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Original paper

The study of local terrain modeling methods for vertical planning of the territory

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Abstract: This work aims to study the vertical planning method for the terrain area as part of the process of construction geodetic support. Such planning will be carried out based on the aerial survey data from UAVs, which allow the creation of a high-quality digital elevation model (DEM) with sufficient node density for reliable surface terrain modelling. During the study, we test the hypothesis of the possibility of using archival aerial photographs from UAVs to model the terrain of the local area. Both the actual achievable accuracy of terrain modeling in the course of photogrammetric processing of archived aerial photographs, and methods for creating a polygonal terrain model using input spatial data in the form of clouds of 3D points of a given density require analysis. To do this, we will perform comparisons of the accuracy of calculating earth masses, carried out based on the digital triangulation elevation models (TIN). These models were based on different algorithms for creating Delaunay triangulation with different degrees of 3D point sparsity. We proposed to use sparsity of dense clouds of points representing the surface of the terrain and which were obtained by the photogrammetric method. Computer terrain modelling and calculation of vertical planning parameters were performed by us for the area with flat terrain at angles up to 3.5 degrees. We evaluated the potential of archived UAV aerial photographs and algorithms for creating Delaunay triangulation at different densities of its nodes for calculating the volumes of earth masses.

Keywords: DEM, RMSE, vertical planning, the volume of earthworks, TIN

1. Introduction

Modern geodetic support of the construction industry widely uses digital modelling techniques for terrain and objects. Such models are created both according to the data of traditional geodetic measurements carried out directly on the terrain and according to the data of photogrammetry and remote sensing of the Earth. In particular, an urgent task is to create high-precision digital elevation models (DEM) and use them to calculate the spatial characteristics of construction objects, control the implementation of earthworks, vertical design and many other tasks of geodetic support. Domestic and foreign scientists have been dealing with the problem of creating DEMs for various types of spatial data for a long time (Burshtynska and Zayats, 2002; Ravibabu and Jain, 2008; Toth et al., 2015; Ostrovsky, 2015a, 2015b, 2016; Kostov, 2016; Rudyj, 2016). The theoretical and practical achievements of these and many other authors, however, constantly need to be supplemented and improved in view of the introduction of new means of obtaining geodata, including laser scanning, surveys from unmanned aerial vehicles (UAVs). Such data have a number of properties that impose special requirements on the conditions for their correct use in computational and modelling algorithms. In particular, we are talking about a large amount of information, which in most cases is excessive in quantity for processing in CAD and BIM systems. Data are often obtained with insufficient or excessive spatial accuracy, they contain artefacts, are significantly noisy, etc. Let's note that the density of photogrammetric data in point representations (such as a point cloud) is not confined to the complexity of the terrain of the modelled surface. Thus, there is a problem of bringing geodata and spatial digital models created on their basis to the conditions set by the geodetic support of the construction industry.

The primary purpose of vertical planning is to transform the earth's surface into the design form. Vertical planning includes the calculation of the volume of earthworks, which significantly affects the final estimate of the project. Issues of execution and calculation of earthworks are considered in (Garasymchuk, 2003; Chudý et al., 2013; Qiu, 2017; Al-Jabbar Hadi and Alhaydary, 2018; Hamid et al., 2019; Haronian and Sacks, 2020; Liu et al., 2021).

For effective use of DEM in computational algorithms, it is necessary to make a reasonable choice of a mathematical model that reproduces the terrain with sufficient accuracy. These algorithms are based on either interpolation or approximation (Burshtynska and Zayats, 2002). The analysis of literature sources shows that the main global types of approximation are approximation using analytical functions and approximation with statistical processing of the terrain survey data (Baran and Marushchak, 2011; Schultz et al., 2013; Schultz and Ostrovsky, 2016).

We are investigating a method that involves the use of aerial survey data from UAVs to solve the problem of vertical planning, which is an important part of geodetic support for the construction industry. Under certain circumstances, the archival footage can be used and the cost of new aerial surveys can be avoided. The modern automated photogrammetric process allows you to create a high-quality DEM with a sufficient density of nodes for reliable modelling of the surface terrain (Akgul et al., 2018). In the research's course, we test the hypothesis about the possibility of using archival aerial photographs from UAVs to model the terrain of the local area. First, the achievable accuracy of terrain modelling during photogrammetric processing of archival aerial photographs needs to be analyzed. The second task is to study the methods of creating a polygonal triangulation terrain model using the input spatial data as more or less dense clouds of 3D points. To do this, we compare the accuracy of the calculation of earth masses, which were carried out based on digital triangulation terrain models (TIN). These models were based on different algorithms for creating Delaunay triangulation: the increment method; the scan line method; the combined method with different degrees of the sparsity of the 3D point cloud. The purpose of the simulation is to present a DEM with the minimum number of points that provide reliable modelling of the surface topography for vertical planning and calculation of earth masses in the CAD software.

