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Measurement of feeder performance during coal discharge from an underroof seam using machine vision

M.S. Nikitenko[1] ✉, **S.A. Kizilov**[1], **Yu.N. Zakharov**[2], **D.Yu. Khudonogov**[1], **A.Yu. Ignatova**[3]

[1] *Federal Research Centre of Coal and Coal Chemistry of the Siberian Branch of the Russian Academy of Sciences (FRC CCC SB RAS), Kemerovo, Russian Federation*

[2] *Kemerovo State University (KemSU), Kemerovo, Russian Federation*

[3] *Kuzbass State Technical University named after T.F. Gorbachev, Kemerovo, Russian Federation*

✉ *ltd.mseng@gmail.com*

Abstract

The technology for extracting and discharging coal from an underroof seam uses the so-called gravitational extraction method in which coal is extracted and discharged from under the roof by gravity. Here, coal can be discharged onto the main conveyor (face conveyor, located in the supported area), central conveyor (rear conveyor in Western literature), and tail conveyor (discharge conveyor, located in the unsupported area). The most common facilities used currently are longwall sets of equipment providing discharge onto tail conveyors. The purpose of this study is to measure the performance of a motorised plate feeder supplying coal from the outlet port of a roof support to a conveyor during the extraction of thick seams with discharge onto the face conveyor. To achieve the goal, it is proposed to measure the coal volume using machine vision. Methods for calculating a unit volume in a measuring section using a three-dimensional model were investigated. Laboratory studies were carried out to estimate the relative errors of the methods. The research allowed properly defining: a method for collecting data to calculate the unit volume of coal; a method for calculating the unit volume in the measuring section; a method for calculating the feeder performance using machine vision, and approaches for physically simplifying the video scene examined by machine vision. A relative error of less than 10 % with the existing measurement accuracy for constructing a coal layer surface height map indicates the sufficiency of the proposed calculation method for engineering use. The developed mathematical apparatus for calculating the unit volume of coal at the measuring section and measuring the feeder performance allows creating algorithmic software using the elementary mathematical functions of addition, subtraction, multiplication, and division. This aspect is important because it lower sights for the software development environment, and therefore expands the range of hardware suitable for calculating the feeder performance.

Keywords

mining, coal mining, coalface, performance, coal discharge, face conveyor, rock mass volume, machine vision, pattern recognition, video image recognition, height map

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РАЗРАБОТКА МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Научная статья

Измерение производительности питателя при выпуске угля из подкровельной толщи на основе технологии машинного зрения

М.С. Никитенко[1] ✉, С.А. Кизилов[1], Ю.Н. Захаров[2], Д.Ю. Худоногов[1], А.Ю. Игнатова[3]

[1] *Федеральный исследовательский центр угля и углехимии Сибирского отделения Российской академии наук (ФИЦ УУХ СО РАН), г. Кемерово, Российская Федерация*

[2] *Кемеровский государственный университет (КемГУ), г. Кемерово, Российская Федерация*

[3] *Кузбасский государственный технический университет имени Т.Ф. Горбачева, г. Кемерово, Российская Федерация*

✉ *ltd.mseng@gmail.com*

Аннотация

Технология выпуска угля из подкровельной пачки использует так называемый гравитационный выпуск, когда уголь выпускается из-под кровли «самотеком» под действием силы тяжести. Выпуск при этом можно производить на главный конвейер (забойный – расположенный в закрепленном пространстве), центральный (в западной литературе – задний) и хвостовой (завальный – расположенный в незакрепленном пространстве). Наиболее распространенными на данный момент времени являются комплексы с выпуском на завальный конвейер. Целью исследования является измерение производительности механизированного пластинчатого питателя, подающего уголь от выпускного окна крепи на конвейер в технологии отработки мощных пластов с выпуском на забойный конвейер. Для достижения цели предлагается осуществлять измерение объема с применением технологии машинного зрения. Исследованы способы расчета единичного объема на измерительном участке на трехмерной модели. Проведены лабораторные исследования, в рамках которых оценены относительные погрешности.

