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Modification of software algorithms to increase the speed and accuracy of 3D mining objects volume identification

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Abstract

The solution of various tasks (determination of production volumes, construction of tunnel sections, accounting for extracted volumes, optimization of quarries, etc.) in mining industries requires the use of resources of geoinformation systems and specialized software complexes. Increasing the accuracy of model products requires an increase in the amount of data. In this case, as a rule, improving the algorithms of software systems allows to increase the speed and/or accuracy of calculations. The work aimed to develop and test an approach to increasing the speed and accuracy of calculating the volume of three-dimensional objects in the mining industry, also by modifying software algorithms. As a result, new algorithms have been developed and programmatically implemented, which suggest a different approach of placing a point cloud in the center of the world coordinate system and constructing a polygon base as a plane with a single horizontal coordinate. The study revealed limitations of existing approaches and software, such as constructing an excessive number of projection edges on the polygon base and using quadratic complexity algorithms. Testing in real production conditions has confirmed the correctness and sufficient accuracy of the results. Testing on geometric primitives showed a reduction in time for measuring the volume of 3D objects by up to 10%.

Keywords: sustainable development, mining, coal warehouses, computational algorithms, digital technologies.

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1. Introduction

Implementation of the sustainable development concept, including the UN Sustainable Development Goals [1-4] and the ESG Agenda [5-8] remains one of the scenarios that many countries adhere to at the current stage of society development. It assumes achieving a balance between economic and social results and preserving the natural environment in the process of comprehensive human activity. Resolution of the objective contradictions present here is largely achieved through new technological solutions that minimize interference with the natural environment and reduce resource costs per unit of economic or production result. Digital technologies have significant potential to ensure optimal decision-making, which, in turn, contributes to improving the effectiveness and efficiency of technical and economic systems [9-12]. Digital precision farming technologies can significantly increase the yield and productivity of livestock and reduce the use of mineral fertilizers and pesticides, thereby reducing the impact on the environment [13].

For the productive use of digital technologies in any field, it is critically important to build digital twins of control objects with the necessary level of accuracy at an acceptable cost. Concerning the mining industry, we are talking about the twins of underground mine workings [14-15], opencast mines [16], coal warehouses [17], etc. Three-dimensional (3D) digital models of volumetric mining facilities are widely used. They allow solving the tasks of surveying, planning, and monitoring the scope of work, assessing the condition of excavations and embankments, and identifying the risks of sloughing, spontaneous combustion, erosion, and subsidence. This technology has such advantages as accuracy, speed of obtaining information, exclusion of subjective and objective human errors and risks for the human agent. In practice, 3D models of coal warehouses, dumps, and open-pit sides are often obtained by laser scanning from unmanned aerial vehicles (UAVs) or ground scanners [18-20].

Currently, there are scientific developments in the creation of 3D models of mining facilities [21-23], as well as specific software and hardware solutions that provide solutions to practical production tasks, including the tasks of determining the volume of three-dimensional objects. Certain experience in using 3D models at coal enterprises in Russia has been gained. However, as will be shown below, existing developments have certain scientific and technical limitations, which makes it possible and necessary to improve them in order to increase accuracy, speed, save time and computing power. In addition, as S.V. Lukochyov rightly points out, the current global situation dramatically increases the importance and demand for the creation of national software and technologies, otherwise there are risks of "significant financial losses and slowing down the process of digital transformation of mining enterprises" [24].

The work aimed to develop and test an approach to increasing the speed and accuracy of calculating the volume of three-dimensional objects in the mining industry, also by modifying software algorithms.

2. Methods

2.1. Objects of research

Small and medium-sized warehouses at a mining enterprise in the Kemerovo region, as well as algorithms for constructing models of volumetric objects were the research objects.

2.2. Methodology

At the first stage, existing software packages that allow to calculate the volume of 3D models of objects were evaluated and analyzed, their limitations which cause a decrease in accuracy, higher time costs and computing power, were identified. These limitations are mainly due to the features of the software algorithms used.

At the second stage, a unique modification of computational algorithms was developed and evaluated, which made it possible to speed up the process of calculating the volume of a model object and/or reduce the need for computing power, as well as increase the accuracy of the calculation performed.

At the third stage of the research, modified algorithms were tested and then practically evaluated using real data.

