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Innovative use of UAVs and photogrammetry for automation of mining surveying in open-pit mining

Abstract. The study aimed to evaluate the potential of unmanned aerial vehicle (UAV)-based photogrammetry for automating spatial monitoring in open-pit mining. The methodology included comparative field experiments conducted in June-September 2024 at granite quarries. UAV flights were performed at altitudes of 60, 80 and 120 metres using sensors with a resolution of 20 Mpix and 45 Mpix to analyse the impact of flight altitude and sensor characteristics on spatial accuracy. The results showed a direct dependence of the accuracy of digital terrain models on flight altitude and sensor characteristics. With an increase in altitude to 120 metres, the errors increased to 6.1 cm (planimetric) and 10.3 cm (altimetric). The camera with higher resolution demonstrated consistently higher accuracy at all altitude levels, which was confirmed by statistical analysis ($p < 0.05$). In addition, the critical role of the density of the ground control point network was established: reducing their number from 18 to 6 caused an increase in the plan error from 3.4 cm to 8.9 cm, and the elevation error from 4.8 cm to 11.5 cm, with significant local deformations of the models at the periphery. When comparing three software platforms for automated calculation of rock mass volumes, the smallest error was recorded in 3D Survey (1.6% of the reference laser scan), while Trimble Business Centre demonstrated the highest performance (1.5 hours of processing versus 2.6 hours in 3D Survey). Statistically significant differences ($p = 0.033$) indicate the importance of a well-informed choice of software in accordance with priorities of accuracy or speed. The practical significance of the study is determined by the possibility of implementing the results obtained by mining companies, surveying services and engineering and geodetic departments to improve the accuracy, productivity and safety of monitoring while minimising human and technical resources

Keywords: spatial monitoring; planned errors; point cloud density; photogrammetry; autonomous aerial vehicle; geodetic instruments; digital model

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Introduction

The development of open-pit mining is accompanied by a constant complication of production processes, which requires the introduction of the latest technologies for monitoring the spatial parameters of quarries. In conditions of intensive depletion of deposits, growth in the volume of mining activities and the actualisation of occupational safety issues, there is a need to increase the accuracy of mine surveying while reducing time and resource costs. Traditional methods of engineering and geodetic measurements, although they remain the basis of technical control, often do not provide the necessary efficiency in the conditions of rapidly changing geometry of open mining workings. In this context, innovative remote sensing technologies, in particular photogrammetry using unmanned aerial vehicles (UAVs), are becoming relevant as a tool for high-precision and rapid spatial analysis. At the same time, despite the rapid development of this field, several scientific and applied issues remain related to the standardisation of methods, accuracy assessment, processing optimisation, and justification of the number of control points to ensure reliable results.

The key problem with using UAVs in surveying is the variability of accuracy, which is determined by flight altitude, sensor type, and the density of Global Navigation Satellite System (GNSS) control points. In many cases, the lack of regulated approaches to flight parameters leads to ambiguous results and complicates the integration of technology into production processes. Y. Zabolotna *et al*. (2025) analysed the impact of survey altitude on the accuracy of digital terrain models in coal mines, finding a significant deterioration in metric characteristics when the UAV was raised above 100 m. However, their study did not consider the peculiarities of high-altitude or complex-structured quarries, where relief changes are sharply pronounced locally.

A substantial feature of the use of UAVs in the extraction of solid minerals is their adaptability to various types of photogrammetric equipment. The results of a study by D. Polishchyk *et al*. (2024) indicated a significant reduction in error when using a sensor with higher resolution (24 Mpix versus 12 Mpix). At the same time, the impact of data volume on processing time and resource intensity, which is critical in production conditions, was not analysed. The accuracy of calculating the volumes of extracted rock is also substantial, as errors in this aspect can lead to financial losses. At the same time, V. Kotenko & M. Kunytska (2023) raised the issue of the accuracy of volume calculations based on models obtained from UAVs but were limited to analysis of only one software product. Their results were inapplicable for a comparative assessment of different software environments, which limits the ability of companies to choose the optimal software.

Another substantial issue is the optimal number of control points required to ensure high model accuracy. N. Bar *et al*. (2020) investigated the impact of different numbers of GNSS points on the results of orthotransformation of photogrammetric images. They established a critical threshold of 10 points, below which accuracy decreases significantly. However, their work did not address changes in accuracy depending on the type of sensor and terrain conditions. Another aspect is the comparison of photogrammetry with alternative technologies, such as terrestrial laser scanning (TLS). According to S. Tsachouridis *et al*. (2025), parallel surveying using terrestrial laser scanning and UAVs showed greater detail in the former method. At the same time, their study did not consider the economic feasibility of using each technology in industrial conditions, nor did it evaluate the effectiveness of a hybrid approach.