Исследования позволили формализовать: способ сбора данных для расчета единичного объема угля; методику расчета единичного объема на измерительном участке; способ расчета производительности питателя на основе системы машинного зрения, а также подходы для физического упрощения сцены, исследуемой машинным зрением. Относительная погрешность менее 10 % при имеющейся точности измерений для построения карты высот говорит о достаточности для инженерного использования предложенного способа расчета. Разработанный математический аппарат для расчетов единичного объема угля на измерительном участке и измерения производительности питателя позволяют создавать алгоритмическое обеспечение с использованием элементарных математических функций: сложение, вычитание, умножение и деление. Данный аспект важен, так как снижает планку требований к среде разработки программного обеспечения, а соответственно, расширяет номенклатуру аппаратных средств, пригодных для выполнения задач расчета производительности питателя.

Ключевые слова

горное дело, добыча угля, лавный комплекс, производительность, выпуск угля, забойный конвейер, объем горной массы, машинное зрение, распознавание образов, распознавание видеоизображений, карта высот

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Introduction

The technology for extracting and discharging coal from an under-roof seam uses the so-called gravitational extraction method in which coal is extracted from under the roof by gravity. In this case, coal can be discharged onto a main conveyor (face conveyor, located in the supported area), central conveyor (rear conveyor in Western literature), and tail conveyor (discharge conveyor, located in the unsupported area) [3]. The most common systems currently are longwall sets of equipment with discharge onto the tail conveyor [4–7].

In the Russian Federation, an approach has been proposed for implementing controlled coal discharge by moving the rock mass flow using a motorised feeder from the outlet post to the main conveyor [8, 9]. Its main advantages include the small dimensions of the support section that are comparable to the dimensions of a classical longwall equipment set, as well as the ability to perform simultaneous group discharge from several sections, implementing promising coal mining technologies using wave and areal discharge [8, 9]. Implementation of such complex technological processes as wave and areal discharge requires developing a system for real-time monitoring of the volume of coal supplied by the feeder from the support outlet port to the main conveyor [9–12]. During group discharge, exceeding the calculated (design) coal supply volume from one feeder can overload the conveyor at the unloading points of the downstream feeders and coal spillage.

Discrete-event models were used to calculate the optimal coal discharge volume for each support section, sequence, and rational number of operating feeders, thus ensuring a steady discharge and maximum conveyor loading, at the FRC CCC SB RAS [13–15]. However, mining equipment capable of effectively measuring the volume of coal produced by a plate feeder under given conditions is not available on the market.

In world practice, solutions that use coherent light sources (laser emitters) to illuminate bulk solids to determine their volumes are known. Among the widely-used applications of such devices are machine vision conveyor performance meters [16–19], which use triangulation to create an array of values characterising the height of the layer of a substance moved by a conveyor at the point where it is intersected by a laser beam. However, this method allows measuring only the volume of bulk material moving through the scanner at a constant speed. There is equipment that uses 3D laser scanners (three-dimensional LIDAR) to determine the volumes of bulk solids moving at different speeds or in a static state [20, 21]. However, the issue of applying the technology in coal mines is poorly developed, with rare exceptions, such as the Australian project ExScan, which has not yet reached the stage of commercial sales and is a one-of-a-kind experimental product [22].

The analysis showed that there has been a significant number of studies published related to machine-vision-based laser volume estimation. However, no specific approaches to measuring the volume of rock mass moved by a feeder during the discharge of underroof coal seam have been identified. The problem of overloading in modern longwall sets of equipment with gravity discharge is solved by a small number of synchronised discharge sections numbering 1 to 5. In this case, an additional conveyor is used that minimises the risk of overload. In addition, the location of the conveyor in an unsupported area makes the effects of overloading less dangerous than when discharging coal onto the main conveyor, but may lead to increased coal losses. To date, automated devices do not record the presence of coal during coal discharge. In the approach described in [3], the outlet port flap opens for a given period of time and then closes without feedback or consideration of the successfulness of the coal discharge. The presence of the discharged coal is recorded visually in the reloader area. The main problem in measuring a plate feeder's performance is the lack of constant coal flow, since the plate feeder performs a reciprocating motion at a frequency close to 1 Hz. This type of feeder moves coal discretely in small batches with a sampling rate equal to the feeder frequency. The design and method of operation of this type of feeder does not allow using standard methods to measure performance by weighing or scanning the flow shape on the conveyors.