For the software implementation of the algorithm, the "Management system for monitoring construction works at facilities that have passed state expertise" web application was used, which was developed at the Institute of Digits of Kemerovo State University with the participation of some of the authors of this study [25]. Data collection was carried out when performing ground surveys using tacheometers, aerial photography, and laser scanning with an air laser scanner "AGM-MS3.200" (Russia) of the earth's surface from a UAV of a territorial facility located in the Kemerovo region-Kuzbass (Russia). The data obtained was processed using traditional approaches or using developed algorithms, and the DJI Matrice 600 Pro UAV (China) was used to build a point cloud. Measurements of the volumetric data of objects were performed on at least 5 objects in each group. When testing the results of the study, the obtained point clouds were used.

3. Results and discussion

Currently, there is a traditional 3D modeling technology based on the results of laser scanning. It includes scanning, obtaining the necessary amount of data, filtering and thinning them to improve quality and reduce noise. After that, using Delaunay triangulation or other methods, a three-dimensional surface (mesh) is created in the form of a set of points and facets of polygons, which allows to determine the volume and geometric characteristics of the object. If dynamic analysis is necessary, two surfaces are compared (for example, to assess changes in stocks in a coal or ore warehouse). The authors conducted a comparative analysis of existing software products that can be used to perform 3D modeling and calculate the volume of a three-dimensional model object (Table 1). It has been established that Autodesk Inc and Bentley Systems Inc. have left the Russian market, therefore their software products are not officially supplied and are not serviced.

In addition, all the programs reviewed had certain limitations and disadvantages. In particular, most of them need manual manipulations by a qualified specialist to adjust certain parameters. Moreover, even when modeling small and complex objects, it usually takes 5-15 minutes. These time costs can become significant when calculating the volume of a large number of objects of complex shape.

During the study, the authors found that all programs, both Russian and foreign, use a single algorithmic approach. It involves the construction of a flat-base surface and a three-dimensional convex object (mesh). Then the sums of the volumes of the prisms formed by the triangles of a particular mesh are calculated, while the height of the prism is set by the projection of the triangle on a flat base. Each triangle corresponds to a truncated prism. After determining the horizontal coordinates of the projection points on the polygon base, the height of each of the edges of the prism is found, after which the volume calculation is performed trivially. Thus, within the framework of existing approaches, the base plane is built on three selected points; there is a need to triangulate the base plane in order to divide it into separate triangles. The projection of the triangle for the construction of the prism must be determined by each of them.

In practical tasks, the source data may include several million points or more, therefore, calculations of object volumes require significant machine time and (or) computing power. Of course, in order to save resources, existing programs provide filtering of source data. For example, Microstation offers options for dividing the point cloud, excluding irrelevant data (for example, technical structures) from consideration. The CREDO VOLUMES provides functions for thinning clouds, filtering points, and eliminating noise. However, such options and functions still require the participation of qualified specialists, slow down the solution of production tasks, and cause the likelihood of objective and subjective errors.

In the authors' opinion, the fundamental limitation of the existing approaches is that when constructing a mesh, it is necessary to create edges that connect all points, including those that lie outside the boundaries of the base polygon. At the same time, the participation of a specialist is necessary to eliminate unnecessary edges that are irrelevant when calculating volumes. Accordingly, time costs increase, and there is a possibility of human errors.

Table 1: Features of the existing software for building 3D models of volumetric mining facilities

Product (company)	Pre-training functions	Algorithm used	Advantages	Note
AutoCAD (Autodesk Inc., USA)	-	Construction of two surfaces by triangulation of a point cloud, calculation of volume difference	Wide functionality of designing any objects, speed of calculations	The need for user participation in correcting the points of the base surface
CREDO VOLUMES (Credo Dialog Company LLC, Russia)	Density filters, threshold and noise below the surface relief, thinning	Construction of two surfaces by triangulation of a point cloud, calculation of volume difference	The ability to control and adjust calculation parameters to meet the needs of the user's tasks	The need for user participation in triangulation and 3D model construction
Micromine (Australia Pty Ltd, Micromine)	Control of the closure of point clouds, intersections of the triangulated mesh	Calculation based on the block model	Well adapted for geodetic tasks, calculation of excavation volumes	Inability to calculate the volume of warehouse stock
Microstation (Bentley Systems Inc., USA)	-	Construction of two surfaces by triangulation of a point cloud, calculation of volume difference	A wide range of options and functions when working with the point cloud	-
ReClouds (Nanosoft Razrabotka LLC, Russia)	Correction of geometric parameters (cropping, cross-section)	Calculation of the volume difference between two clouds	Relative simplicity of the interface	Manual adjustment of the triangulated mesh is required

