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REAL-TIME POSITIONING OF EQUIPMENT AND MATERIAL TRACKING OF WASTE STREAMS IN SURFACE COAL MINING – A CASE STUDY

The primary objective of the case study is to improve monitoring, controlling, planning and managing the extraction processes in surface lignite mining. Under the North Bohemian Lignite Basin (also Most Basin) conditions and the Sokolov Basin, wheeled excavators are deployed as the main technology for extracting coal and overlying rock. Their real-time spatial position can be tracked based on data from GNSS technology, inclinometers, and incremental rotary encoders. The measured data is sent to a remote server and stored in the database. It also serves to calculate volumes of extracted masses. Volume calculation, space position visualisation, and wheel boom movements are performed in KVASoftware. It is a program designed for modelling and designing quarries. Knowing the position of the wheel against the digital terrain (quarry), the model is essential for the implementation of many risk-elimination applications, namely with respect to the geological conditions, occupational safety, observance of the profile grade line, the area of extraction, qualitative parameters of the raw material, etc. The mathematical model of backfilling extracted materials is also an integral part of the above-mentioned system.

Keywords: bucket wheel excavator, geology, GNSS, digital terrain model, opencast mining, real-time

Highlights:

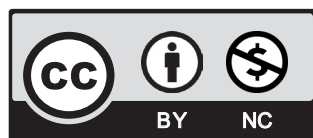
- The system is deployed on all 22 excavators and 6 spreaders of Severočeské doly a.s.,
- The system has proven itself useful, and since 2011 there have been no landslides. The emphasis is mainly on prevention,

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- The result of the project is the creation of a tectonic fault point system with a risk assessment for bucket wheel excavator procedures. The tectonic fault database is constantly updated (several thousand tectonic disorders),
- In most cases, the excavator advancement has been preconditioned for highly hazardous faults so that the risk is as low as possible.

1. Introduction

In the surface mining of coal, as well as some other minerals in the Czech Republic, extraction, transport, storage, dumping of large masses occur both in the case of the main mined mineral itself and the necessary volume of overlying rock, mine waste, bands, accompanying raw materials and sometimes the necessary underlying rock volume. One of the ways to ensure the safety and continuity of mining in increasingly complex mining-geological and economic conditions is the automation of operation [1]. At present, lignite mining in the Czech Republic is concentrated in several large opencast mines in the North Bohemian Lignite Basin and the Sokolov Basin. At Severočeské doly a.s. (North Bohemian Mines PLC), a research project was launched in 2006 to design and realise a system on wheeled excavators that would meet these objectives and make it possible to track the position of the excavator wheel in real-time [2]. This system is currently deployed on all stripping and coal excavators of Severočeské doly a.s.

In surface lignite mining, digital mapping is used in all mining companies in the Czech Republic. At Severočeské doly a.s., at the Nástup Tušimice Mines, a complex digital open-pit mine 3D model – KVASoftware software called the “Mine Model” has been used since 1990. It includes not only the digital terrain model but also the digital geological model of coal strata and overlying rock layers. It makes it possible to create maps and provides the means for the various calculations and analyses needed to plan and control the operation of the quarry.

In 2017, a total of 21.8 million tonnes of coal and 78.8 million m³ of overburden were extracted at two mines operated by Severočeské doly a.s. [3]. The surface shape of lignite mines is continually changing. For the proper control and management of mining, it is necessary to know the real volumes of mining and to have the mine surveyed as often as possible. Surveying mines using aerial photogrammetry is carried out up to 12 times a year at Severočeské doly a.s. The photographed area during one flight is a few tens of km². Mining maps are updated, and mined volumes are calculated. The volume calculation takes place between two areas, i.e. between two models. For example, it is the volume between the MASTER model (the surveyed initial state of the mine) and the REFERENCE model (change model after extracting a part of the mine) [4]. However, aerial photography, evaluation of the photographs, and updating digital models usually take several days, which is a long time for expeditious management of the operation. The feedback needs to be much shorter. Therefore, a surveying system has been developed to track the position of excavators and the spreader. For the usability of the system in practice, the spatial coordinates of the wheel must be calculated accurately. The technical details of the individual parts of the system, including the precision of determining the spatial position of the wheel, are described in more detail in [5] and [6].

2. The essential components of the system

In order to calculate real-time space coordinates of the excavator wheel, it is necessary to create a set of measuring devices, which ensure the measurement of the data needed for the calculation. The selection of measuring instruments is primarily influenced by the need:

- To measure X, Y and Z coordinates of at least two points on the excavator as often as possible.
- To measure the inclination of the excavator as a whole in relation to the horizontal plane.
- To measure the inclination of the wheel boom in relation to the horizontal plane.
- To measure the wheel boom extension (in the case of excavators with an extension).

It is best to use GNSS technology to measure the absolute position of two points on a moving excavator [7]. The measurement of the inclinations of parts of the excavator design is ensured by the inclinometers, and the wheel boom extension (if it can be extended) is measured by the incremental rotary encoders. The boom extension is calculated by recalculating the toothed wheel axis speed, which transmits the electric motor torque to the wheel boom movement using the pinion. Measuring devices must be placed on a heavy-equipment machine to obtain the relevant input values for the calculation and be in positions where the excavator operation is not impaired. On the contrary, they will not be endangered by the deterioration of the working environment [8]. GNSS receivers, inclinometers, sensors and control units are part of the measurement segment. The communication segment includes radio modems using GPRS data transfer technology. The user segment or the KVASoftware evaluator works with a dynamic model describing the area affected by mining (GeoTel s.r.o., KVASoftware), [8]. The main requirement is to calculate the modification (update) of areas quickly with as little data flow as possible as the data is shared over a network with many other applications. All calculations are performed in parallel applications called the “GNSS Mining Model” (one application for each excavator) above the shared data space [9].