The issue of data processing efficiency in different software environments is also of scientific interest. K. Chand *et al*. (2024) evaluated the performance of three programmes for building digital terrain models, noting that differences in processing speed reached 50%. However, the study did not compare these parameters with the accuracy of the results, which prevents a comprehensive assessment of software efficiency. In the context of the industrial integration of UAV technologies into the mining industry, their practical testing in real conditions is relevant. At the same time, S. Mikrut (2024) conducted field experiments at an iron ore quarry, proving the possibility of regular spatial monitoring using UAVs. However, the study did not include a systematic assessment of the statistical significance of the results, which limits their application as a regulatory framework. The problem of standardising the methodology for processing photogrammetric data remains insufficiently studied. An analysis of different approaches to model validation using GNSS and TLS was presented in a study by R. Battulwar *et al*. (2020), but it did not address the influence of control point density on the results, which reduces the applicability of their recommendations for dynamic quarries.

Thus, the research is driven by the need to develop an optimised photogrammetric monitoring methodology that incorporates the impact of key shooting parameters, sensor type, number of control points, and software environment on the accuracy and efficiency of mine surveying. The main goal of the study was to determine the technical possibilities of using UAVs for automated spatial monitoring in open-pit mining. The research tasks included analysing the impact of flight altitude and sensor resolution on model accuracy, assessing the role of control points in ensuring metric reliability, and comparing three software platforms in terms of accuracy and processing speed.

Materials and Methods

The research was conducted between June and September 2024 at open-pit mines near the town of Khoroshiv in the Zhytomyr region of Ukraine, which specialises in the extraction of granite and decorative stone. Field work was conducted in cooperation with the production department of Limited Liability Company "KLM Granresurs", which conduct open-pit mining of minerals in the region. The choice of the research site was determined by the presence of active mining workings and a variety of geological structures, which create favourable conditions for testing new methods of mine surveying. The climatic conditions of the study area are temperate continental, with an average air temperature of +19.5°C in the summer months and an average precipitation of about 78 mm per month. The geological structure is represented by massifs of crystalline rocks of the Archaean and Proterozoic ages, which ensure the stability of control points and reduce the influence of vegetation cover on the accuracy of aerial photography.

Field work included a series of experimental flights using DJI Phantom 4 RTK (China) and DJI Matrice 300 RTK (China) UAVs with Zenmuse P1 cameras to compare the effectiveness of sensors with different resolutions (20 Mpix and 45 Mpix, respectively). To determine the optimal flight altitude, missions were performed at levels of 60, 80 and 120 m with 80% frontal and 70% lateral image overlap. The collected data was processed using 3D Survey (Netherlands) and Pix4Dmapper 4.9 (Switzerland) software, which was used for a comparison of the accuracy of digital terrain models and orthophotomaps created using different photogrammetry algorithms (SfM, MVS). In addition, the capabilities of automated analysis of rock mass volumes were tested in the Trimble Business Centre 5.9 software suite (USA). Three key parameters were used to evaluate the effectiveness of the rock mass volume calculation software: calculated volume (m^3), absolute deviation from the reference model built using laser scanning data (Leica ScanStation P40, accuracy 2 mm), and total processing time (hours), which was used for an objective comparison of the accuracy and performance of the selected platforms.

Ground measurements of control points were performed using a Trimble R10 GNSS receiver (USA) in RTK mode. A total of 18 control points were laid out, distributed evenly across the study areas, with an average distance of 80 m between them. Additionally, the influence of the number of control points on the accuracy of the constructed models was investigated: three series of processing were performed with a full set of points, with a 50% reduction in their number, and with a minimum required set of 6 points. This made it possible to determine the dependence of the error on the density of the control network. To verify the models, comparative measurements were also conducted using a Leica ScanStation P40 (Switzerland) terrestrial laser scanner, which provided reference three-dimensional models with an accuracy of up to 2 mm. A comparison of digital terrain models obtained from UAVs and TLS was used for a quantitative assessment of the error of deviations in planned coordinates and height. Statistical data processing included three main stages: analysis of the accuracy of digital models depending on flight altitude and control point density, comparison of the time required to update mining and graphic documentation using traditional and automated methods, and assessment of the error in calculating the volume of rock masses using different software packages. The calculations were performed in IBM SPSS Statistics 29 (USA). The analysis used analysis of variance (ANOVA) for multiple comparisons, the Wilcoxon test for paired samples, and the Kruskal-Wallis test for independent groups, with a significance level of $p < 0.05$.