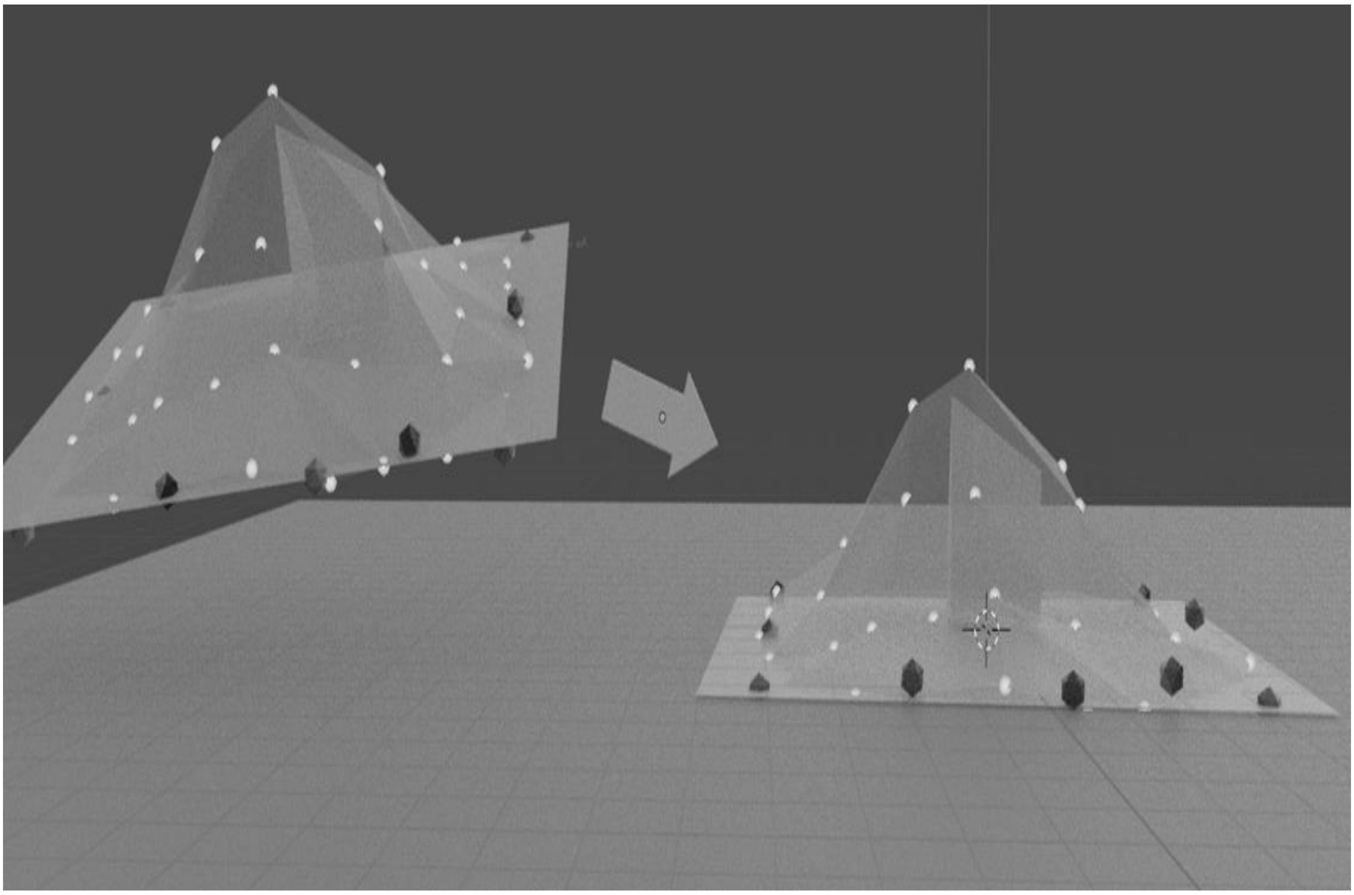

Figure 1: The option of placing the results of laser scanning in the center of the world coordinate system

This problem is caused by the fact that existing triangulation algorithms connect all points of the selected polygon. If extra edges are not removed, the calculation error becomes unacceptably large. Along with this, in the existing software, triangles are not set in the most rational way (the boundaries are distorted so that they seem to "stretch out"), which also entails the need for user intervention and the placement of new reference points on the base.