2. Materials and methods

In the task of calculating the volume of earthworks, the input data is a digital model of the existing terrain surface, a model of the design (desired) surface and a certain region on the map, within which it is necessary to move the soil. In this case, it is advisable to set complex terrain surfaces as a polygonal model with elements of a rectangular (DEM model) or triangular (TIN model) shape. From the analysis of the literature, the TIN triangulation surface representation model has obvious advantages for our case. It does not require height interpolation procedures because it comes from point data arrays (point clouds) directly collected by geodetic or remote sensing methods. The object of our study is the land plot with an area of 0.044 km^2 near the Vynnyky city in western Ukraine (Fig. 1).

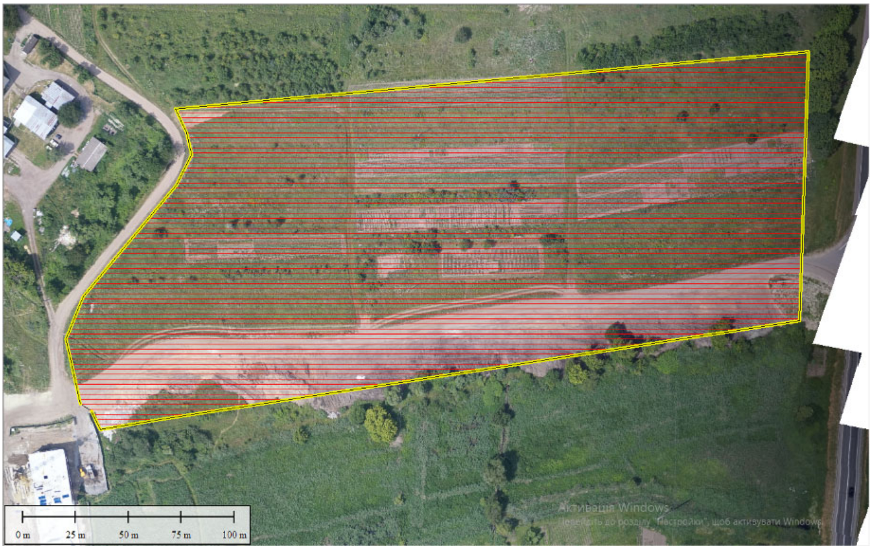

Fig. 1. The investigated area on the archived orthophoto map

As a source of spatial data in our study, we chose aerial surveys from UAVs. Moreover, given the fact that there was no economic activity associated with changes in the terrain over the past 5 years in the study area, it was decided not to carry out a new aerial survey, but to use the archival materials that were received in 2018 and described in (Hlotov et al., 2018). The work tested a new model of the UAV aircraft type "Arrow" from the Ukrainian company Abris Design Group (2021). The survey was performed from a height of 500 m with a 20.4 Mp SONY UMC-R10c camera with a focal length of $f = 25$ mm. Images have a ground sample distance of 7.6 cm/pixel. The terrain of this area is a plane with a slope of about 3.5 degrees in the north-south direction and without a pronounced slope in the east-west direction. The area is covered with grassy vegetation with sparse bushes. The results of earthworks related to the preparation of the dirt road are recorded in the pictures in the southern part of the site (Fig. 2).

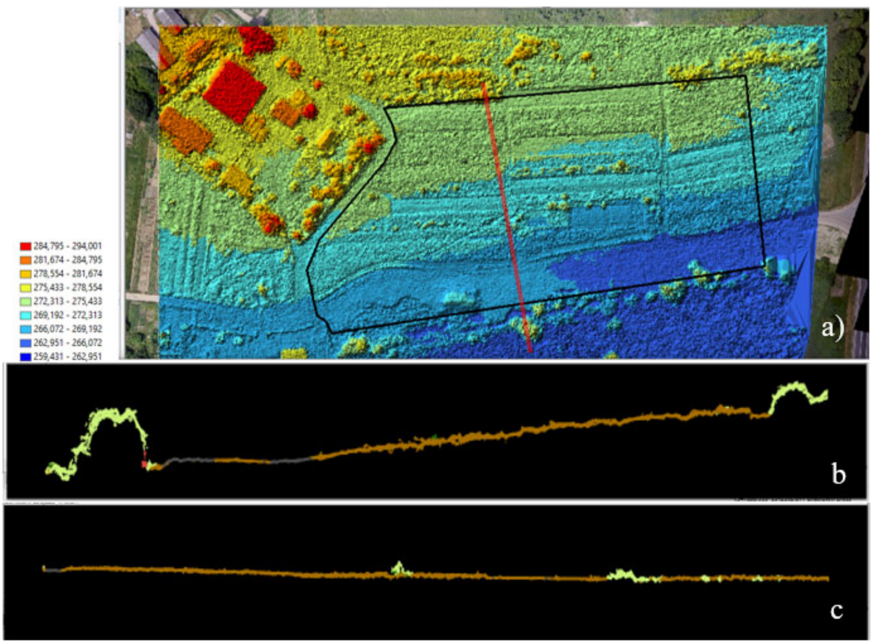

Fig. 2. DSM survey surface model (a) and transverse profiles: north-south (b) and east-west (c)

The survey site is provided with a network of 24 ground reference points, evenly spaced on the survey site. The accuracy of determining the spatial coordinates of reference points by GNSS survey is $m_X = m_Y = m_Z = 3.7$ cm. The described circumstances, as well as the high quality of aerial photographs create generally favorable conditions for the photogrammetric process of processing aerial photographs from UAVs. The result of this process is the creation of a dense cloud of 3D points and a high-quality digital terrain model. The general technological scheme of automated photogrammetric processing of images obtained by digital imaging systems of UAVs is well developed and is used as a typical scheme in many applied research (Aguilar et al., 2019). In our case, its result is the creation of a triangulation network (TIN) for modelling the earth's surface (Fig. 3).

