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METHODOLOGY DEVISING FOR BUCKET-WHEEL EXCAVATOR SURVEYING BY LASER SCANNING METHOD TO DETERMINE ITS MAIN GEOMETRICAL PARAMETERS

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Abstract. The application of laser scanning techniques to bucket-wheel excavator surveying seeks primarily to determine the machines' key geometric parameters and to establish realistic mathematical descriptions of their movement dynamics in 3D space. The data will be used to visualize excavator movement and to control the coal extraction process in real time. The measurements take place at Doly Nástup Opencast Coal Mine, Tušimice, North-Bohemian Lignite Coal Field, Czech Republic. GNSS technology and inclinometric measurements are used to calculate 3D positions of the bucket-wheel excavators. The data is transferred to the research team workplace and stored in a database. KVAS software is used to visualise the bucket-wheel excavators and their 3D movements in real time.

Keywords: GNSS, bucket-wheel excavator, laser scanning, 3D modelling.

1. Introduction

3D laser scanning technology is one of the cutting-edge techniques for generating 3D geo-data. The system is used for contactless generating of 3D coordinates and for creating DSM (digital surface model) planes consisting of point clouds. Some of the primary applications include generating high-precision detailed topographic models of terrain and surveying objects with complex features or those difficult to access. The focus of the present project was to survey one category of complex objects: the bucket-wheel excavators K800/N1/103, K800/N2/104, and KU 300–88 (Fig. 1), and to generate data sets (vector images) allowing the identification of the machines' key geometric parameters. The present paper deals with K800/N1/103 bucket-wheel excavator.

The primary output of laser scanning consists of a set of 3D coordinates of reflection points, i.e. of the so called point cloud. Follow-up data processing, filtering and classification consist of several automatic, semi-automatic and manual procedures. Each laser reflection point record also contains auxiliary data like reflection intensity and even the reflection's real colour where digital photographic images are taken during the scanning process.

In our case, the final output of the laser scanning process is a generalized 3D vector model.

Thus the surveying provides the following outputs:

– 3D coordinates of points, i.e. the point cloud;
– A vector model identifying key excavator geometric parameters.

The main goal is to use the measured data to create an automated surveying system that allows tracking of overburden and coal cuts "without measuring" in real time.

2. Measurement

2.1. Instruments and software

A Leica ScanStation C10 3D pulse laser scanner was used to scan the K800/N1/103 bucket-wheel excavator. The Leica ScanStation C10 is the most popular model of the ScanStation pulse laser scanner series. The advantages of the Leica ScanStation C10 include high accuracy, long range and fast full-dome scans. Lengths are measured by phase technology achieving a margin of error of 6 mm and 4 mm in position and length respectively over a 300 m range at 90% reflectivity and scanning speeds up to 50,000 points per second. The field of vision is a fully open dome of 270° by 360°. The scanner uses the Smart X-MirrorTH technology with automatic mirror spin adjustment to scan the area for optimum productivity. The scanner aligns the images from its integrated high-definition camera with laser images for fast surveying of the target marks and for adding real-world colours to cloud points in real time.

Bucket-wheel excavators K800/N2/104 and KU 300-88 were scanned by the Faro Focus 3D laser scanner with 120 m range and scanning speed up to 1 million points per second. The scanner has an integrated colour camera producing photo-realistic colour scans. A Canon EOS 7D camera was used to make a detailed photo set of the excavators and of the key points (Fig. 2).

Software used:

– Leica Geosystems HDS Cyclone – (version MODEL), an all-round high-precision point cloud processing and export-to-CAD tool;
– Leica CloudWorx, a CAS system point cloud processing application;
– AutoCAD Map 3D or MicroStation V8, tools used to create vector images from point clouds and to derive key excavator geometric parameters;
– SCENE, software using to link up and register different scans and to do automatic object recognition;
– 3D computational module IMAlign programming environment PolyWorks 11.0.7. – Plug-in allows you to scan directly into the PolyWorks software package that can be used for point cloud digitizing, dimensional analysis and conversion to CAD.