Geodetic measurements on the excavator revealed parameters for deriving the mathematical relations needed to calculate the spatial position of the excavator wheel axis centre. These are mainly the distances of individual gauges with respect to one another and some mechanical “nodes” of the excavator design (Fig. 1) [10]. For each type of wheel excavator, a mathematical model based on its unique calculation scheme is created. Additionally, in different versions, it is based on the position of the wheel boom and the excavator (Fig. 2) [11].

Consequently, it was necessary to develop a suitable algorithm that includes the measurement results of individual measuring and surveying instruments. This algorithm is supposed to calculate the spatial position of the wheel centre in any general position of the excavator [12].

3. Applications using a system for calculating the excavator wheel position

In the Mine Model program environment, applications have been developed that provide the necessary tools to control and manage the mining process. These are, in particular, tools to meet the established profile grade line of the working plane and the mining area [13]. This is important both for the fulfilment of the overall mining concept and for the drainage of the mine. In the figure (Fig. 3), the corresponding mining mark shows the surveyed coal cut; a red line represents the

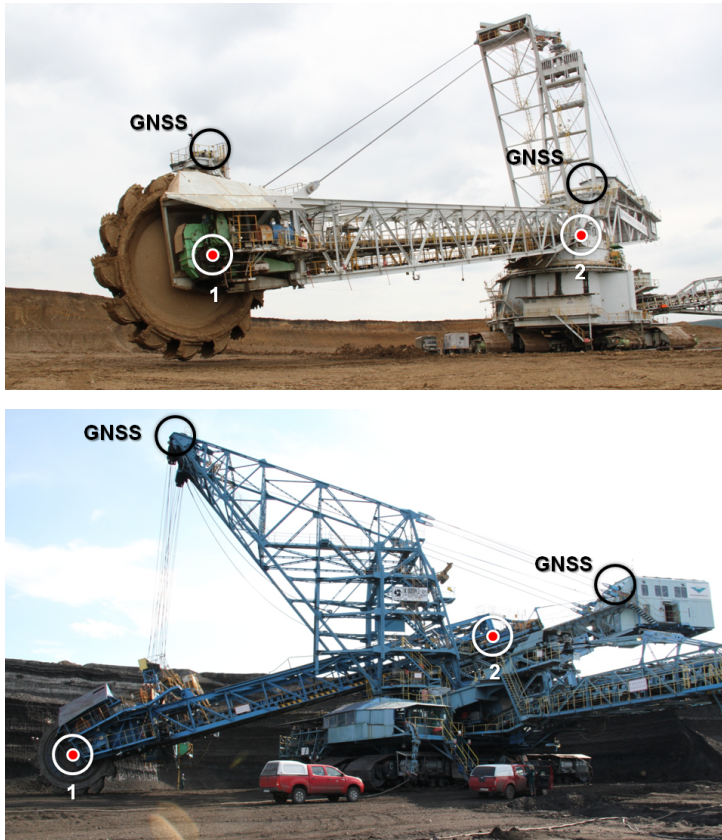


Fig. 1. The excavators SchRs 1550 and K800 (legend: GNSS receivers, 1 – wheel axis and wheel axis centre, 2 – boom arm axis)

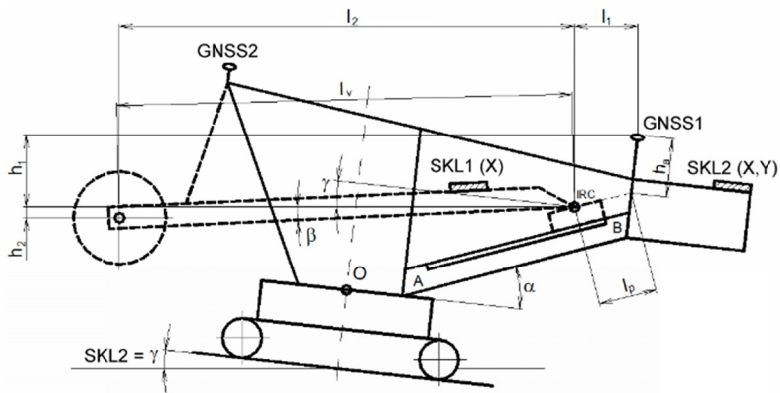


Fig. 2. One of the variants of the computerised scheme for the K800 wheel excavator with the orientation of gauges, GNSS receivers, SKL – inclinometers, IRC – incremental rotary encoders, O – the centre of the ball track