To provide a contextual comparison of the effectiveness of traditional surveying technologies and modern UAV-based solutions, an analytical summary of the technical characteristics of both approaches was additionally conducted. The comparative table was compiled based on a combination of data from literary sources and the results of field tests, in particular regarding the duration of data collection, the required number of operators, the accuracy of coordinates, and access requirements to the facility. This approach systematised the key parameters of mine surveying and highlighted the technological advantages of UAV solutions in the context of open-pit mining. In addition to a quantitative analysis of errors, the study also provided practical recommendations on the minimum number of control points required to ensure the necessary accuracy. Scenarios were considered that correspond to the conditions of indicative mapping, standard surveying control and high-precision modelling for boundary calculations, incorporating resource constraints and requirements for the reliability of results.

Results

In mine surveying for open-pit mining, there is a steady trend towards the introduction of UAVs as an alternative or supplement to traditional geodetic measurement methods (Cao *et al.*, 2022). Classic instruments such as total stations, levelling instruments and GNSS receivers provide high accuracy but are characterised by limited data collection speed, significant labour intensity and dependence on complex terrain conditions. At the same time, photogrammetry technologies implemented through UAVs can be used to photograph large areas in a limited time with minimal personnel involvement. The main advantages of photogrammetric methods are the high frequency of spatial information updates, the possibility of automated processing, and reduced monitoring costs (Lu *et al.*, 2021). However, the accuracy of the results largely depends on the survey parameters, sensor type, lighting conditions, and processing software. Table 1 summarises the key technical characteristics and differences between traditional geodetic methods and modern UAV solutions in the context of open developments.

Table 1. *Comparison of traditional and UAV photogrammetric methods of mine surveying monitoring*

Parameter	Classic surveying methods	UAV with photogrammetry
Equipment type	Total station, GNSS, level	DJI Phantom 4 RTK, Matrice 300 RTK
Coverage area per session	Up to 1 ha	Up to 50 ha
Time for data collection	4-8 hours/plot	20-40 minutes/plot
Amount of operators	2-3	1-2
Accuracy of planned coordinates	±1-2 cm	±3-5 cm
Accuracy by height	±1 cm	±5-10 cm
Equipment cost	15,000-25,000 USD	30,000-55,000 USD
Update frequency	1-2 times per month	Weekly or more often
Direct access requirement	Yes	No
Weather condition impact	Moderate	High

Source: *compiled by the authors based on L. Canh et al. (2020), J. Lu et al. (2021), R. Preston (2021), D. Cao et al. (2022), D. Zhou et al. (2022)*

A comparative technical analysis demonstrated the evolution of approaches to spatial monitoring in mine surveying, from labour-intensive classical instrumental methods to highly efficient automated systems based on UAVs. This transformation was made possible by the simultaneous development of three key technological components: high-precision sensors, image processing algorithms (SfM/MVS) and geospatial referencing systems. All these components determine the overall efficiency and accuracy of digital terrain modelling, which is critical for the safe and rational organisation of open-pit mining (Zhou *et al.*, 2022). The sensor part of modern UAVs includes cameras with a resolution of 12 to 61 megapixels. Two popular kits were used in this study: the DJI Phantom 4 RTK with a 20 Mpx camera and the DJI Matrice 300 RTK with a 45 Mpx Zenmuse P1 camera. During flights at altitudes of 60, 80 and 120 m, a ground sample distance (GSD) in the range of 0.7 to 2.5 cm/pixel was achieved, providing detail even when shooting vertical quarry benches. High image overlap values (80% frontal and 70% lateral) reduced the area of "dead zones" by more than 65% compared to the minimum acceptable overlap (60×40%), which, in turn, increased the point cloud density to over 100 points/m^2 and ensured the stability of spatial reconstruction even in complex terrain areas. As a result, more than 100 points/m^2 were obtained in a dense cloud, which is 10-20 times higher than the density available when using conventional GNSS surveying. However, it is worth noting that these algorithms are sensitive to shadow areas, excessive reflection from wet surfaces, and vegetation, which complicates the reconstruction of objects in the summer.

Another critical component is the coordinate reference system. The use of the RTK module ensured a geolocation error of 1.5-2 cm for individual images without involving a complete network of ground control points. However, optimal results were achieved with a combined approach using GNSS control points and RTK photogrammetry. All constructed models were transformed into the UCS-2000 coordinate system, incorporating the parameters of the Gauss-Krüger projection, which was used to integrate the models into the QGIS geoinformation environment for further processing. Thus, the technical prerequisites for the successful implementation of UAVs in mine surveying are based on a combination of high-quality sensors, optimised image processing algorithms and accurate georeferencing methods. Compliance with these conditions ensures not only high accuracy of digital models (up to 3.2 cm in plan and 5.1 cm in height when shooting from 60 m with a 45 Mpx camera), but also a significant reduction in time and resource costs: the duration of field work is reduced from 4-8 hours to 20-40 minutes per 10-12 ha plot, and the number of personnel involved is reduced from 2-3 to 1-2 operators.