Fig. 1. Bucket-wheel excavator K800/N1/103

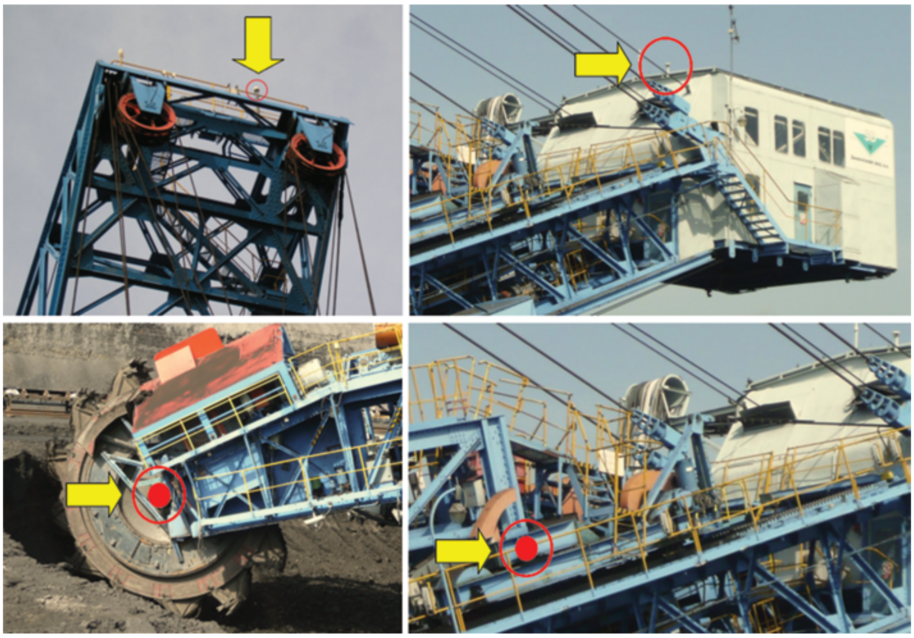

Fig. 2. Key points of bucket-wheel excavator K800/N1/103

2.2. Laser scanning

Site examination was carried out to determine suitable scanner stations around the excavator covering positions on machine movement level as well as cross-sectional stations.

The excavator must stand in its starting position with the boom extended. A detailed inspection of the excavator to identify key survey points and detailed photographic documentation must precede the scanning process.

Key points (Sládková *et al.* 2011; Staňková, Černota 2010):

- GPS aerial in front above the boom;
- GPS aerial in from the back above the machine cabin;
- Bucket-wheel pivot shaft;
- Boom pivot shaft.

Control points were identified on the ground and on the bucket-wheel excavator to place the model in a reference system and to combine all partial scans into one. The K800/N1/103 bucket-wheel excavator was scanned from 11 scanner stations and 23 control points were marked by square or round blue target marks, 5 of which were tilting targets attached by magnets (Fig. 3). Control points were placed on tripods around excavators or magnetic target on its structure. Points were targeted with total station Leica TCR 1202 with standard deviation of the measured direction 2" and standard deviation of the measured length of 2 mm ± 2 ppm. Measurements were performed in the local coordinate system. The Faro Focus 3D control points were marked by black-and-white chequered squares. The Cyclone software identifies the targets by automatically looking for a contrast in reflections between target mark middle sections (light-tone reflective area) and the rest of the area (blue).

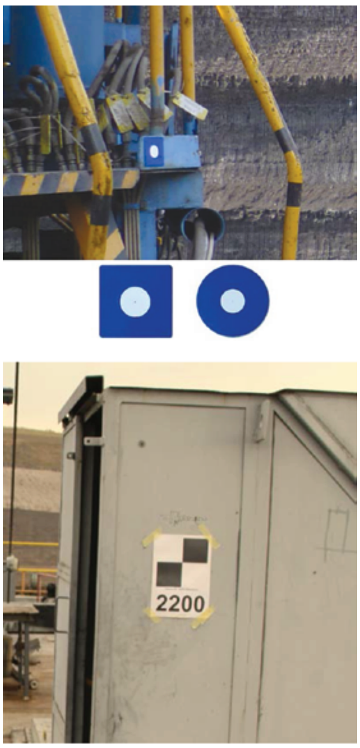

Fig. 3. Control point marks for ScanStation C10 and for Faro Focus 3D

2.3. Data processing

By registering, we combined point clouds from individual scanning positions and placed them in the chosen coordinate system. To connect individual frames, control points were used, focussing on classical geodetic methods. Control points are scanned during measurement with higher density, automatically calculating the exact position in space. Levelling and error analysis can be done from redundant control points. The average results of the analysis give the limits of identifying control elements after transformation to a value of 3 mm in space. The maximum correction to control elements then has the value of 6 mm in the area (Gašinec *et al.* 2012).

Series data taken from individual positions were combined into one unit and at the same time, unwanted objects and surrounding terrain were cut out (Fig. 4). Point clouds, which formed the structure of the excavator bucket wheel contained 600 million points.