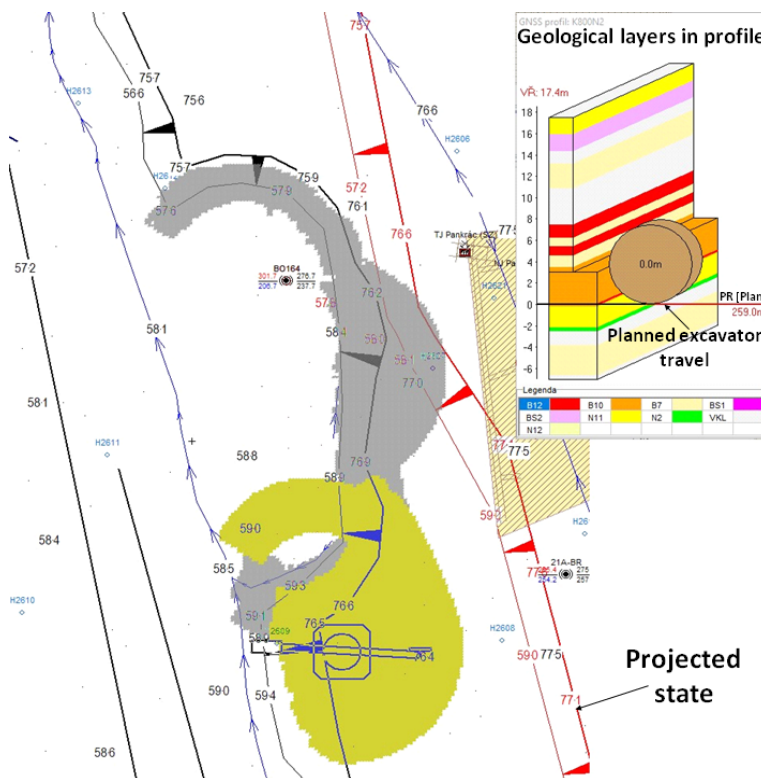


Fig. 3. The application for the control and management of the mining plan compliance – K800/104 the excavator position as of 13 August 2018 at 10:01 a.m.

mining plan, a schematic position of the excavator, and a vertical profile of the coal seam with the real-time position of the wheel. In the vertical profile of the coal seam, the profile grade line of the planned excavator mining plane is indicated. The area with coloured background shows the places already extracted by the excavator (where the wheel was present). The figure shows that the excavator extracted the lowest excavation bench. The entry 0.0 m on the wheel profile means that the profile grade line of the projected advance of the excavator has been respected.

The figure (Fig. 4) shows a section of the application demonstrating how the specified profile grade line of the mining working plane (wheel heel spot height) and the ash content (Ad% Parameter) of the mined coal over time is observed. Real-time tracking is also possible for other parameters, such as the calorific value of coal, sulphur and water content. Using the Mining Model and Technology Model programs, these applications are used by surveyors, geologists, production preparation, and operation supervisors. From the heavy equipment machine cabin, the driver tracks the real mining of the mineral by the excavator wheel. At the same time, the GPS application is running, which is a simpler version of the above-mentioned Mining and Technology Model programs, where he can choose several graphical and numeric tools to achieve the mining plan with the highest possible accuracy. The expert opinion “Draft classification of tectonic faults given their risk level for the process of large bucket wheel excavators” was drafted [14]. Its

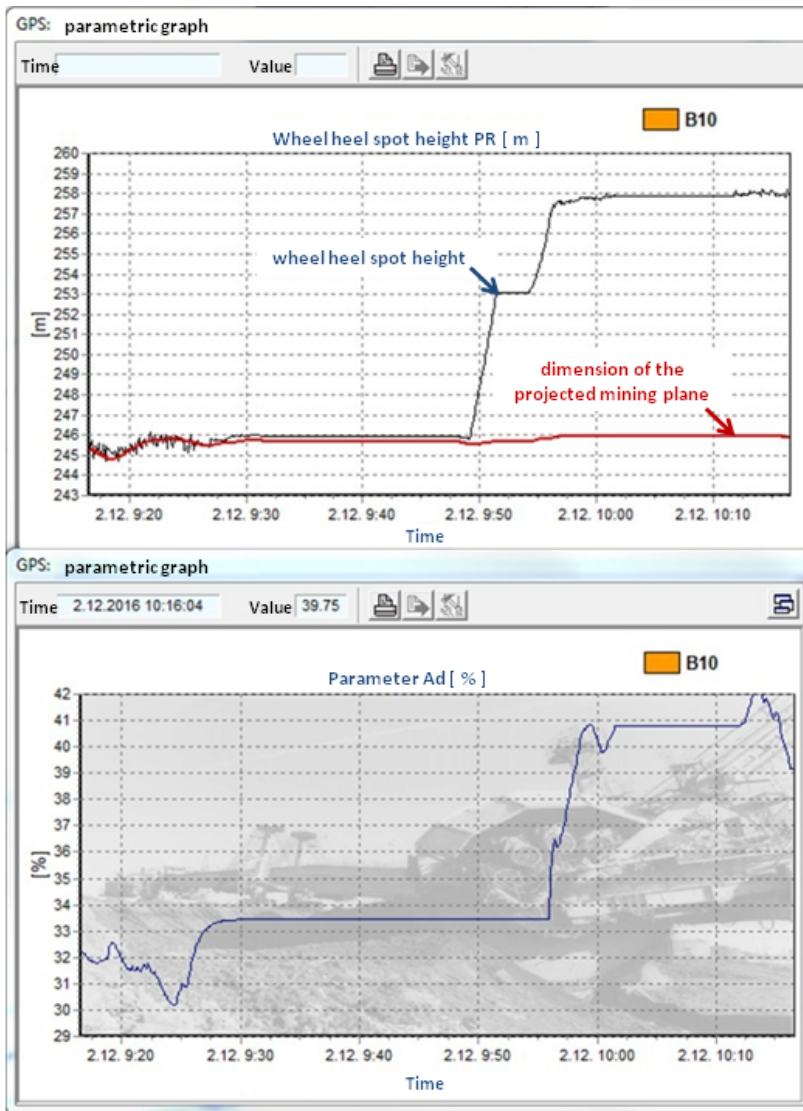


Fig. 4. Monitoring the levels and development of ash ingots in excavated coal

result is creating a tectonic fault point system with a risk assessment for bucket wheel excavator procedures. The result of the project is creating a tectonic fault point system with a risk assessment for bucket wheel excavator procedures [15,16].

Other application features [15]:

- Deep mine workings (potential wheel damage).
- Boreholes with retained reinforcement (potential wheel damage).
- Tectonic faults (risk of landslides).