For experimental development, the task of measuring the volume of coal supplied by each feeder to the conveyor was divided into several subtasks:

1. Developing a method for calculating the performance based on the data on unit volume and its replacement rate.

2. Selecting the mathematical apparatus for calculating the unit volume of coal located in the measuring section.

3. Developing a methodology for primary verification and validation of the calculation of the coal unit volume in the measuring section.

4. Conducting primary verification and validation of the calculation of the coal unit volume in the measuring section.

5. Analysing the results of the primary verification and validation on the basis of which an algorithm for obtaining the calculation data by the machine vision system is chosen.

Research Methods

Initially, the measurement point along the area of coal reloading by the feeder from the inlet port to the conveyor was determined. The operation of the feeder in reciprocating motion can change the order of distribution of the discharged rock mass as it moves at any point along almost the entire path of coal transportation from the inlet port to the conveyor. The only transportation section where the coal mass movement direction and substitution rate is constant is the outlet channel. The outlet channel is a hinged element mounted on the feeder through which coal passes from the feeder to the conveyor via the process opening between it and the support section. A feasible method for calculating the feeder performance is by first calculating the volume of coal in a given section of the feeder channel (measuring section), then determining the time it takes to replace this section with a new portion of coal. The mathematical apparatus for calculating the feeder performance in this case is reduced to calculating the volume of the body representing the volume of the coal mass in the measuring section per unit time:

$$P_{feed} = V_{unit} \cdot T_{repl}, \quad (1)$$

where P_{feed} is feeder performance, m^3/s; V_{unit} is the unit volume of coal in the measuring section, m^3; T_{repl} is the replacement frequency of coal portions in the measuring section, s^{-1}, directly proportional to the frequency of the feeder and coming into the calculation formula from the automation devices of the longwall set of equipment.

On this basis, the input data for calculating the volume of coal in the measuring section are set. Correspondingly, to measure the volume of the discharged coal per unit time, its volume and replacement rate are measured at the measuring section. The optimal performance of the feeder according to the discrete-event discharge model [13] is calculated in kilograms per second. Thus, using the coal bulk density, the performance is calculated as

$$P_{feed(kg/)} = \rho_{coal} \cdot V_{unit} \cdot i_{repl}, \quad (2)$$

where ρ_{coal} is the bulk density of coal at the section of the extracted seam.

The replacement rate is a value that is determined using data obtained at the pre-commissioning stage and depends on the size fraction of coal discharged and the feeder frequency. When measuring the volume, the shape of the measuring section is taken to be rectangular. The measured coal mass in the measurement area has a variable height over its entire area. To calculate the coal volume, data characterising its height relative to the level of the measuring section at given points is required.

The most obvious option for obtaining the dataset required for the mathematical apparatus is a machine vision system combined with a neural network interface for pattern recognition [13, 14]. However, for the correct operation of a pattern-recognising neural network, a significant training set is typically required that will not be available until the pilot commissioning of a longwall set of equipment of an appropriate design. Besides, the low image quality obtained from modern video cameras certified for installation in longwall sets of equipment limits the applicability of classical algorithms of video scene recognition. This clearly demonstrates the relevance and need to simplify the analysed video scene prior to its computer processing.

To solve this problem, it was proposed to project a rectangular grid of laser beams of contrasting colour (hereinafter referred to as light markers) onto the studied surface. The light markers will provide a projection onto an uneven surface and will change their shape from being straight to the shape of the area on which they are projected, which will provide information about the shape of the area under the light markers. The next step is determining the light marker coordinates relative to the level of the measuring section at any of its points in manual mode without using neural network video recognition techniques.

The presence of a light marker greatly simplifies the recognition of a video scene by machine vision, creating in the scene picture a clear contrasting area in terms of illumination and colour relative to other objects. This area is processed by eliminating unnecessary information from the image at the preprocessing stage. This approach will determine the pattern recognition algorithms, reducing the computer power requirements of the device on which the video signal is processed.

Research Findings

To calculate the volume of coal in the measuring section, the coal layer height was measured only at the points of the layer intersection with light markers, thus forming a map of heights of the coal layer in the measuring section.

