7 \cdot 6.5 \cdot 3718) / (23.5 \cdot 100) = 72 \text{ m.}$$

The flight altitude should be 72 m to ensure that the terrain is photographed at a scale of 1:1000 with a GSD of 7 cm/pixel. In order to increase the accuracy of the flight task, the photography altitude was reduced to 40 m, with 80% overlap of the photographs. Twelve photographs were taken of the site, with an overlap of adjacent photographs covering more than 70 percent of the site.

To increase the accuracy of the survey, markers were fixed on the surface of the warehouse and at the points of the geodetic base, the coordination of which was performed using an electronic tacheometer and a GNSS receiver (figure 2). The flight task was organized in such a way that at least two marks (identifiers) were visible in each photograph. A total of 6 marks were fixed.



Figure 2. Appearance of a fixed mark for positioning photographs.

3. Results and discussion

The volume of the mineral deposit was determined using Digitals (Vinnitsia, Delta/Digitals 5.0 hardware network security key No. 157409324-06491-261) and SAMARa (Laboratory of Complex Technologies, Pavlohrad, Cooperation agreement dated October 4, 2024.) software products. Three-dimensional models of the mining areas were constructed based on the surface survey points. The triangulation grid of the surface was constructed in the SAMARa software complex using the Delone method (figure 3). The color gradation from green to red corresponds to an increase in the absolute elevation of the survey surface.

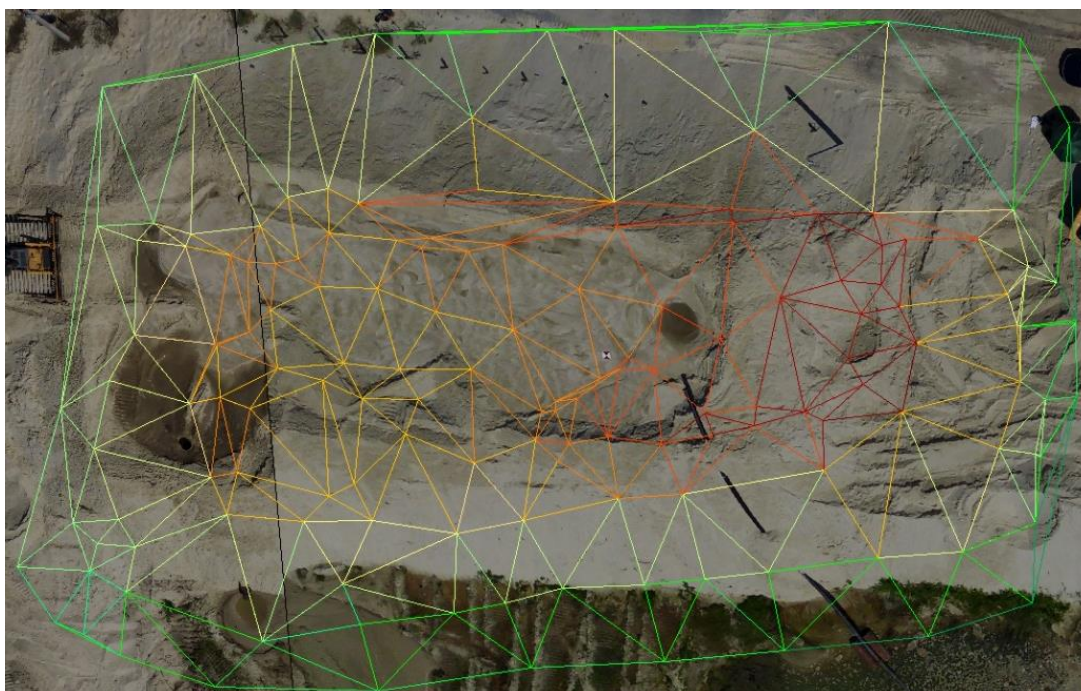


Figure 3. Triangulation model of the survey surface (SAMARa).

To calculate the volume in the Digitals software environment, TIN (irregular grid) and CMR (regular grid with a defined distance between nodes of 2 m, figure 4) models were used.