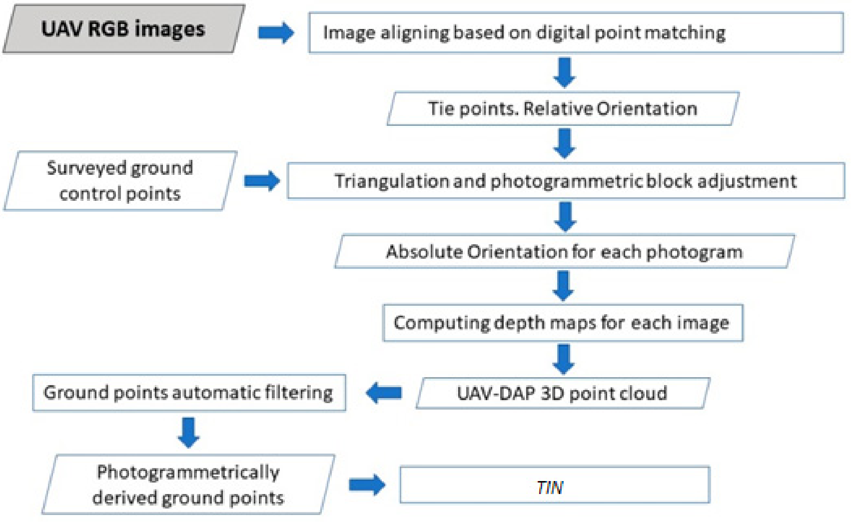

Fig. 3. Flowchart representing the applied UAV-based photogrammetric workflow for DĹM generation

It is important to assess the achievable accuracy of the created terrain model from the archived aerial photograph. First of all, we should evaluate the accuracy of determining the spatial coordinates of the model points. We will use the formulas known in photogrammetry for a priori accuracy calculation of the spatial model points (Dorozhinsky and Tukay, 2008).

$$m_X = \frac{H}{f} \cdot m_x \qquad m_Y = \frac{H}{f} \cdot m_y \qquad m_Z = \frac{H}{b} \cdot m_p = \frac{H^2}{B \cdot f} \cdot m_p \,, \tag{1}$$

where m_x, m_y, m_p is the accuracy of measurement of point's coordinates and para'laxes on aerial photographs, b is the basis of aerial photography, f is the focal length of the camera and H is the shooting height.

As follows from these formulas, the accuracy of determining the planned coordinates of points depends on the scale of shooting and the accuracy of measuring images, and the accuracy of determining the height – also based on photography. Note that aerial photography is usually designed with the less significant inter-route overlap of images compared to the overlap of neighbouring images on the route. In addition, an increase in the survey basis between routes (which improves the accuracy of determining the heights of the model points) is influenced by the placement of the camera in such a way that the long side of the rectangular CCD matrix is located in the air chamber in the direction of flight. Therefore, we propose to use only the so-called "transverse" stereo pairs, composed of images of neighbouring routers, which have overlapping images of the terrain to create a dense cloud of 3D points. For other stages of the photogrammetric process, in particular phototriangulation, no changes are proposed (both conventional and transverse stereo pairs are used) (Kolb, 2000).

Let's also consider that the 3D point cloud, which is obtained as a result of dense computer stereo reconstruction, is excessively dense to define the vertical layout and determine the volumes of the earth masses. Such models are subjected to sparsity and simplification for practical use in engineering software (Christ et al., 2018). The use of transverse stereo pairs will provide a fairly dense cloud of points in open (without tall buildings and vegetation) terrain areas. At the same time, the refusal to use conventional stereo pairs of images in this task will avoid excessive density of the point cloud and significantly reduce the time of photogrammetric processing.

Let's calculate the expected accuracy of determining the coordinates of the model points based on the description of this aerial survey given in (Hlotov et al., 2018), and take $f = 28$ mm, $m_x = m_y = m_p = 0.003$ mm; $H = 500$ m.