We will represent the measuring section as a set of parallelograms with equal bases and heights, corresponding to the data from the height map. The sum of the volumes of the obtained parallelograms will be the volume of the figure in the studied section.

Primary verification of the proposed method is performed using a reference geometrical figure with a curved surface (a hemisphere), the volume of which can be pre-calculated by the formula by setting the overall dimensions comparable to the size of the measuring section with the actual feeder. The expected volume of the hemisphere V_{exp} was calculated by formula (1) and amounted to $261.8 \cdot 10^6$ mm^3:

$$V_{exp} = \frac{\frac{4}{3}\pi r^3}{2}. \quad (3)$$

Input data: radius r, mm, 500; light marker grid pitch along the X axis, mm, X = 50 (constant); light marker grid pitch along the Y axis, mm, Y = 50 (constant); point coordinate along the X axis, x_i; point coordinate along the Y axis, y_n; layer height, mm, at point with coordinates $h_{x,y}$.

Thus, the reference figure with the volume calculated using the proposed method has a circle with a radius of 500 mm at its base. The measurement area is represented by a 1,000 × 1,000 mm square simulating the measuring section on the feeder surface. The reference figure is inscribed in the measurement area. The light markers are represented by vertical and horizontal sections in the measurement area at 50 mm increments in both directions.

To collect the data, it was proposed to perform a conditional dissection of the reference figure at the places where the light markers pass to obtain a set of small figures. Thus, the small figure is a volumetric body with two equal parallel side surfaces that are curvilinear trapezia obtained by dissecting the hemisphere at the h_y coordinate. The volume of the small figure V_1 can be calculated by the formula:

$$V_1 = S_{ss} \cdot Y, \quad (4)$$

Where S_{ss} is the side surface area; Y is the dimension of the small figure along the Y axis. The area of the curvilinear trapezium is calculated using a definite curvilinear integral. High accuracy is not required when calculating the feeder performance; the calculated volume is negligible relative to the total second performance. However, the calculation speeds are important. The heights of the rectangles h_x in increments of X are entered into the table for the calculations. The resulting table is a map of heights for calculating the volume of a small figure. Then S_{ss} can be calculated by the following formula:

$$S_{ss} = X\sum_{x=1}^{x_2} h_x; \quad (5)$$

correspondingly,

$$V_1 = YX\sum_{x=1}^{x_2} h_x. \quad (6)$$

Consequently, the volume of the whole reference figure V_{calc} is represented as a sum of the volumes of all rectangular parallelepipeds included in all small figures into which the reference figure was divided. Then, V_{calc} is calculated by the formula:

$$V_{calc} = XY\sum_{y=1}^{y_2}\sum_{x=1}^{x_2} h_{x,y}, \quad (7)$$

where

$$\sum_{y=1}^{y_2}\sum_{x=1}^{x_2} h_{x,y}$$

is the sum of all heights measured in the sample sections with coordinates $h_{x,y}$.

The reference figure was built using the CAD modeling system Free CAD. The resulting volumetric model of the hemisphere was sequentially dissected along the *X axis* in increments specified in the condition, after which a curvilinear surface height map was created in each resulting section, representing a small figure. The heights were measured in increments of X. The process of sequentially obtaining the height coordinates as data to form the height map is shown in Fig. 1.

Further, the height data are entered into the table, the general view of which is shown in Fig. 2.

The resulting height map simulates the information from the machine vision system. To control the reliability of the measurement results, the surface diagram based on the table data was built, see Fig. 3, *a*.

The surface diagram built using MS Excel shows that the measurements during the construction of the height map were made with no gross errors and can be used for primary verification of the volume calculation method.

As can be seen from Fig. 1, the sections Y form small bodies with flat sides and a base bounded from above by a curvilinear surface that corresponds to the proposed calculation method. Thus, the whole reference figure is represented as a set of corresponding rectangular parallelepipeds having a base of size X by Y. Fig. 3, *b* presents an image of a simplified reference body obtained by converting all small bodies into rectangular parallelepipeds.

The volume of the reference figure calculated by formula (7) was $259.3 \cdot 10^6$ mm^3. The measurement relative error is 0.95 % of the expected result.