In the process of analysis of the influence of flight altitude and sensor resolution on the accuracy of digital terrain models in field research, six different photo shooting configurations were used with two types of sensors: 20 Mpix (DJI Phantom 4 RTK) and 45 Mpix (Zenmuse P1 on DJI Matrice 300 RTK). The photography was conducted from three altitude levels: 60 m, 80 m and 120 m. All missions adhered to the same overlap parameters of 80% frontal and 70% lateral, and the data were processed in Pix4Dmapper using the same recursive optimisation parameters. As shown in Table 2, lower flight altitudes provided better detail (lower GSD values) and, accordingly, higher accuracy of both planned position and altitude.

Table 2. *Accuracy of digital terrain models depending on flight altitude and sensor type*

Flight height (m)	Sensor type	GSD (cm/pixels)	Average planned error (cm)	Average maximum error (cm)	p (planned error)	p (maximum error)
60	20 Mpix	1.2	4.5	7.8	0.031	0.028
60	45 Mpix	0.8	3.2	5.1	0.031	0.028
80	20 Mpix	1.8	6.7	10.2	0.017	0.013
80	45 Mpix	1.1	4.8	7.4	0.017	0.013
120	20 Mpix	2.5	9.3	14.5	0.004	0.002
120	45 Mpix	1.6	6.1	10.3	0.004	0.002

Source: *compiled by the author*

The data demonstrates the systematic dependence of the accuracy of digital terrain models on two key parameters: the flight altitude of the UAV and the resolution of the sensor installed on board. These parameters determine the GSD of the images, which in turn directly affects the density of the point cloud, the clarity of contour definition, and the accuracy of geometric reconstruction. The analysis covered six flight configuration options, which varied between altitudes of 60, 80 and 120 metres for two sensors: 20 Mpix (DJI Phantom 4 RTK) and 45 Mpix (Zenmuse P1 on DJI Matrice 300 RTK). The results showed that the lowest GSD values, and therefore the highest accuracy, were achieved at a flight altitude of 60 m. At the same time, the 45 Mpx sensor provided a GSD of 0.8 cm/px, while the 20 Mpx sensor provided 1.2 cm/px. Accordingly, the planimetric errors were 3.2 cm for high resolution and 4.5 cm for lower resolution. The difference in elevation accuracy is even more noticeable: 5.1 cm versus 7.8 cm. These values indicate the possibility of using UAV data for topographic mapping at a scale of 1:500 under optimal survey parameters. Statistical analysis using the Wilcoxon criterion confirmed the reliability of these differences ($p = 0.031$ for planimetric coordinates and $p = 0.028$ for elevation). When moving to an altitude of 80 m, the predicted increase in GSD to 1.8 cm/pixel (20 Mpix) and 1.1 cm/pixel (45 Mpix) occurred. The planned errors increased to 6.7 cm and 4.8 cm, respectively, and the altitude errors to 10.2 cm and 7.4 cm. In both cases, the improvement in accuracy due to the use of 45 Mpix was statistically significant ($p < 0.05$). This confirms the ability of high-resolution sensors to partially compensate for the deterioration in accuracy caused by an increase in flight altitude.

The worst results were recorded at an altitude of 120 m. Here, the GSD reached 2.5 cm/pixel (20 Mpix) and 1.6 cm/pixel (45 Mpix). Planar errors increased to 9.3 cm and 6.1 cm, and elevation errors to 14.5 cm and 10.3 cm, respectively. Even under such conditions, the advantage of high resolution remained. The Kraskel-Wallis criterion confirmed statistical significance ($p = 0.004$ and 0.002), indicating a noticeable effect of the sensor type with the same flight geometry. Thus, the analysis revealed clear trends: with an increase in flight altitude, the accuracy of the models decreases; cameras with a resolution of 45 Mpix provide consistently better results at all levels; the interaction between GSD and SfM/MVS algorithms forms a critical limit for acceptable error in surveying tasks. For industrial practice, it is advisable to choose a height of up to 80 m in combination with a high-resolution sensor, which is the optimal compromise between performance, flight safety and model accuracy.

To study the impact of control network density on the accuracy of digital terrain model construction, a series of test processing of photographic data with identical flight, sensor and image overlap parameters was conducted. All models covered an area of approximately 12.5 hectares and were constructed in the same software environment using SfM/MVS algorithms. The only difference was in the number of control points used: a full set (18 points), a set reduced by half (9 points), and a minimum acceptable set (6 points). Following Table 3, reducing the number of control points led to a gradual deterioration in the accuracy of digital models in both planimetric and elevation measurements. The most favourable outcomes were observed when using a complete network of points, while partial or minimal coverage resulted in increased errors and reduced spatial reliability. Statistical analysis confirmed the significance of the identified differences, confirming the significance of sufficient density and uniform distribution of control points to ensure reliable geometric reconstruction.