Another drawback identified by the authors is the construction of a base polygon with deviations from a single plane. In practice, in 99% of cases, the points that form the boundary of the polygon may have different vertical z coordinates. Consequently, the results of calculating the volume of the object are distorted. Along with this, triangulation of the same base polygon (when it is necessary to determine the change in the volume of an object in dynamics) usually gives different results due to the divergence of the x and y coordinates of the points forming the boundary. This also leads to a distortion of the results.

From the point of view of computational complexity, it should be noted that for each prism it is necessary to check over which part of the base polygon it is located, calculate the corresponding equation of the plane, calculate the projection and only after that calculate the coordinates of the base. When working with clouds containing several tens of thousands of points, calculations using modern personal computers can take less than a second. However, the complexity of the algorithm is quadratic – $O(n^2)$. Therefore, with an increase in the amount of input information, the calculation time slows down significantly.

The following modifications of the calculation algorithm have been developed in the study, providing increased accuracy, as well as speed and(or) savings in computing power. Firstly, unlike existing approaches, the base of a three-dimensional object (for example, a coal warehouse) was considered to be in the same plane. In addition, this plane was placed in the local x and y coordinate system. This solution significantly reduced the number of calculations since the height of the prism edges was determined only by comparing z_i to z_0. Secondly, we not only placed the 3D object on an absolutely flat surface of the base polygon, but also excluded the projection calculation for each triangle compared to the algorithms used. To solve this problem, the base polygon and the dense point cloud were arranged in such a way that the former was located parallel to the directions of the x and y axes of the world coordinate system, and also contained its center. The following matrix (1) was used to recalculate the coordinate values:

$$R = \begin{pmatrix} cos\Theta + {u_x}^2(1 - cos\Theta) & u_x u_y(1 - cos\Theta) - u_z sin\Theta & u_x u_z(1 - cos\Theta) + u_y sin\Theta \\ u_y u_x(1 - cos\Theta) + u_z sin\Theta & cos\Theta + {u_y}^2(1 - cos\Theta) & u_y u_z(1 - cos\Theta) - u_x sin\Theta \\ u_x u_z(1 - cos\Theta) - u_y sin\Theta & u_z u_y(1 - cos\Theta) + u_x sin\Theta & cos\Theta + {u_x}^2(1 - cos\Theta) \end{pmatrix}, \quad (1)$$

where u is the current position of the object point relative to the world coordinates.

The coordinates of all the points obtained during scanning were multiplied by the matrix (1), which made it possible to place a dense cloud of points in the necessary way (Figure 1).

After performing these operations, only the volumes of triangular prisms formed by a polygon mesh were calculated. Their sum was the value of the total volume of the object. For this, the areas of the triangles are calculated, which are multiplied in pairs by the average value of the edges of the corresponding prism.

The developed modifications of traditional algorithms after software implementation were tested on geometric primitives placed on a plane with the addition of noise. Here are the test data using regular quadrangular pyramids with a height of 2 m and a base area of 4 m (calculated volume 2.67 m^3). That is, the volume of one such pyramid was about 2.67 m^3, of five pyramids – 13.38 m^3. When using a web application implementing the unique modification of computational algorithms, it was determined, in particular, that the volume of 5 pyramids was 13.68 m^3, which indicates sufficient calculation accuracy (deviation by 0.3 m^3 or less than 2.5%). Some time savings have also been achieved. In particular, when working with a test point cloud (218,426 points, 433,271 triangles), calculations using previously created software products (Table 1) required from 148.8 to 158.2 milliseconds. In a web application where a modification of computational algorithms is implemented, this calculation required 90.9-103.5 milliseconds. To this value, one needs to add the time to transfer data from the world to the local coordinate system (from 40 to 50 ms). In general, the total time to complete all necessary work including point selection and visualization decreased on average from 581.0 to 533.8 ms, or about 8%. When working with small point clouds using modern personal computers, such a difference is not problematic. However, in practice, it is often necessary to use clouds with 1 million points and 2 million triangles, so the difference in calculation time can reach several seconds. This already affects the design of the software interface and the usability of it. Thus, testing showed that the algorithm for measuring the volume of three-dimensional objects had a sufficiently high accuracy and provided greater performance.