For stereo pairs made up of images related to the same route, the shooting is performed using the basis of photography $B = 60$ m

$$m_X = m_Y = 0.05 \text{ m}, \qquad m_Z = 0.45 \text{ m}. \tag{1a}$$

For stereo pairs made up of images related to the adjacent routes, the shooting is performed using the basis of photography $B = 203$ m

$$m_X = m_Y = 0.05 \text{ m}, \qquad m_Z = 0.13 \text{ m}. \tag{1b}$$

As we can see, the use of transverse stereo pairs will allow determining the heights of the model points much more accurately than with the traditional use of conventional stereo pairs for photogrammetry. Simplification of the TIN model by thinning its nodes (3D cloud points) reduces the accuracy of determining the areas of the triangular faces of the TIN model (and thus reduces the accuracy of determining the volume of earth masses). On the other hand, the achievement of high accuracy in determining heights will partially compensate for these losses in the accuracy of determining areas and volumes.

Implementation of photogrammetric image processing is carried out with the help of specialized software products Pix4D and Photomod. In particular, the Photomod software allows to selectively form regular and transverse stereo pairs. Instead, Pix4D offers more advanced methods of classifying the resulting cloud of 3D points to highlight points on the earth's surface. The resulting point cloud has an average density of 8–12 points/m^2 in open ground and approximately 0.12 points/m^2 (2.9 m is the average distance between survey points) in areas covered with vegetation. The total number of survey points (the part of the point cloud that was classified as ground points) is 5.765. The classified cloud of 3D points is shown in Figure 4. The transverse stereo pairs for dense stereo reconstruction are used.

In our work, we consider three algorithms for creating Delaunay triangulation, namely: the method of "Increment"; the method of "Scanning line", built based on the Fortune algorithm; method of "Combinations" (Fig. 5–7). We took the developments described in (Kong, 2011) as a basis for these algorithms for modelling the surface of building sites.

These methods were chosen by us based on the assumption that they can provide to some extent a rapid creation of triangulation of the terrain surface. In this case, all

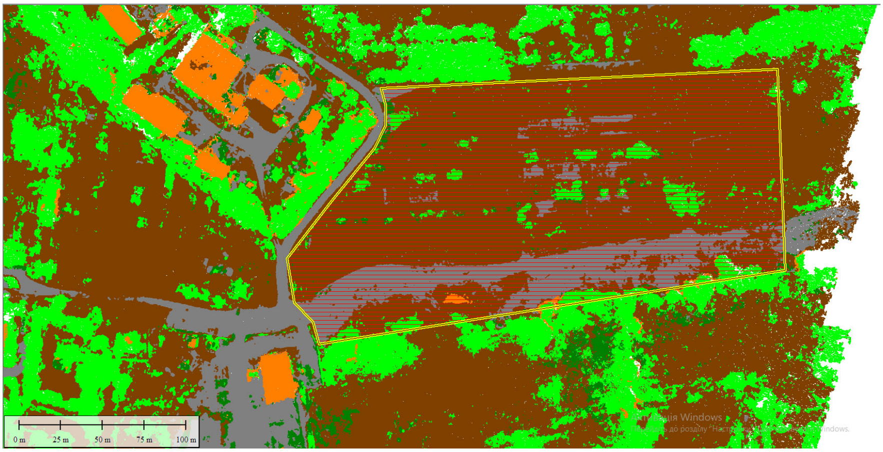

Fig. 4. A classified cloud of 3D points obtained by photogrammetric processing of aerial photographs obtained from the UAV