Geology – tracking wheel position relative to:

- Geological layers – assignment of the qualitative parameters of the currently mined coal from the geological model.

Surveying – there is a reduction or duplication of some routine surveying work in operation:

- Laying out mining advance of excavators.
- Laying out boreholes where equipment was left in place.
- Laying out some of the objects of the former deep mining, laying out tectonic lines.

One of the most important and most complex surveyors' tasks at surface mines is the calculation of the volumes of the extracted masses. By updating the real-time digital model of the terrain using the described system, it is possible to perform calculations of volumes for an arbitrarily selected period (shift, day, month). An interesting and relatively frequently used feature is the ability to create a traditional vector map from a visualised 3D model. By moving to any point in this model, X, Y, and Z coordinates can be obtained.

The planned and actual shape of the mining advance can also be displayed three-dimensionally (Fig. 5). Figure 6 shows the situation of the K200/101 excavator at the Bilina Mine on 12 September 2018, at 11:17. Before the overburden cut, the wheel excavator boom position is visualised in its current spatial position – it is currently extracting the second lowermost mining bench. One Mining Model function is the possibility to vector the state of the mine at any time of the system operation. The principle is similar to photogrammetric evaluation. Using a pointing device (e.g., a mouse), points that are supposed to be evaluated are marked. For wheel excavator excavation, these are usually the points of the upper and lower edges of the cuts and the points on the working plane. Points and vectors are obtained to create a model of the mine cut state as of a given date. The current state of the terrain as of a given date in a vectorised form can be used as a standard digital map for a variety of analyses, calculations, or as an input for planning a further excavator advance.

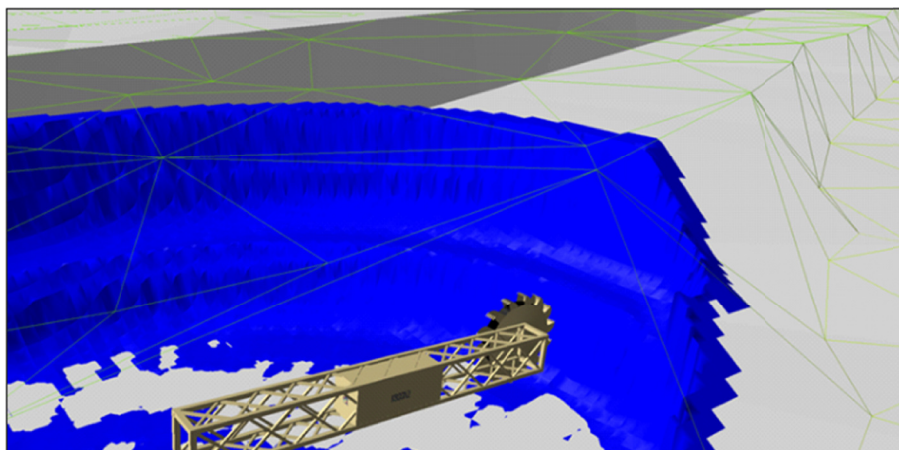


Fig. 5. The current position of the K800/104 excavator on 5 January 2018 at 12:48 – three-dimensional space

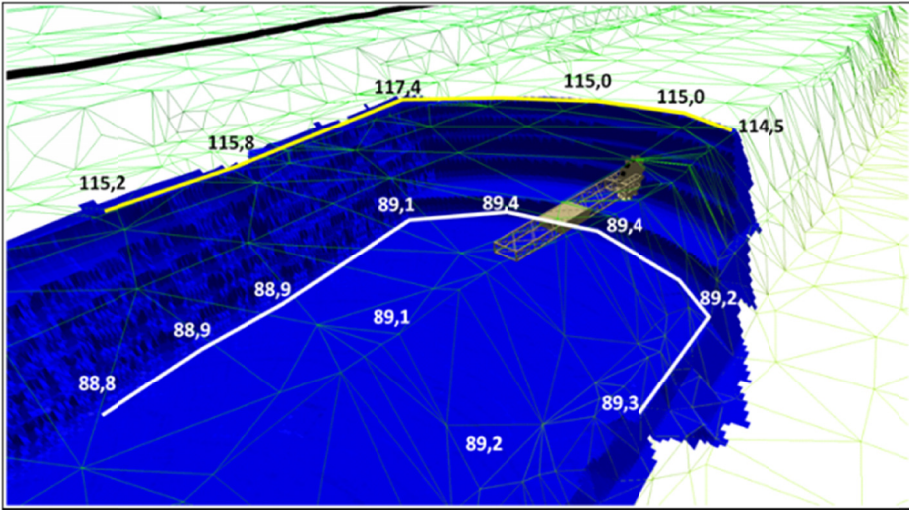


Fig. 6. Evaluation of the K2000/101 excavator advance as of 12 September 2018 11:17

4. A model of dumping extracted masses

At the Bílina Mines, some spreaders with a belt conveyor (GeoTEL s.r.o. solution) are equipped with a similar GNSS system as excavators. On the conveyor belt of the spreader, the profile of the conveyed material is scanned, and the volume is continuously calculated in 5-second intervals. The spreaders are equipped with the LMS511 Bulkscan laser scanner (Fig. 7). It is a 2D scanner designed to measure the volume and volume flow of the material on the conveyor belt [17].