The final stage of the study was testing on real production data at one of the coal enterprises of the Kemerovo region – Kuzbass, namely, measuring volume in small and medium-sized warehouses. Volumes were measured in various ways, as a result of which it was determined that the calculation method used in the developed algorithm is suitable for the tasks due to a high level of accuracy, lower time costs and required computing power (Tables 2, 3).

Table 2: Comparison of the accuracy of determining the volumes of real enterprise objects by different methods (small warehouses, n=5)

Initial data, m^3	**Methods of determination**	**Survey object**	
		x	**Δ, %**
53.98	I	49.84	7.45
	II	51.64	6.86
	III	53.60	3.50
	IV	53.87	0.82
	V	53.22	1.36
45.6	I	44.3	2.85
	II	41.4	9.21
	III	41.6	8.77
	IV	45.03	1.25
	V	45.57	0.07
57.5	I	52.1	9.39
	II	51.6	10.26
	III	56.1	2.43
	IV	57.21	0.50
	V	56.49	1.76
57.6	I	52.4	9.03
	II	52.6	8.68
	III	58	0.69
	IV	57.56	0.07
	V	57.17	0.75
52.6	I	49.4	6.08
	II	53.5	1.71
	III	53.5	1.71
	IV	53.39	1.50
	V	51.39	2.30

x – empirical data on the volume of the object, m^3; Δ - deviation from the initial data, %. I - Ground photography using total stations; II – Aerial photography; III – Aerial laser scanning with standard processing; IV - Volume measurement according to the unique algorithm using a cloud of aerial survey points; V - Measurement of the volume of an object using a cloud of laser scanning points.

Table 3: Comparison of the accuracy of determining the volumes of real enterprise objects by different methods (medium-sized warehouses, n=5)

Initial data, m^3	Methods of determination	Survey object	
		x	**Δ, %**
77.2	I	72.24	6.42
	II	75.96	2.18
	III	76.82	1.47
	IV	77.34	0.34
	V	76.14	1.37
79.1	I	73.8	6.70
	II	78.2	1.14
	III	77.3	2.28
	IV	78.77	0.42
	V	77.84	1.59
75.6	I	69.8	7.67
	II	74.3	1.72
	III	76.6	1.32
	IV	75.74	0.19
	V	74.66	1.24
74.7	I	70	6.29
	II	75.8	1.47
	III	74.3	0.54
	IV	74.72	0.03
	V	73.41	1.73
79.4	I	74.1	6.68
	II	77.8	2.02
	III	80.3	1.13
	IV	79.89	0.62
	V	78.16	1.56

x – empirical data on the volume of the object, m^3; Δ - deviation from the initial data, %. I - Ground photography using total stations; II – Aerial photography; III – Aerial laser scanning with standard processing; IV - Volume measurement according to the unique algorithm using a cloud of aerial survey points; V - Measurement of the volume of an object using a cloud of laser scanning points.

The developed algorithm has the following advantages over existing analogs: there is no need to adjust the source data manually, automatic verification is performed for the belonging of Delaunay triangulation elements to the computational domain, and the time-consuming computational task of searching for the base polygon element on which the projection of the triangle from the rising surface fell is reduced to a single construction of the base plane by selecting the coefficients of the plane equation based on the least squares method.

The presented technique has great practical benefits for enterprises in the real sector of the economy, as it makes it possible to quickly and accurately determine the volume of bulk objects, as well as such objects of the coal industry as coal warehouses, rock dumps, based on laser scanning data. In the future, the described approaches can also be used to monitor the condition of bulk objects (detection of erosion of dumps, potential slopes and collapses of coal mass located in warehouses, etc.) [26].

4. Conclusions

The work presents the results of a study on the development of methods to improve the accuracy and speed of determining the volume of 3D models in the mining industry based on the results of laser scanning and processing of dense point clouds in the developed web application "Management system for monitoring construction works at facilities that have passed state expertise". Testing and approbation of developments based on geometric primitives and laser scanning data of coal warehouses have been carried out. It has been shown that the required level of accuracy is maintained while reducing the time for calculating volumes. The research materials can be used to create digital twins of mining enterprises and solve other applied problems involving the calculation of the volume of three-dimensional objects.

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