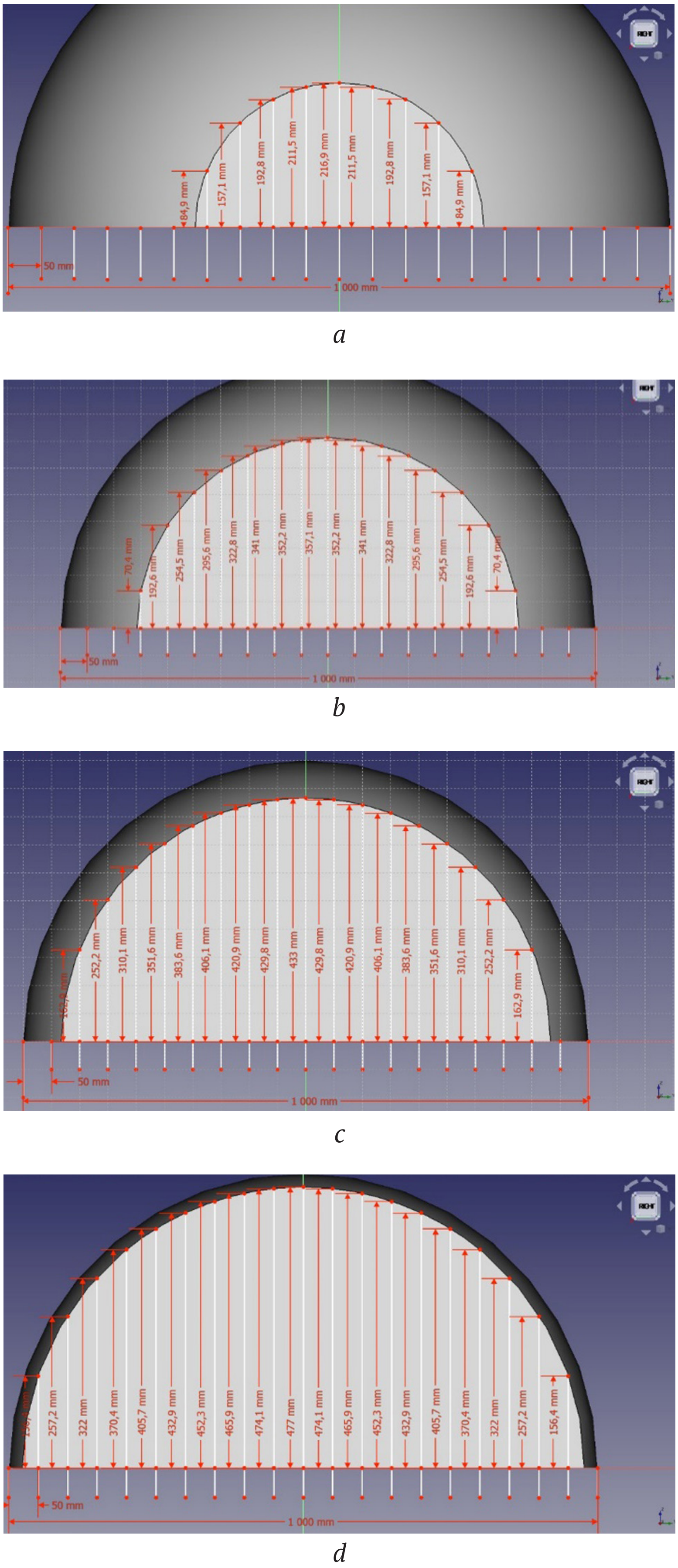
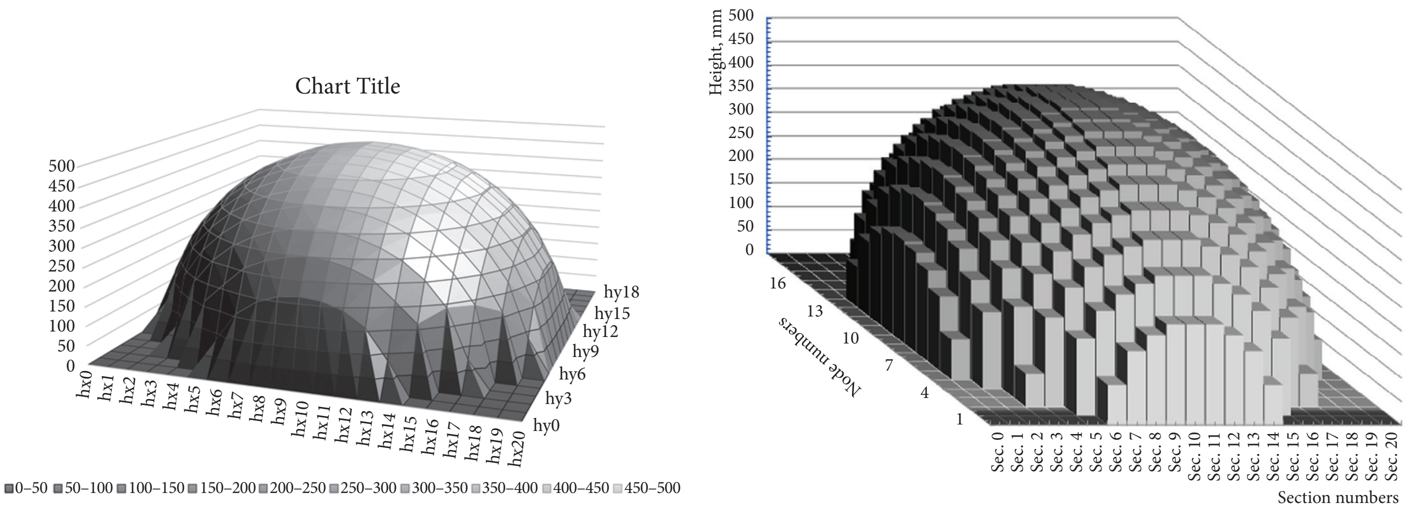