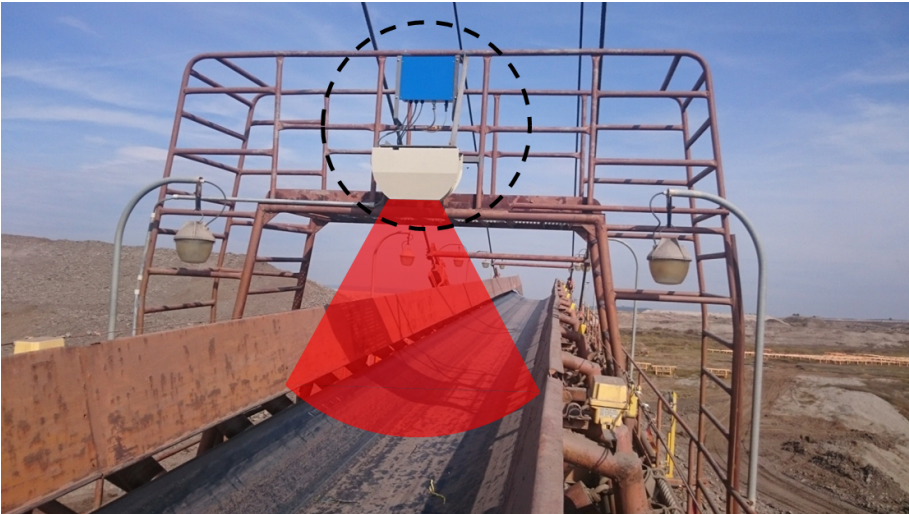


Fig. 7. Location of the LMS511 Bulkscan Laser Scanner

Figure 8 shows the ideal position of the Bulkscan laser scanner with respect to the belt conveyor or transport rollers.

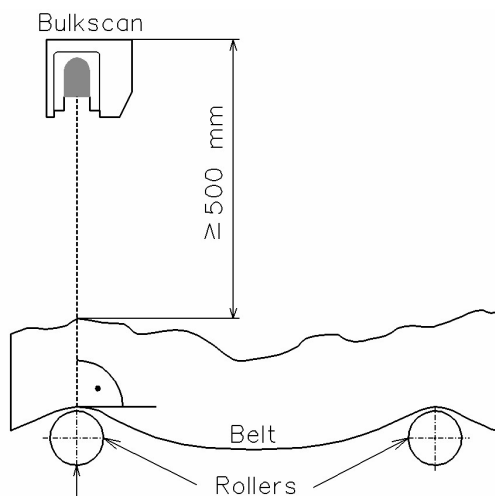


Fig. 8. The position of the scanner with respect to the conveyor belt

The spreader boom position data (GNSS1, GNSS2, boom inclinometer, and elementary scanner volumes) are sent to the server to be processed by the GNSS Zmodel application (KVASoftware s.r.o.).

Among other things, based on parametric data, this application generates the geometry of the throw parabola of the loaded material movement from the end position of the boom and models the shape of the bulk materials. [18]. Figure 9 illustrates a model of the beginning of the throw parabola with the material detachment at point B, for which the equality of the centrifugal force acting on the material and the concentric component of the material weight applies (the calculation of the material weight from the known volume and the parametrically defined density).

$$\frac{m \cdot v^2}{R} = m \cdot g \cdot \sin \alpha_B \quad (1)$$

Then

$$\alpha_B = \arcsin \frac{v^2}{g \cdot R} \quad (2)$$

where m – the weight of the material calculated from the known volume and the parametrically defined density, v – belt velocity, g – gravity acceleration, R – cylinder radius, and α_B – the angle from the horizontal plane passing through the centre of rotation of the drum to point B where the material is detached.

The tangent angle β to the throw parabola can be determined from the relationship.

$$\beta = 90^\circ - \alpha_B \quad (3)$$

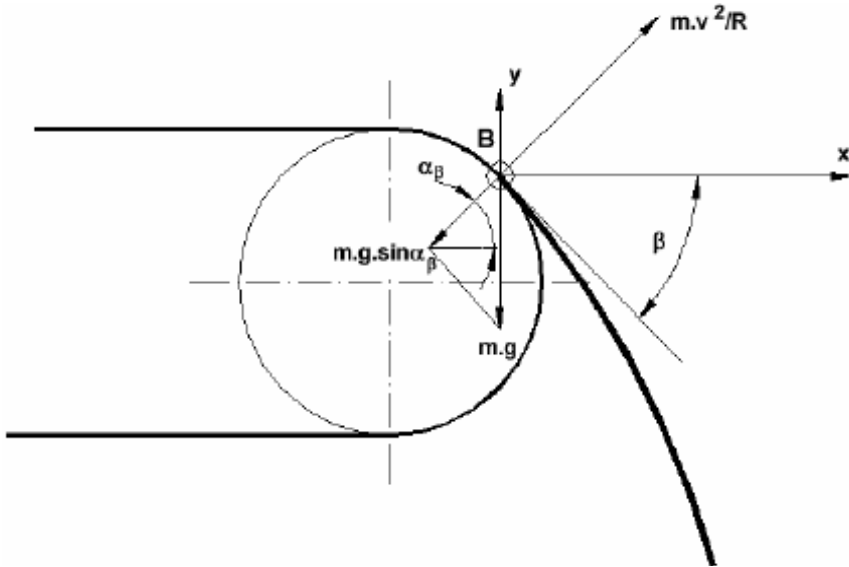


Fig. 9. The geometry of the throw parabola

The movement of the material can be expressed in a parametric relationship in the direction of the X- and Y-axes. A positive direction along the Y-axis is the downward direction.

$$x = v \cdot \cos\beta \cdot t \tag{4}$$

$$y = v \cdot \sin \beta \cdot t + \frac{g \cdot t^2}{2} \tag{5}$$

After substituting for parameter t from equation (4), by substituting to equation (5) and its modification, the proposal of the throw parabola equation has the following form:

$$y = x \cdot \text{tg}\beta + \frac{g \cdot x^2}{2 \cdot v^2} \cdot (1 + \text{tg}^2 \beta) \tag{6}$$

where t – incremental unit.