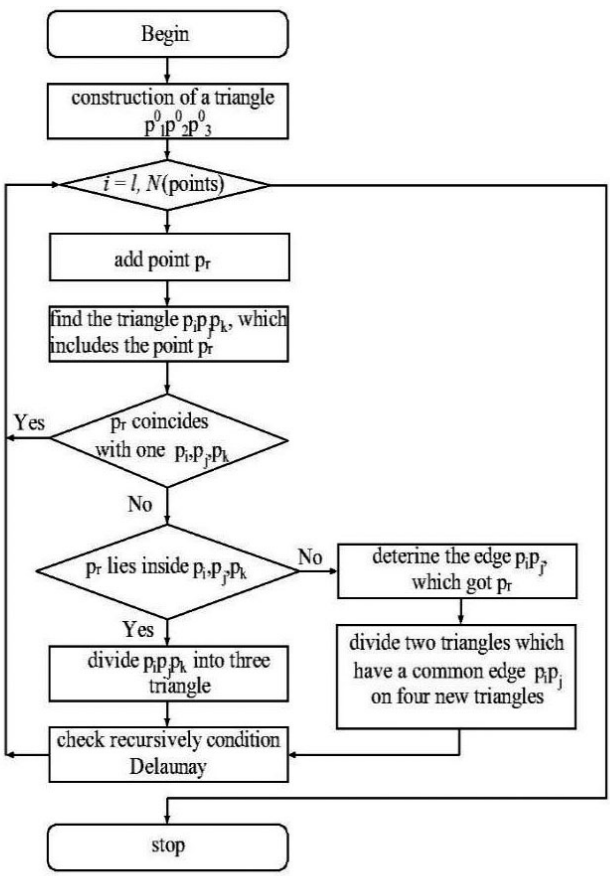

Fig. 5. Block diagram of the “increment” method

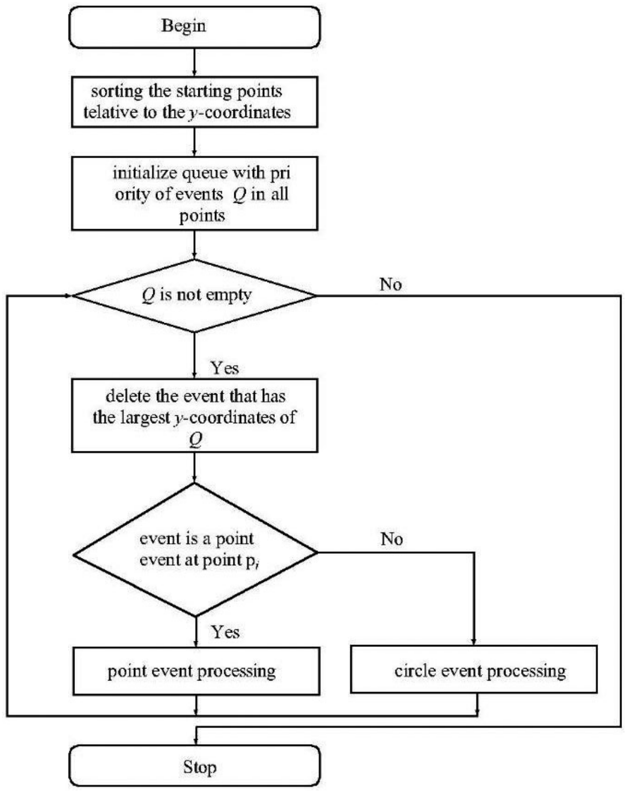

Fig. 6. Block diagram of the "scanning line" method

three methods guarantee the creation of Delaunay triangulation, which has useful properties for accurate calculation of the areas of triangles – this is primarily the maximum approximation of the triangles of the TIN model to equilateral. However, it is not known how these methods will perform at different densities (number of 3D points per unit surface area) of the input information. A computer program for the implementation of the three algorithms described above was compiled by Dr. Anenkov A.O. from KNUBA. Our experiment aims to answer these and other questions.

For vertical planning of the territory, it is necessary to calculate how much territory needs to be cut off and which one needs to be covered to get the desired surface. Here, it is necessary to determine the volumes of the masses of soil that are moving (the sum of the cut and filled volumes) and the balance volume (the difference between the cut and filled volumes, excess or lack of soil). This is necessary to assess the scope of work when digging pits with vertical or inclined walls.

The algorithm of actions for calculation of earthworks by the terrain digital model at the digging of a pit or performance of excavations or mounds:

Step 1. An extraction from the general triangulation of some part along the plot boundary is made. In essence, a copy of the input triangulation is first made and the

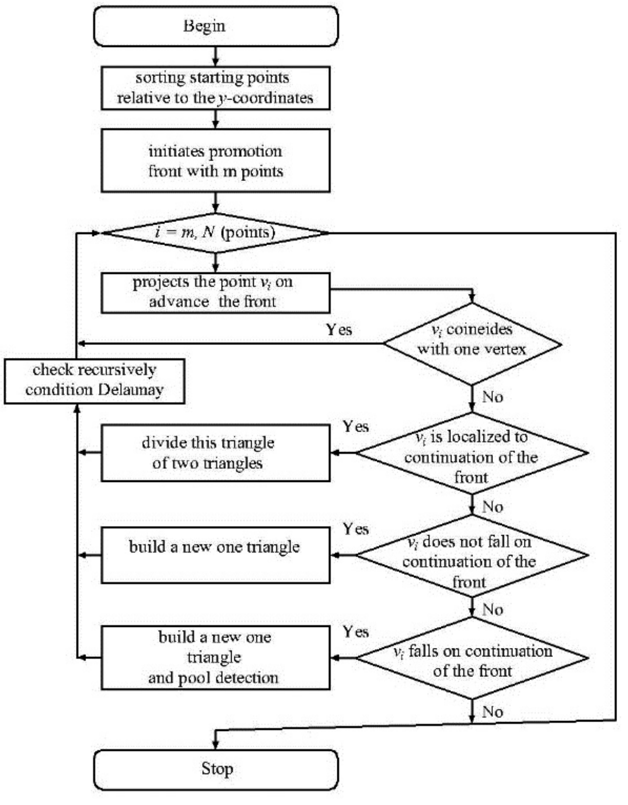

Fig. 7. Block diagram of the "combinations" method

limit of the pit or excavation/mound section is inserted as the outer boundary of the triangulation. All triangles outside the plot are discarded.

Step 2. The algorithm for constructing iso-contours for the cut triangulation at the required level of the vertical plan is called. The algorithm will return two polygons defining areas with excess and shortage of soil, respectively.

Step 3. For each triangular face of the cut triangulation, a comparison with the required level of vertical planning is performed. If the triangle is completely above the bottom, it should be covered, if completely below – then cut. The backfill, or cut volume is defined as the volume of the corresponding triangular prism with two bases, one of which is a triangle approximating the terrain surface, and the other is the projection of this triangle onto the design plane.