Fig. 1. The process of obtaining the coordinates of the rectangles vertices by section: For height map building: *a* – section 2; *b* – section 4; *c* – section 6; *d* – section 8

Height coordinates	$\boldsymbol{h_x}$	$\boldsymbol{h_{x+1}}$	**…**	$\boldsymbol{h_{x+i}}$
$\boldsymbol{h_y}$	$h_{x,y}$	$h_{x+1,y}$	…	$h_{x+i,y}$
$\boldsymbol{h_{y+1}}$	$h_{x,y+1}$	$h_{x+1,y+1}$	…	$h_{x+i,y+1}$
…	…	…	…	…
$\boldsymbol{h_{y+n}}$	$h_{x,y+n}$	$h_{x+1,y+n}$	…	$h_{x+i,y+n}$

Fig. 2. General view of the height map data table:
$h_{x,y}$ is the height from the zero mark with coordinates x, y to the curve limiting the surface of the section at the dissection location



a *b*

Fig. 3. Representation of the reference figure:
a – in the form of a surface diagram based on measurement data; *b* – obtained by the rectangle method based on measurements

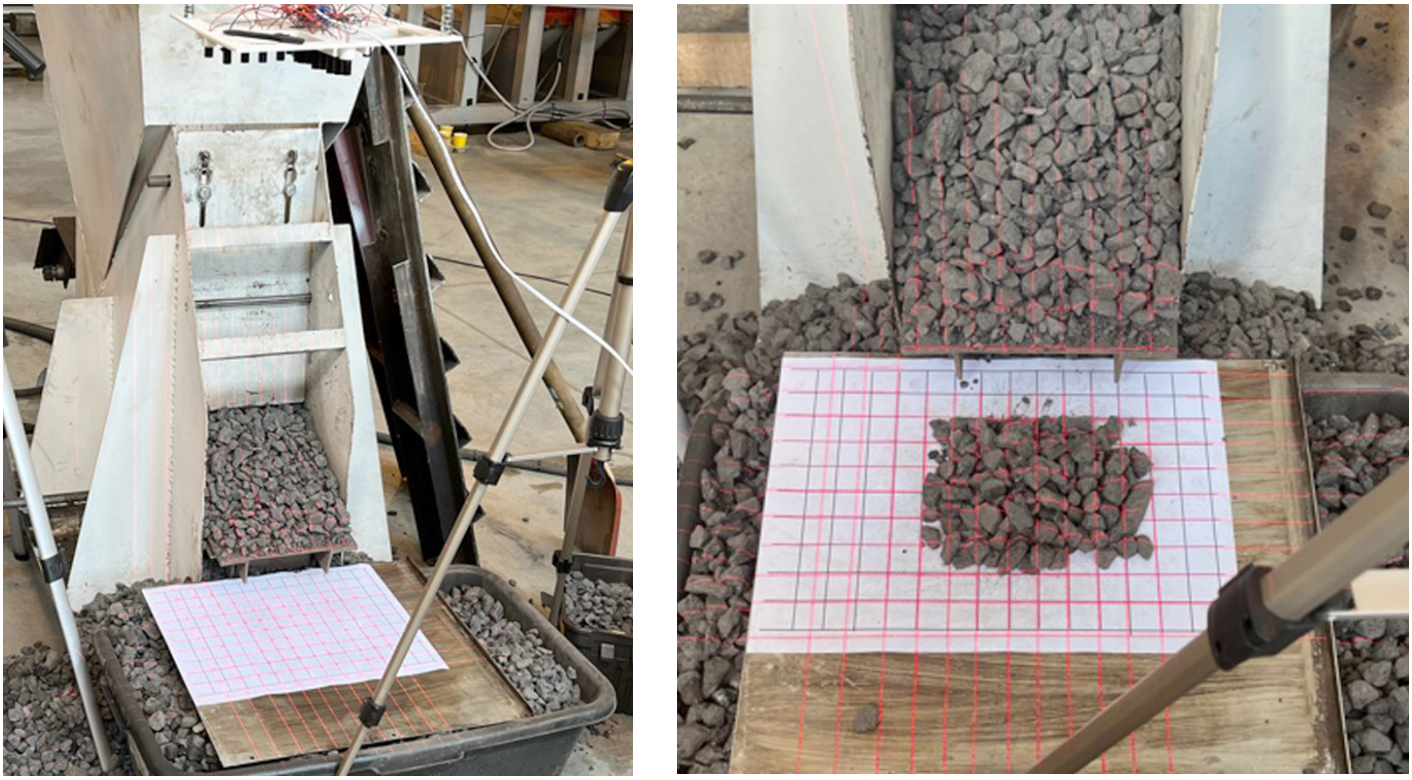


Fig. 4. Technique validation process using a measuring section model

To validate the technique, a series of laboratory experiments were carried out using laser grid projection tools on a flat surface (measuring section) simulating the support section feeder outlet channel. In the experiments, a known volume of coal (Fig. 4) with pre-measured bulk density and weight was placed at the measuring section that enabled mathematical calculating its volume.