The modelling of the spreader’s travel area and the modelling of the deposited material at the site of impact per part s on the current terrain area, and subsequently, on the dynamically changing area of the dumping model is calculated in the dynamically structured partial index matrix with each matrix element internally divided into 8 triangles (as a result of the eight plane equations). The impacting dumped material continuously modifies the dimension of each point (= triangle peak) in the given element of the matrix and, at the same time, always in the adjacent elements [9].

The impacting material only changes the parameters of the equations of elementary surfaces organised in partial index matrices.

Each elementary plane ($1/8 \text{ m}^2$) of a matrix element is dynamically defined, modifying the resulting dimensions at individual points with given elevation using geometric and physi-

cal parameters (modelling of the material dumping after reaching the dimensionally specified dimension difference, the dumping angle, etc.).

The impacting material is modelled as a dynamically behaving “body” that has trajectory and kinetic energy. The area on which the material impacts may have any shape and slope in the model. According to the parametrically specified boundary dumping angle, the special spatial cascade recursion algorithm (the number of recursion steps is limited to 6000 immersions) models the resulting hopper shape.

The mathematical model can be used for downward (Fig. 10) and upward (Fig. 11) dumping.

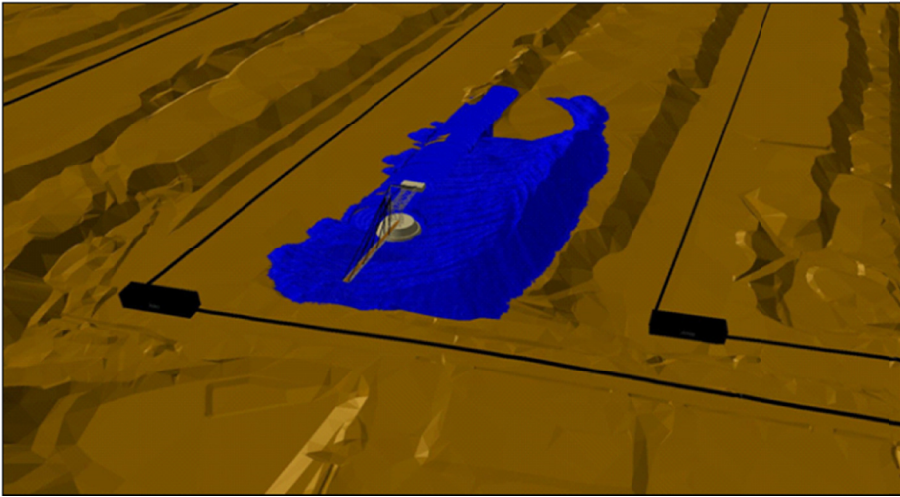


Fig. 10. Completion of downward dumping as of 24 July 2018 – Z85 spreader

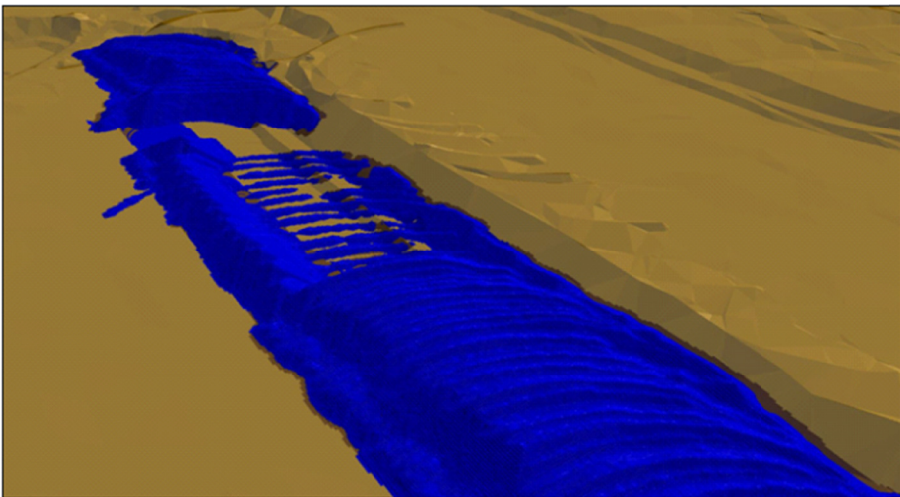


Fig. 11. Upward dumping as of 31 July 2018 – Z85 spreader

The aerial photogrammetry evaluation showed a relatively high match between the mathematical model of dumping and the surveyed reality (Figures 12 and 13).

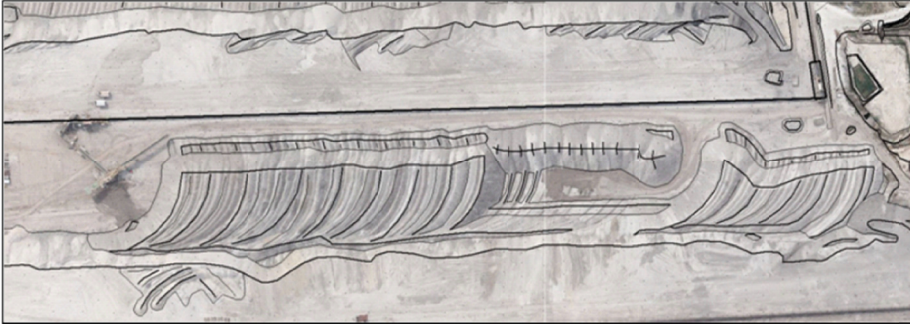


Fig. 12. Aerial photogrammetry photograph as of 31 July 2018 (left Z85 spreader)