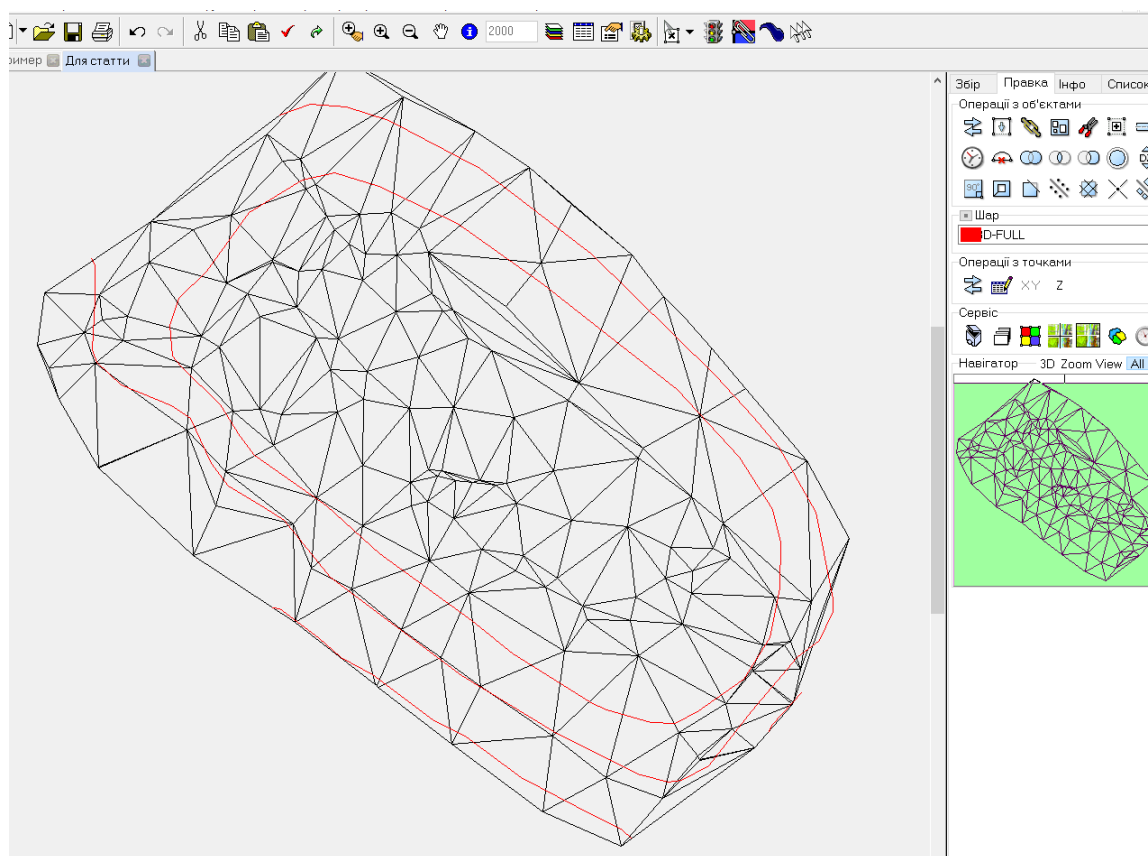


Figure 4. Triangulation model in the Digitals software environment.

Errors in determining the spatial coordinates of the survey points on the surface of the warehouse, calculated based on the results of tacheometric and satellite surveys. Their values do not exceed 19 mm in the horizontal plane and 32 mm in the vertical plane.

The area of the survey contour was 2577 m². The total volume of the warehouse according to the survey results:

- electronic tachymeter – 8228 m³ (SAMARa), 8267 m³ (Digitals). The average value is 8242 m³;
- GNSS receiver – 8299 m³ (SAMARa), 8332 m³ (Digitals). The average value is 8315 m³.

The slight error in volume determination is due to the use of identical three-dimensional grids (TIN, irregular grid) in both software products, the vertices of which coincided under the conditions of the experiment methodology.

The processing of the survey data collected by an unmanned aerial vehicle (Xiaomi FIMI X8 quadcopter) was performed using the PIX4D Mapper software product. The processing of the survey results was performed sequentially in the following order:

- analysis of photographs, removal of poor-quality ones;
- alignment of photographs, camera calibration;
- linking the model to the local coordinate system;
- obtaining a point cloud and a polygonal three-dimensional model;
- noise removal (technological equipment), outlining the surface within the calculation area, exporting the model in DXF format.

The model was tied using two reference points and four control points, the number of which corresponds to the number of marks (identifiers) fixed on the surface. The maximum error of the control points was 38 mm in plan and 57 mm in height.

The three-dimensional model of the warehouse surface is shown in figure 5.



Figure 5. Initial three-dimensional model of the warehouse surface based on the results of quadcopter surveying.

After exporting the discharged point cloud, a three-dimensional model is obtained, the density of which is higher than the previous ones (figure 6).