To calculate the volumes of each prism, bounded by the planes of two inclined triangles above and below, the well-known formulas are used (Zhilin et al., 2005; Novakovsky and Permyakov, 2019)

$$V = \frac{Z_1 + Z_2 + Z_3}{3} S_{\Delta}, \tag{2}$$

where Z_1, Z_2, Z_3 – exceeding the corresponding points of the vertices approximating the terrain of the triangle above the design plane and S_Δ – projection area of the inclined triangle approximating the terrain onto the plane of the design (desired) surface

$$S_\Delta = \sqrt{P(P-D_1)(P-D_2)(P-D_3)}, \tag{3}$$

where D_i is the side length of a triangle, opposite to the vertex i, $P = \frac{1}{2}(D_1 + D_2 + D_3)$,

$$D_1 = \sqrt{(X_3-X_2)^2 + (Y_3-Y_2)^2 + (Z_3-Z_2)^2},$$
$$D_2 = \sqrt{(X_3-X_1)^2 + (Y_3-Y_1)^2 + (Z_3-Z_1)^2},$$
$$D_3 = \sqrt{(X_1-X_2)^2 + (Y_1-Y_2)^2 + (Z_1-Z_2)^2}.$$

If the triangle approximating the surface of the terrain intersects with the design plane, then this triangle is divided into two parts along the line of mutual intersection, for which the volumes of the corresponding triangular prisms are calculated separately. Let's evaluate the results of the proposed techniques for modelling the terrain. To do this, we will gradually exclude the points of the model (sparse out the model), then build the Delaunay triangulation and fix the deviations of each triangular face of the triangulation from the plane of the reference surface. In this case, the magnitude of the modelling error due to the deviation of its nodes from the final surface will be determined by the formula:

$$\delta_D = \sqrt{\frac{\sum\limits_{n_D=1}^{N_D} D^2_{xyz}[n_D]}{N}}, \tag{4}$$

where $D^2_{xyz}[n_D]$ is the spatial vector of node deviation from the final surface and N is the number of nodes in the triangulation model.

3. Results and discussion

The essence of the experiment is that it is necessary to simulate a terrain area with a different density of survey points per unit area, for example, 1 m^2. The assessment of the terrain modelling quality for vertical planning was carried out by us according to the following scheme:

- choosing the reference model, which has the maximum density of survey points. As a reference model, we take the survey data of the terrain with a density of 0.11 m^2. The distance between the points is about 3–5 m;
- building a standard model of the TIN terrain with the help of the Surfer software package;
- designing the earthwork construction plan of earthworks and calculate the volumes of excavation and mound for the reference model in the Civil3D software;

– performing artificial sparsity of digital model points by removing points from the array of survey data;
– construction of Delaunay triangulation according to three algorithms ("increment", "scanning line", "combinations");
– performing vertical planning design according to the received models. We calculate the volume of earthworks and build an earthwork construction plan;
– comparison of the obtained data with the reference model and conduct statistical analysis.

Comparison of models with different point densities per 1 m^2 was performed in the ArcGIS software. To evaluate the created models with a different number of survey points required for vertical design, the heights of the reference model, which was created with maximum density, were subtracted from the heights of digital models created with point sparsity and different interpolation methods. Further, statistical processing of the received errors and root-mean-square errors was carried out. Mean errors of the terrain survey relative to the nearest points of vertical control network at a terrain section height of 0.5 m should not exceed height (Ministry of Justice of Ukraine, 1998):

– $\Delta = 0.5\text{ m} \times 1/4 = 125$ mm at tilt angles up to 2 degrees;
– $\Delta = 0.5\text{ m} \times 1/3 = 166$ mm at tilt angles from 2 degrees or up to 6 degrees for plans of scales 1:5000, 1:2000 and up to 10 degrees for plans of scales 1:1000 and 1:500.

In forest areas, these tolerances increase 1.5 times. Mean errors in the position on the plan of objects and contours of the terrain with clear outlines relative to the nearest points of the survey network should not exceed 0.5 mm, and in mountainous and forest areas – 0.7 mm. In territories with capital and multi-storey buildings, the mean errors in the relative position on the plan of points of the nearest contours (capital structures, buildings, etc.) should not exceed 0.4 mm. For the transition from mean errors (Δ) to mean square errors (m), a factor of 1.25 is applied:

– $m = 1.25 \times 125 = 156$ mm at tilt angles up to 2 degrees;
– $m = 1.25 \times 166 = 207$ mm at tilt angles from 2 degrees or up to 6 degrees.

When comparing the root-mean-square errors and mean errors of the terrain survey and digital terrain models with vertical planning, we took the obtained values to be the maximum permissible. Further, we compare the reference digital terrain model, which includes all survey points, with sparse models. Vertical planning is performed in the form of an earthwork construction plan in Civil3D software. Volumes are calculated using the triangular prism method. The calculated area is divided into triangular prisms, the volume is calculated for each triangular prism, after which all volumes are summed. As a design site, we conditionally choose a horizontal surface.