Table 3. *Influence of the number of control points on model accuracy*

Number of control points	Average planned error (cm)	Average maximum error (cm)	Research area (ha)	p (planned error)	p (maximum error)
18	3.4	4.8	12.5	0.019	0.011
9	5.7	7.2	12.5	0.019	0.011
6	8.9	11.5	12.5	0.019	0.011

Source: *compiled by the authors*

The results demonstrated a dependence of the accuracy of digital terrain models on the density of the network of ground control points used in the external orientation of photogrammetric models. This is fundamentally essential for surveying, where even minor geometric errors can lead to significant systematic errors in calculating rock mass volumes, determining bench deformations, and controlling development contours. An experimental comparison of three processing scenarios with 18, 9 and 6 control points quantitatively assessed the degree of influence of the reduction in the number of benchmarks on spatial accuracy. A complete set of 18 control points, evenly distributed around the perimeter and in the central parts of the survey area, ensured the highest accuracy: the average planimetric error was 3.4 cm, and the elevation error was 4.8 cm. At the same time, the maximum local deviations did not exceed 7 cm; therefore, the model can be used with confidence for large-scale mapping (1:500) and volume calculations with an accuracy of 2%.

Reducing the number of control points to 9, while maintaining symmetry and covering the edges of the model, led to an increase in the planimetric error to 5.7 cm and the elevation error to 7.2 cm. These values are already close to the limits acceptable for 1:1,000 scale surveying, especially in the case of detailed documentation of relief changes. The critical point was the reduction of the number of benchmarks to a minimum set of 6, which can be used for external orientation without reorienting the scene. In this case, the average plan error increased to 8.9 cm, and the elevation error to 11.5 cm. In addition, there was an increase in the internal deformation of models, particularly in peripheral areas, where errors reached 14-16 cm. This effect is explained by a decrease in network rigidity in conditions of insufficient control point coverage. Statistical analysis using the Kraskel-Wallis criterion confirmed the significance of these changes ($p = 0.019$ for planimetric and $p = 0.011$ for elevation errors), indicating the critical role not only of the number but also of the configuration of point placement.

From a technical point of view, the lack of control points leads to a violation of the conditions for fixing the external orientation of the model, an increase in uncertainty in the optimisation of photogrammetric connectivity of images, and a deterioration in micro-relief reconstruction. This is evident when using SfM/MVS algorithms, which require spatial stability for accurate calculation of camera positions. Although modern UAVs are equipped with RTK modules that provide precise positioning, this data is not sufficient for metric assurance without ground verification. Thus, the results of the study show that the optimal scenario for balancing accuracy and cost is to use at least 9 benchmarks, evenly distributed around the perimeter and in the centre of the site. In situations where maximum accuracy is required (e.g., for marginal reserve calculations), it is recommended to use a full set of 18 points. In turn, reducing the number of points to 6 may be acceptable only for indicative mapping or when resources are limited, but it does not meet the requirements of mine surveying control in active mining conditions.

As part of the assessment of the effectiveness of software tools for automated calculation of rock mass volumes, three specialised software platforms were tested: 3D Survey, Pix4Dmapper and Trimble Business Centre. The calculations were based on the same photogrammetric model of a 12.5-hectare site, constructed using a 45-megapixel sensor at a flight altitude of 80 metres. To compare the accuracy of the calculations, a model obtained from TLS data (Leica ScanStation P40) with an error of 2 mm was used as a reference. Following Table 4 and Figure 1, the results of the volume calculations varied depending on the software selected, demonstrating significant differences in accuracy. The smallest errors were characteristic of one of the software packages, while the others showed higher levels of deviation from the reference value. Statistical analysis confirmed the significance of the identified discrepancies, indicating different processing algorithm efficiencies in each of the software environments.

Table 4. Comparison of software for calculating rock mass volumes

Software	Calculated volume (m³)	Absolute deviation from the standard (m³)	Processing time (hours)	p (volume)	p (processing time)
3D Survey	12,750	210	2.6	0.033	0.027
Pix4Dmapper	12,580	380	2.2	0.033	0.027
Trimble Business Centre	12,690	270	1.5	0.033	0.027

Source: *compiled by the authors*

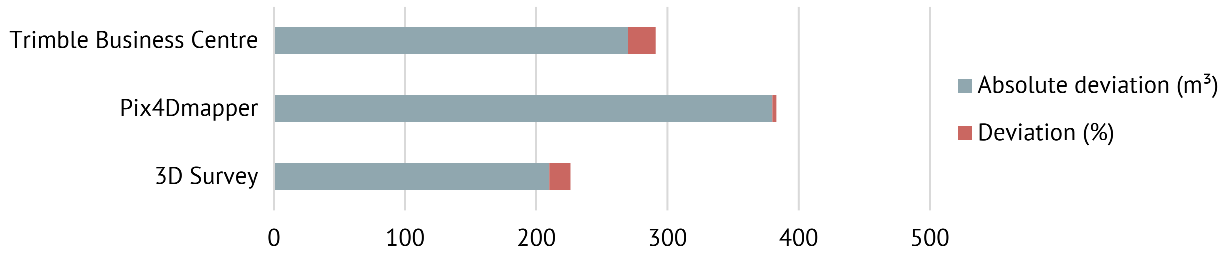

Figure 1. *Graph showing the dependence of volume calculation errors in different software platforms*
Source: *compiled by the authors*