To construct the height map, the layer of coal used was probed with a wire spoke in the locations of its intersection with laser beams, then the coal level was fixed on the spoke with a marker. The measurement data was used to build the height map presented in Table 1, where *y* is the coordinate of the measuring point in the cross section of the measuring section with the reference point on the feeder side and *x* is the coordinate of the measuring point in the longitudinal section of the measuring section with the reference point in the leftmost part of the coordinate grid.

Table 1

Map of coal layer heights at the measuring section, mm

$h_{x,y}$	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
y_1	10	27	8	5	16	16	0	0
y_2	14	23	11	27	15	26	23	0
y_3	20	25	35	34	40	13	35	17
y_4	18	19	34	43	32	29	27	12
y_5	25	20	30	25	26	21	20	0
y_6	20	5	12	26	28	21	13	0
y_7	0	0	17	13	10	8	24	0

Based on the bulk density of coal and the weight of the sample, the expected volume $V_{exp} = 0{,}74 \cdot 10^6$ mm^3 was calculated.

The size of the light marker grid cells $h_x = 25$ mm, $h_y = 25$ mm.

The calculated volume $V_{calc} = 0{,}63 \cdot 10^6$ mm^3 is determined by formula (5).

The relative error of V_{calc} (the difference with V_{exp}) was 13.55 %.

The resulting relative error is quite large due to two factors. The first is the imperfect measurement methods used, and the second factor is the simplification of the methodology for calculating the volume, poorly taking into account the heterogeneity of the surface of the coal volume and its distribution over the measuring section.