As a design mark of the site, we take the average mark of all points of the test site, so that it is possible to reliably assess both the excavation and the mound in the vertical planning. We will take the average mark as the design mark Hd = 270.7 m. The earthwork construction plan is presented in Figure 8. The excavation volume is Ve = 422.4 m^3. The mound volume is Vm = 1922.7 m^3.

In For the transition from mean errors (Δ) to mean square errors (m), a factor of 1.25 is applied (at tilt angles up to 2 degrees): $m = 1.25 \times 125 = 156$ mm.

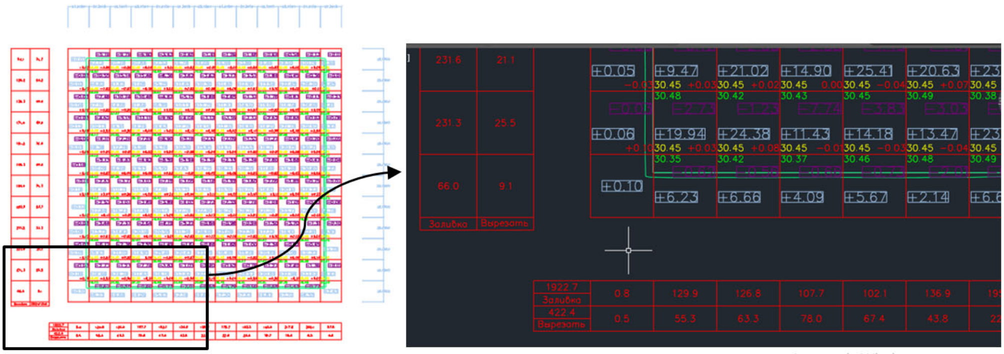

Fig. 8. Earthworks construction plan

The output data is RMSE = 0.207 m. Next, we perform a differential sparsity of the input points of the terrain model. This process involves removing points that are very dense or close to each other from the general array. As a result, the specified percentage of points are removed in the order of their influence on the quality of the terrain representation – the least significant points are removed first. The algorithm for such a sparsity is implemented in the photogrammetric software package Photomod (Photomod, 2019). The number of points in the terrain models obtained after sparsity is given in Table 1. In Figure 9 the investigated surface with different degree of sparsity of the TIN model, built in the software Surfer is presented.

Table 1. Characteristics of digital terrain models of the test plot

Characteristic	Percentage of model sparsity					
	Reference	20%	30%	50%	70%	90%
The total number of model points (pcs)	5.77	4.61	4.04	2.88	1.73	577.00
Point density (pcs/m$^{2)}$	0.12	0.09	0.08	0.06	0.03	0.01
Average distance between points of the model (m)	2.90	3.30	3.50	4.20	5.40	9.30

The results of estimating the accuracy for determining the volumes of mounds and excavations, which are calculated by the above method (for terrain models obtained by creating Delaunay triangulation by different algorithms at different densities of the input data) are shown in Tables 2–4.

Figure 10 shows a dependence graph of the accuracy of determining the volumes of earth masses on the density of the DEM points, expressed as the average distance between the survey points. To construct this graph, we took the RMSE for determining the volumes of earth masses from Tables 2– 4, the dashed line indicates the maximum permissible RMSE.

The analysis of Figure 10 indicates that the combined method of creating a TIN flat terrain model has some advantage over the incremental method and the scanning line

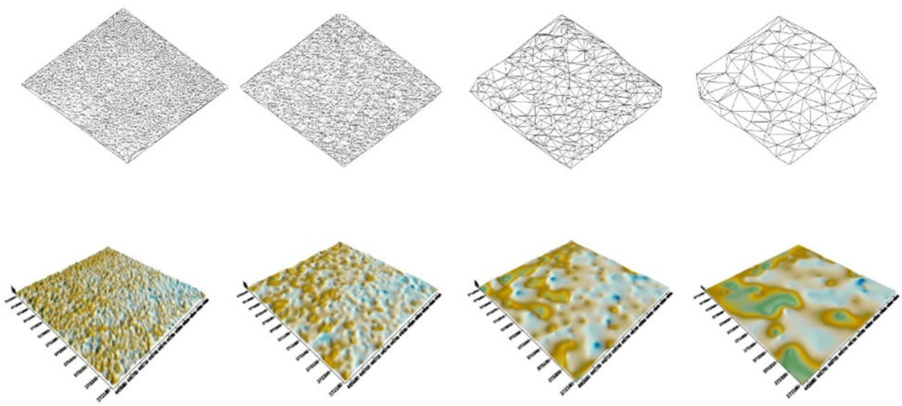

Fig. 9. Digital models of flat terrain with sparse point 30%, 50%, 70%

Table 2. The statistical processing of the site by the increment method

Characteristic	Percentage of model sparsity					
	Reference	20%	30%	50%	70%	90%
Excavation volume (m^3)	422.40	418.12	411.11	408.13	406.45	405.12
Excision volume error (%)		–1.00	–2.70	–3.40	–3.80	–4.10
Mound volume (m^3)	1922.70	1911.25	1899.21	1865.21	1851.20	1844.81
Mound volume error (%)		–0.60	–1.20	–3.00	–3.70	–4.10
Minimum error (m)	–0.09	–0.09	–0.10	–0.10	–0.03	–0.14
Maximum error (m)	0.15	0.13	0.15	0.14	0.14	0.18
Mean square error (m)	0.15	0.14	0.15	0.15	0.15	0.18