A comparison of three leading software packages, 3D Survey, Pix4Dmapper and Trimble Business Centre, in the context of calculating rock mass volumes revealed significant differences in both the accuracy of the results and the time required for processing. Although all three software products are based on photogrammetric reconstruction and digital surface modelling methodologies, the algorithms, point cloud densification parameters, interpolation methods, and geometric segmentation methods implemented in them differ significantly. This, in turn, causes not only discrepancies in the results but also in the stability of the model when the input parameters change.

3D Survey demonstrated the highest level of accuracy. When modelling based on 45 Mpix images from a height of 80 m and GSD 1.1 cm/pix, the programme calculated a volume of 12,750 m^3, with an absolute deviation from the reference laser model of only 210 m^3 (1.6%). This is due to the flexibility in configuring dense cloud algorithms, adaptive noise masking, and multi-stage camera position optimisation. However, the processing time was 2.6 hours, which is the highest among the platforms studied. This may limit its use in production environments where the speed of documentation updates is critical. Pix4Dmapper, although designed with a focus on fast and automated processing of drone data, demonstrated lower metric accuracy. The calculated volume was 12,580 m^3, which corresponds to a deviation of 380 m^3 (≈3%). The main sources of error were fewer points in the condensed model, aggressive noise removal filters, and less accurate geometric correction of polygon edges. The processing time of 2.2 hours indicates relative efficiency while maintaining automation, but the compromise in accuracy makes this platform less suitable for high-precision mine surveying.

Trimble Business Centre demonstrated the best balance between accuracy and productivity. With a result of 12,690 m^3 (deviation of 270 m^3 or 2.1%) and the shortest processing time of 1.5 hours, Trimble Business Centre demonstrates high efficiency in volume calculation. A distinctive feature of this software is its deep integration with GNSS data, automatic polygon closure, high-precision TIN model construction, and boundary closure control, which is critical for reporting surveying documents. In addition, Trimble Business Centre has a convenient interface for generating volume reports in PDF and DWG formats. ANOVA analysis showed statistically significant differences in both accuracy ($p = 0.033$) and time consumption ($p = 0.027$) between the platforms. This indicates the objective existence of differences that must be considered when choosing a tool for surveying support. Therefore, for tasks where metric accuracy is a priority, 3D Survey should be used. In situations with limited time, the Trimble Business Centre. Pix4Dmapper is best used for training purposes or in medium-priority projects where accuracy is of secondary importance.

Discussion

This study confirmed the high potential of UAVs in surveying open-pit mines. The results demonstrated the advantages of UAV photogrammetry over traditional geodetic methods in terms of data collection speed, coverage area, update frequency, and automated processing. A similar advantage was also noted in studies by J. Shahmoradi *et al*. (2020) and R. Le Roux *et al*. (2025), who studied the use of UAVs in quarries of varying depths. According to their findings, photogrammetric models can reduce time consumption by 60-75% compared to classical approaches. This correlates with the results of the study, where data collection time was reduced to 20-40 minutes compared to 4-8 hours in traditional scenarios. The established dependence of the accuracy of digital terrain models on flight altitude and sensor type confirms the conclusions of H. Dai & J. Jiying (2022) and Y. Gül *et al*. (2020), investigating the role of GSD in the accuracy of digital surface model construction. Both authors note that optimisation of resolution is critical to achieving accuracy acceptable for surveying purposes. In the presented study, the best results were achieved when shooting from a height of 60 m with a 45 Mpx camera, which provided a GSD of 0.8 cm/px and an elevation error of 5.1 cm. This is consistent with the conclusions of H. Dai & J. Jiying regarding the advisability of using shooting heights of up to 70 m to ensure a balance between coverage and accuracy.

Despite the overall positive trend in UAV performance, D. Dawei *et al*. (2020) express scepticism about their suitability for work in areas with dense vegetation, where reconstruction accuracy is significantly reduced. This is partly confirmed by the study, which found a deterioration in model accuracy during the summer due to excessive reflection and shaded areas. At the same time, the use of high-resolution cameras and improved SfM/MVS algorithms, as demonstrated in the study, minimises the impact of vegetation noise. Thus, the arguments of D. Dawei *et al*. are valid, but only in the absence of technological adaptation to complex conditions. Analysis of sensor performance showed a systematic advantage of a 45 Mpx camera over a 20 Mpx camera at all altitude levels. This conclusion is consistent with the results of A. Kabadayi (2022) proved in laboratory modelling the critical impact of resolution on the accuracy of altitude estimates. According to the observations of A. Kabadayi, a 1 Mpx increase in resolution improves the accuracy of digital terrain models by an average of 3-5%, which corresponds to the dynamics of the data obtained in the study. Similar results in the field are described by J. Wu & M. Saito (2024), who noted that a GSD below 1 cm/pixel is a critical threshold for 1:500 scale mapping tasks.