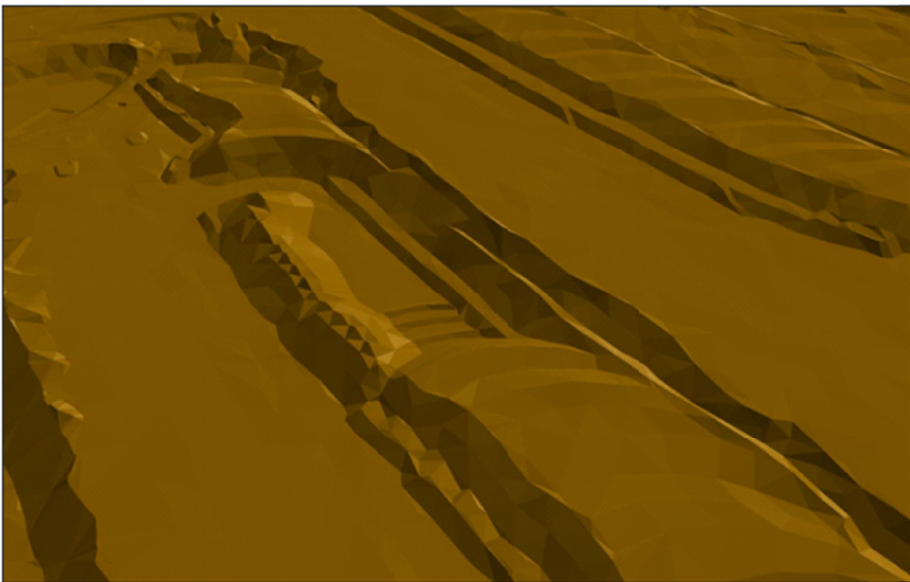


Fig. 13. A generated 3D view of the mine condition surveyed as of 31 July 2018 – Z85 spreader

The mathematical model of dumping the extracted material is an entirely new part of the GNSS technology deployed on spreaders. It exhibits a very high sensitivity to many parameters, the values of which will need to be made more accurate eventually (belt velocity, throw parabola parameters, limit dumping angle values, density, etc.). However, this model cannot cover a whole range of external influences (especially the geo-mechanical properties of the dumped material, atmospheric influences, etc.). Meanwhile, the model cannot include material transfer using bulldozers (especially for winze dumping) [19].

However, the critical parameters are mainly the reliability of transferring the data on the position of the spreader and the volumes provided by the laser scanner. On a long-term basis, in the conditions of Severočeské doly a.s. (SD a.s.), achieving data reliability and data processing ranges on average from 88% to 94%, data losses can be attributed to the significant extent to the fact that all data transmission takes place over the mobile network. For comparison, in the conditions of Sokolovská uhelná, právní nástupce, a.s. (SU a.s.), where all machines are equipped with the same GNSS technology and covered by their WiFi network, the reliability of data reception and processing is less than 97% only in exceptional cases.

Unlike the excavators, where the whole system is not so sensitive to data loss or a short time, the data loss has highly adverse consequences in the case of spreaders. In no way can the lost data be approximated, nor can the situation of the model be calculated when the excavator wheel passes through the same space. The accuracy of partial volume data provided by the laser scanner is also essential. However, for most spreaders equipped with the GNSS system, a simple dependency applies when one excavator “supplies” the spreader with dumped material by its extraction. Therefore, it is possible to determine the correlation of the extraction volumes with the data of partial volumes of the scanner. A 24-hour time-lapse image can largely eliminate possible 5-second sample errors on the excavator and spreader. Fig. 14 shows a chart with the K111 excavator daily mining data [m³/day] compared to daily summations of partial volumes provided by the scanner at the Z102 spreader.

When comparing the daily values of the two machines, it does not matter at all that the scanner, for any reason, provides smaller volumes than actual mining (as in this case). If the correlation (Fig. 15) between machine volumes is sufficiently tight and stable over time, a coefficient can be calculated to correct the scanner values and take the assumed swell factor into account [19].

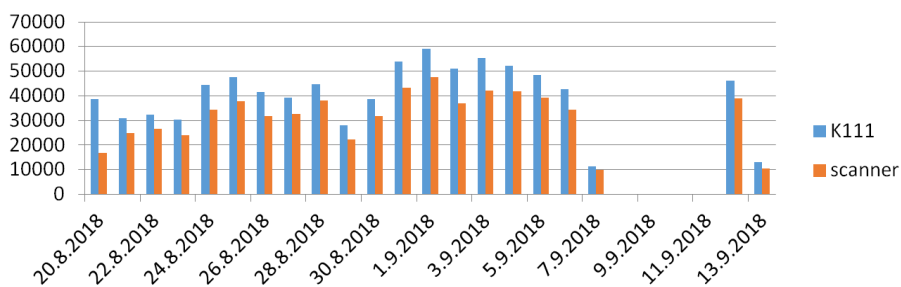


Fig. 14. The K111 excavator daily mining and the sum of the Z102 spreader scanner volumes

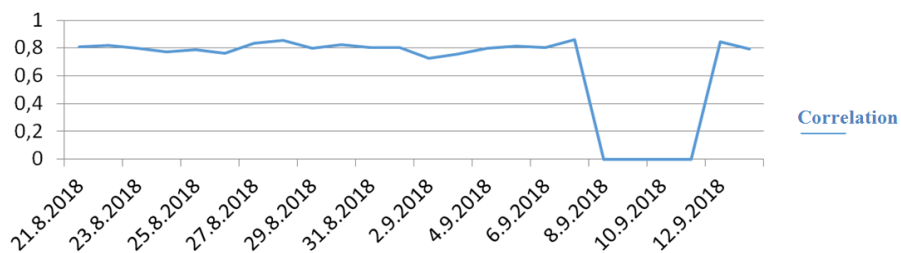


Fig. 15. The correlation of the K111 excavator and the Z102 spreader scanner volumes

The follow-up application, the Mining Model (or the Technology Model), provides information on the spreader status and the 2D dumping model as well as 3D drawing along with the longitudinal profile window, including a chart of partial volumes provided by the laser scanner (Fig. 16).