Table 3. The statistical processing of the plot by the scanning line method

Characteristic	Percentage of model sparsity					
	Reference	20%	30%	50%	70%	90%
Excavation volume (m^3)	422.40	420.10	412.40	410.10	408.40	403.33
Excavation volume error (%)		–0.50	–2.40	–2.90	–3.30	–4.50
Mound volume (m^3)	1922.70	1910.10	1892.20	1863.50	1840.90	1835.10
Mound volume error (%)		–0.70	–1.60	–3.10	–4.30	–4.60
Minimum error (m)	–0.02	–0.13	–0.09	–0.09	–0.13	–0.15
Maximum error (m)	0.14	0.14	0.14	0.14	0.14	0.18
Mean square error (m)	0.14	0.14	0.14	0.14	0.15	0.19

method when performing vertical planning. This advantage is manifested in the ability to carry out vertical planning with a given accuracy in determining volumes with a significantly smaller number of TIN model nodes. According to the results of the experiment, it

Table 4. The statistical processing of the plot by the combined method

Characteristic	Percentage of model sparsity					
	Reference	20%	30%	50%	70%	90%
Excavation volume (m^3)	422.40	420.80	415.30	415.00	411.40	409.80
Excavation volume error (%)		–0.40	–1.70	–1.80	–2.60	–3.00
Mound volume (m^3)	1922.70	1902.40	1892.10	1879.20	1868.10	1850.30
Mound volume error (%)		–1.10	–1.60	–2.30	–2.80	–3.80
Minimum error (m)	–0.02	–0.09	–0.01	–0.13	–0.10	–0.11
Maximum error (m)	0.14	0.12	0.11	0.12	0.13	0.15
Mean square error (m)	0.13	0.13	0.13	0.14	0.14	0.16

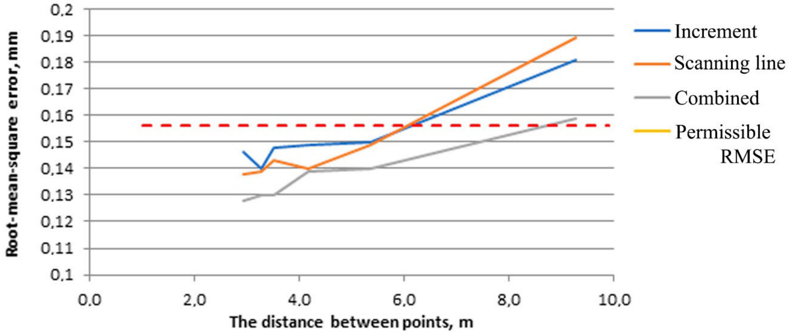

Fig. 10. Dependence of the root-mean-square error of constructing a digital flat terrain model on the distance between points

can be concluded that to ensure sufficient accuracy of the digital model for vertical planning (for flat terrain), the minimum density of survey points should be 0.013 pcs/m^2, which corresponds to an average distance of 8.6 m between points. As shown above, the use of stereo pairs composed of UAV images obtained from adjacent shooting routes significantly affects the accuracy of determining the heights of surface points. The surface is modeled with higher accuracy and, as a result, the accuracy of determining the volume of the earth will be higher. However, this approach is not sufficiently described in the literature. This technique allows you to find the minimum required number of survey points for the construction of digital terrain models in solving problems of vertical design without loss of accuracy and maximum saving of the geometric characteristics of the terrain.

4. Conclusions

The described method covers all stages of geodata processing in the vertical planning of territories from obtaining the initial data to the construction of an earthwork plan. Its key feature is the use of UAV aerial photographs. The possibility of using archival aerial photography from the moment of completion of which there were no pronounced changes in the terrain in the study area is shown. This will often avoid the need for a new aerial survey. Analysis of the basis (distances between the centres of the projections of the images) of the existing aerial survey shows the expediency of using the so-called transverse stereo pairs formed by images of neighboring routes for a dense computer stereo reconstruction of the earth's surface. This approach will allow more accurately determine the altitude coordinates for a dense point cloud. Implementing vertical planning of flat areas in CAD software is recommended to perform a combined method of creating a terrain model TIN with a permissible sparseness of network nodes to an average distance between these nodes of 8.6 m. Thus, the approach to the accuracy assignment of the geometric position of the digital model elements can be carried out based on both the scale of the display of the digital model, its detailing and according to technological tolerances at all stages of the construction process.

Author contributions

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Data availability statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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