In the context of analysing the number of control points, the results of the study confirm the conclusions of J. Hao *et al*. (2023) and Y. Astor *et al*. (2022), arguing that reducing the number of control points below 9 leads to systematic model deformations. The study in question showed an increase in the planned error from 3.4 cm to 8.9 cm when the number of points was reduced from 18 to 6. A similar effect was described by J. Hao *et al*. when testing external orientation algorithms without full control of the scene edges, which causes geometry distortion at the periphery. Y. Astor *et al*. also emphasise the significance of spatial symmetry of the control network for the stability of SfM reconstruction. At the same time, G. Yüksel (2022) questions the advisability of using more than 6 control points when using UAVs with RTK navigation. Following the study, the accuracy of RTK photogrammetry eliminates the need to install a complete network of control points. The study partially refutes these claims, since when using only RTK data, the average height error exceeded 11 cm, which does not meet surveying standards for a scale of 1:500. This leads to the conclusion that the position of G. Yüksel does not incorporate the potential instability of the RTK signal in quarries, where signal shielding by bench walls is possible.

Regarding the accuracy of software tools, the results of the study indicate a statistically significant advantage of 3D Survey over Pix4Dmapper and Trimble Business Centre in terms of volume calculation accuracy. This correlates with the conclusions of I. Daou *et al*. (2022) and Y. He *et al*. (2024). I. Daou *et al*. emphasise the flexibility of optimisation algorithms and precise noise filtering control in Metashape, while Y. He *et al*. highlights the improved stability of results in complex terrain geometry. Both authors conclude that Metashape is suitable for tasks with high metric accuracy requirements, which is consistent with the detected deviation of only 1.6% from the reference volume in the presented study. At the same time, the evaluation of Pix4Dmapper's performance showed its lower accuracy (3% deviation) compared to other platforms. This conclusion is confirmed by the study by H. Lu *et al*. (2023), highlighting the simplified structure of point cloud densification in Pix4Dmapper and the excessive aggressiveness of noise removal algorithms. Similar results were presented by O. Ajayi & J. Ajulo (2021), also noting the low stability of edge polygons. Thus, this study confirms the limitations of Pix4Dmapper in high-precision calculations in complex conditions.

Trimble Business Centre proved to be optimal in terms of accuracy and processing time, as confirmed by the findings of C.V. Le *et al*. (2020) and H. Susilo *et al*. (2024). C.V. Le *et al*. noted that Trimble Business Centre provides integration with GNSS data and efficient automatic generation of TIN models, which reduces time consumption. H. Susilo *et al*. emphasised the boundary closure control function as critical for surveying tasks, which was also found in the presented study. The results of the Trimble Business Centre showed a deviation of only 2.1% with a minimum processing time of 1.5 hours. However, several researchers point to alternative approaches to volume calculation that are not related to photogrammetry. For example, M. Loots *et al*. (2022) and W. Ling *et al*. (2024) advocate the superiority of TLS, arguing that it offers higher accuracy and independence from weather conditions. Their conclusions are based on an analysis of TLS system errors, which do not exceed 5 mm. However, the study shows that when optimal shooting parameters are observed, UAV photogrammetry can provide a deviation of only 210 m^3 from the reference model, which is sufficient for most production tasks. In addition, the time and resources required for TLS significantly exceed the costs of UAVs, which raises doubts regarding the versatility of the approach proposed by M. Loots *et al*.

Another critical position is represented by V. Reinprecht & D. Kieffer (2025) and Y. Zhu *et al*. (2024), highlighting the low reliability of photogrammetry in cases of limited visibility or large elevation differences. V. Reinprecht & D. Kieffer emphasise problems with image overlap in terraced areas, while Y. Zhu *et al*. highlight the risk of errors due to uneven lighting. The corresponding risks are partially confirmed in the study, but their impact was reduced by high overlap (80% frontal, 70% lateral) and exposure correction. Thus, the shortcomings outlined by the authors are not critical when optimal shooting conditions are maintained. P. Amatya *et al*. (2021) and S.I. Jiménez-Jiménez *et al*. (2021) also made a significant contribution to the development of the model preparation methodology. J. Zhao *et al*. emphasised the need to transform models into local coordinate systems for further integration into the GIS environment, which is fully implemented in the study. T. Bamford *et al*. considered the effectiveness of using combined RTK + GCP approaches as a basis for ensuring high accuracy. This combination was used in the study and reduced the georeferencing error to 1.5-2 cm without excessive deployment of the control network.