To compensate the heterogeneity of the measured coal volume surface in the calculation, calculation by the rectangle method with double recalculation in opposite directions and subsequent averaging of the result was proposed:

$$V_{calc1} = \frac{\left(\sum_{y=1}^{y_2-1} \sum_{x=1}^{x_2} h_{x,y} + \sum_{x=1}^{x_2} h_{x,y_2-1} + \sum_{y=2}^{y_2} \sum_{x=1}^{x_2} h_{x,y} + \sum_{x=1}^{x_2} h_{x,2} \right) YX}{2}. \quad (8)$$

Applying formula (8) to the data from Table allows determining $V_{calc1} = 0{,}67 \cdot 10^6$ mm^3.

The relative error of V_{calc1} (the difference with V_{exp}) was 8.87 %.

Discussion

The method used in the experiment to build a coal layer height map has an error because a bulk material (coal) of varying grain size is used; correspondingly, the material particles shift in the course of the measurements. Despite this, the above approach demonstrates acceptable accuracy in the direct calculation of the volume with a relative error of less than 14 %. Using the measurements with passage in two opposite directions relative to the cross section of the measuring section with subsequent averaging of the measurement data allows reducing the relative error for this case by almost 5 %. The 5 % error is a variable value and depends on the distribution of the coal volume relative to the cross section of the measuring section. The relative error of less than 10 % with the available accuracy of the measurements for constructing a height map proves the sufficient accuracy of the proposed calculation method for engineering use and the small influence of the errors of individual measurements on the overall volume calculation result.

Based on the validation results, a formula for calculating the feeder performance, P_{feed}, kg/s, can be obtained by substituting (8) into (2). Then:

$$P_{feed} = \frac{\left(\sum_{y=1}^{y_2-1} \sum_{x=1}^{x_2} h_{x,y} + \sum_{x=1}^{x_2} h_{x,y_2-1} + \sum_{y=2}^{y_2} \sum_{x=1}^{x_2} h_{x,y} + \sum_{x=1}^{x_2} h_{x,2} \right) YX}{2} \rho_{coal} T_{repl}. \quad (9)$$

The resulting formula (9) allowed initiating the development of machine vision software, measuring the height of the coal layer at the points of its intersection with light markers.

Conclusion

The proposed method allows for a rapid assessment of the volume of rock mass moved by a plate feeder using machine vision. The problem of controlling the volume of coal discharged by the feeder when extracting thick seams using longwall sets of equipment with coal discharge to the face conveyor having an accuracy sufficient for practical application was solved. The developed mathematical apparatus for calculating the unit volume of coal at the measuring section (formula (8)) and measuring the feeder performance (formula (9)) allows creating algorithmic software using the elementary mathematical functions of addition, subtraction, multiplication, and division. This aspect is important because it lower sights for the software development environment, and therefore expands the range of hardware suitable for calculating the feeder performance.

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Information about the authors

Mikhail S. Nikitenko – Cand. Sci. (Eng.), Head of Laboratory, Federal Research Center of Coal and Coal-Chemistry of Siberian Branch of the Russian Academy of Sciences, Kemerovo, Russian Federation; ORCID 0000-0001-8752-1332, Scopus ID 55748886500, ResearcherID E-3893-2014; e-mail: ltd.mseng@gmail.com

Sergey A. Kizilov – Researcher, Federal Research Center of Coal and Coal-Chemistry of Siberian Branch of the Russian Academy of Sciences, Kemerovo, Russian Federation; ORCID 0000-0003-2554-1383, Scopus ID 57203142801; e-mail sergkizilov@gmail.com

Yuri N. Zakharov – Dr. Sci. (Phys. and Math.), Professor, Kemerovo State University, Kemerovo, Russian Federation; Scopus ID 56825350700; e-mail zaxarovyn@yandex.ru

Danila Yu. Khudonogov – Researcher, Federal Research Center of Coal and Coal-Chemistry of Siberian Branch of the Russian Academy of Sciences, Kemerovo, Russian Federation; e-mail: admolv@gmail.com

Alla Yu. Ignatova – Cand. Sci. (Biol.), Associate Professor of the Department of Chemical Technology of Solid Fuels and Ecology, T.F. Gorbachev State Technical University, Kemerovo, Russian Federation; ORCID 0000-0001-8061-8684, Scopus ID 6701747560; e-mail allaignatova@rambler.ru

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