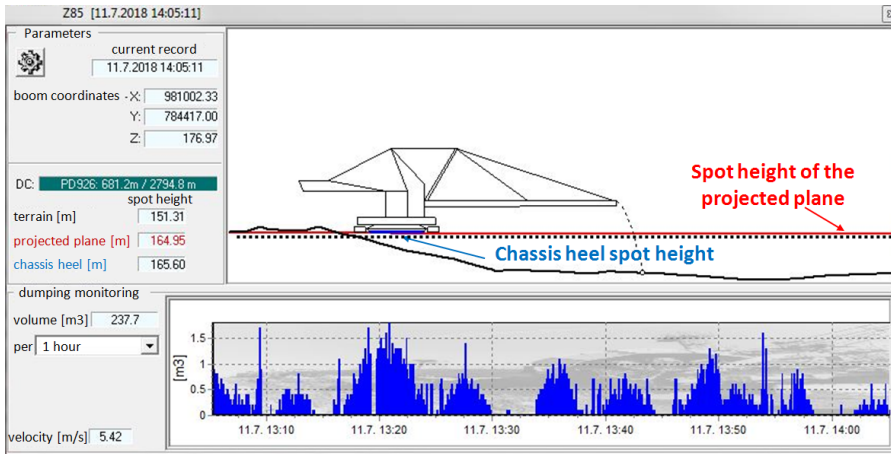


Fig. 16. The Z85 spreader status window on 11 July 2018 at 14:05:11

Like the excavator, the spreader cabin is equipped with a monitor in which the GNSS Zkabina application displays data on the current situation of the spreader graphically and numerically (Fig. 17).

6. Conclusions

The surveying system for real-time determination of the wheel axis centre proved to be viable in its ten-year practice of surface lignite mining. Accuracy analyses prove the appropriate accuracy of the system (according to the ČBÚ (Czech Mining Authority) Decree No. 435/1992 Coll., as well as the needs of the organisation) [5]. At present (12/2019), the system is deployed on all 22 excavators and 6 spreaders of Severočeské doly a.s. The application development using real-time knowledge of the position of excavator wheels and spreaders is increasingly focused on operating support as one of the tools for mining control and management. The manuscript presents new information about dumping overburden materials modelling on dumps.

The research concludes the following:

- The wheeled excavator tracking system creates a new, real-time, digital terrain model (DTM). This was often checked by geodetic and photogrammetric methods.
- The system modelling the gradual construction of the individual dumping benches captures the shape and position of the created dump bench very well. The problem is that the device for monitoring the volumes of material transported to the spreader does not give correct results. Therefore, the modelled benches are lower in height and smaller in volume than in reality (checked by geodetic and photogrammetric methods).

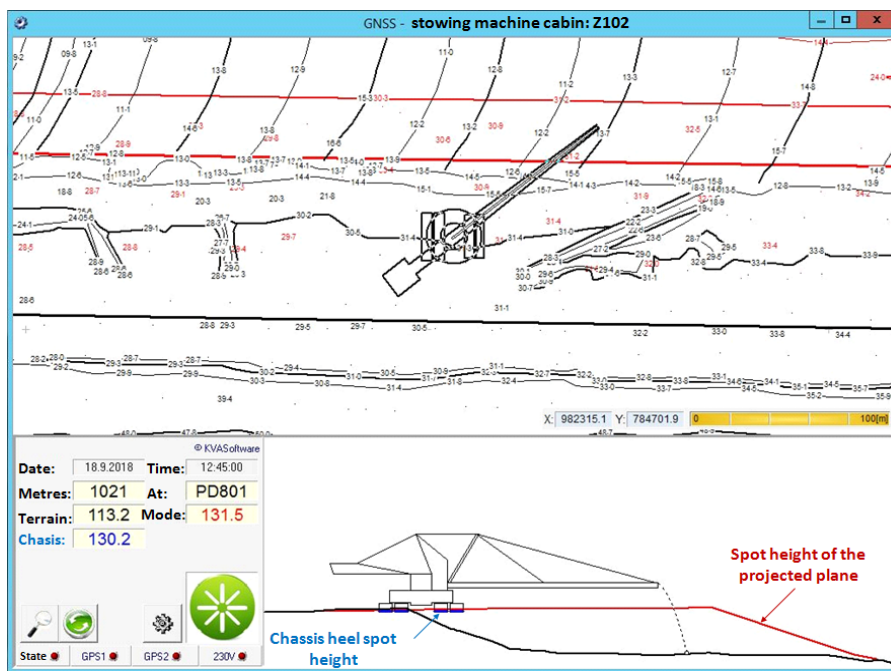


Fig. 17. Zkabina application screen on the Z102 spreader

The possibilities from further research:

- Determining the coefficients or mathematical relationships that will balance the volumes of a mass detected by the scanners based on the comparison of volumes and heights of the modelled floors and the actual benches after their surveying.
- Trying to design a solution that will perform these corrections automatically using knowledge of the exact volumes of mass extracted by wheeled excavators in real-time.

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