The total volume of the deposit, based on the results of surface surveys using UAVs, was: 8058 m³ (SAMARa), 8074 m³ (Digitals). The average value is 8115 m³.

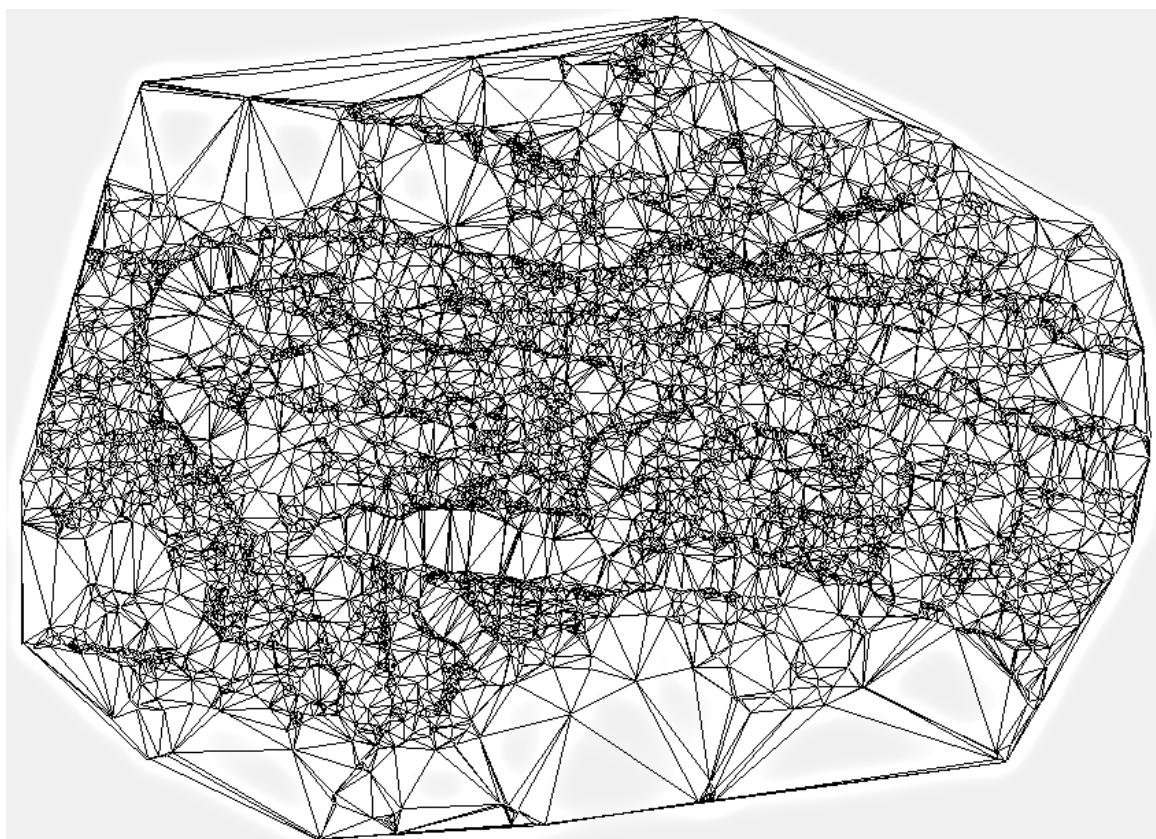


Figure 6. Three-dimensional model of the warehouse surface based on the results of photo processing.

4. Conclusions

Results of determining the volume of sand with an area of 2577 m² using three measurement methods (table 2).

Table 2. Comparison of the results of determining the volume of sand.

Measurement method	Processing method	Volume value, m ³	Average value, m ³	Volume value, m ³ / %
Electronic tachometer	SAMARa	8228	8242	35/0.4
	Digitals	8267		
GNSS surveying	SAMARa	8299	8315	108/1.3
	Digitals	8332		
UAV	SAMARa	8058	8066	141/1.7
	Digitals	8074		
Average, m ³			8207	

According to the rules [21], the permissible relative difference in the volumes of extracted rock during the control count for deposits smaller than 20 thousand m³ should not exceed 15%. The results of experimental and analytical studies presented in table 2 indicate the possibility of using semi-professional UAVs to determine volumes with sufficient accuracy (less than 2%). When implementing the flight task, a methodology should be followed that will ensure the required accuracy in the absence of tall vegetation. It should be noted that the use of unmanned aerial vehicles is possible within the framework of current legislation [1].

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