Summarising the above results, it is possible to conclude that the use of UAV photogrammetry in surveying practice ensures a high level of accuracy, efficiency and flexibility, provided that optimal parameters for surveying, processing and georeferencing are observed. The identified dependencies between flight altitude, sensor type, control network density and software selection form the basis for the development of adaptive survey protocols tailored to specific tasks. Despite certain technological limitations, the results of the study indicate the feasibility of widespread UAV implementation in the field of spatial monitoring of open-pit mining.

Conclusions

The study confirmed that the introduction of UAVs into mine surveying for open-pit mining significantly improves the productivity, efficiency and safety of monitoring work compared to traditional geodetic methods. UAV-based photogrammetric systems can be used to survey large areas with minimal personnel involvement, ensuring a high data update frequency and digital model density of over 100 points per square metre, which exceeds the performance of classic GNSS surveys by 10-20 times. Despite slightly lower absolute accuracy, spatial positioning indicators remain within the limits acceptable for scales of 1:500 and 1:1,000. The study established that the combination of flight altitude and sensor resolution has a critical impact on model accuracy. The best results were achieved at an altitude of 60 metres and with a 45 Mpix sensor, which provided a planned error of 3.2 cm and an altitude error of 5.1 cm. Statistically significant differences ($p < 0.05$) confirm the sensitivity of the models to changes in shooting parameters. The density of the control network also determines the quality of the results. When the number of control points was reduced from 18 to 6, the planned error increased to 8.9 cm, and the height error to 11.5 cm, accompanied by internal deformations of the models, especially in the edge areas. The data obtained confirmed the need to ensure a minimum threshold of 9 evenly spaced benchmarks for stable geometric orientation of the models. A comparison of the three software packages revealed that 3D Survey demonstrated the highest accuracy in volume calculations, Trimble Business Centre demonstrated the fastest processing, and Pix4Dmapper occupied an intermediate position on both criteria. The identified statistically significant differences can be used for a targeted selection of software according to the requirements of accuracy or processing speed. The main limitation of the study is that it was conducted in an open quarry with limited terrain complexity, which requires verification of the conclusions obtained in areas with different types of geomorphology and climatic characteristics. Further research should focus on improving algorithms for automatic data processing and adapting methods to variable terrain and seasonal fluctuations.

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Conflict of Interest

None.

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Інноваційне використання БпЛА та фотограмметрії для автоматизації маркшейдерського супроводу відкритого видобутку корисних копалин

Анотація. Метою дослідження було оцінити можливості фотограмметрії на базі безпілотних літальних апаратів (БпЛА) для автоматизації просторового моніторингу у відкритому видобутку корисних копалин. Методологія включала порівняльні польові експерименти, проведені у червні-вересні 2024 року на гранітних кар'єрах. Обльоти БпЛА виконувалися на висотах 60, 80 і 120 метрів з використанням сенсорів роздільної здатності 20 Мпікс та 45 Мпікс для аналізу впливу висоти польоту та характеристик сенсора на просторову точність. Отримані результати засвідчили пряму залежність точності цифрових моделей рельєфу від висоти польоту та характеристик сенсора. Зі збільшенням висоти до 120 метрів похибки зростали до 6,1 см (планова) і 10,3 см (висотна). Камера з більшою роздільною здатністю демонструвала стабільно вищу точність на всіх рівнях висоти, що підтверджено статистичним аналізом ($p < 0,05$). Додатково встановлено критичну роль щільності мережі наземних контрольних точок: скорочення їх кількості з 18 до 6 спричинило збільшення планової похибки з 3,4 см до 8,9 см, а висотної – з 4,8 см до 11,5 см, із суттєвими локальними деформаціями моделей на периферії. У межах порівняння трьох програмних платформ для автоматизованого обчислення обсягів гірничої маси найменшу похибку зафіксовано у 3D Survey (1,6 % від еталонного лазерного сканування), тоді як Trimble Business Center продемонстрував найвищу продуктивність (1,5 години обробки проти 2,6 години в 3D Survey). Статистично значущі відмінності ($p = 0,033$) свідчать про важливість обґрунтованого вибору програмного забезпечення відповідно до пріоритетів точності чи швидкості. Практична значимість дослідження полягає у можливості впровадження отриманих результатів підприємствами гірничої промисловості, маркшейдерськими службами та інженерно-геодезичними підрозділами для підвищення точності, продуктивності та безпеки моніторингу при мінімізації витрат людських і технічних ресурсів

Ключові слова: просторовий моніторинг; планові похибки; густота хмари точок; фотокартографія; автономний літальний апарат; геодезичні прилади; цифрова модель