Subject to subsequent evaluation, there was determined the spatial relationship between the turntable axis telescopic arm, the turntable axis of the wheel and the front and rear GPS antenna devices located on the excavator. Using the modular system Cyclone, there were modeled, the individual details and intended intersections of the wheel axis with the axis of the telescopic arm, intersections of the shoulder rotating axis with the axis of the retractable shoulder and the GPS antenna reference points. The wheel circumference was also determined. One of the outputs is a 3D drawing of the relationship between the rotating axes and GPS devices (Fig. 5).

The data series gathered from different scanner stations were combined (Fig. 4) and the following step was data filtering and data processing. The CloudWorx for AutoCAD application allows simple tools to be used for the processing of large point clouds, such as selecting sections of the point cloud. Time consuming and demanding for computer hardware as the processing of large data volumes is, it is crucial to select appropriate point field density in each point cloud section. In this application, the main structural elements of the excavators were gradually vectorized, until a generalized 3D model was created (Fig. 5). Selected geometric parameters obtained from laser scanning are checked against the parameters obtained on the basis of Geodesy, GPS and inclinometer measurements (Table 1).

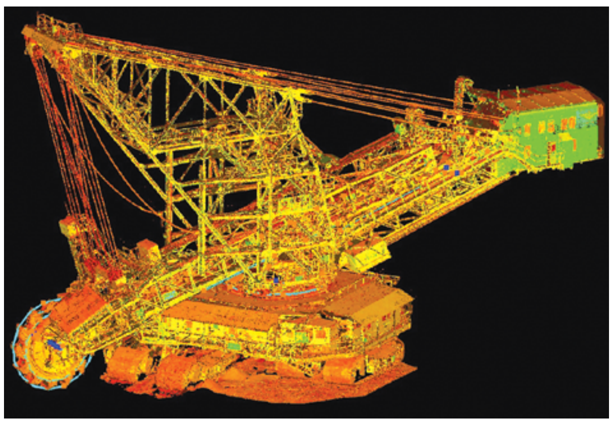

Fig. 4. The point cloud

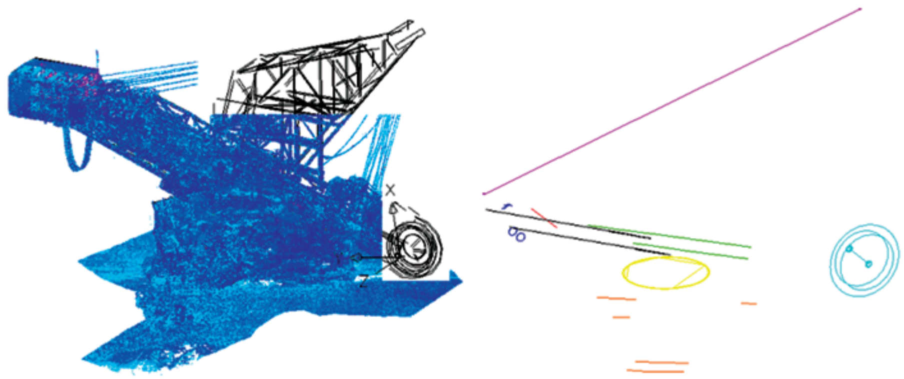

Fig. 5. Bucket-wheel excavator vector model

Table 1. K800/N1/103 bucket-wheel excavator geometric parameters, in [m]

Dimension	Symbol	Geodesic surveying, GPS, inclinometers	Laser scanning	Difference
Bucket-wheel boom length	lv	35,966	35.95	–0.02
Distance from IRC centre, having a point of intersection on GPS1 vertical, to a parallel with the boom running through IRC centre	l_{po}	7,557	7.57	+0.01
Vertical distance of GPS1 sensor from the joint of bucket-wheel boom in upper position	h_{1o}		4.29	
Vertical distance between bucket-wheel centre and IRC centre	h_2		10.2	
GPS1 head over the notional point of intersection on GPS1 vertical determining l_{p0}	h_a	1,770	1.8	+0.03
Horizontal distance of GPS1 sensor from the joint of bucket-wheel boom in upper position	l_{1o}		7.16	
Horizontal distance between GPS sensors	h_{GPS}		41.18	
Vertical distance between GPS sensors with excavator in horizontal position	Z_{GPSo}			
Vertical distance between GPS sensors	Z_{GPS}		12.4	
Bucket-wheel axis distance from GPS1	L_o		41.64	
Bucket-wheel boom travel hoist angle	α	19,648°	19.2°	–0.4°
Vertical distance between GPS1 sensor and ball bearing slewing ring	Z_{IRC}		12.43	
Bucket-wheel max. diameter to teeth edge	D_k		7.52	
GPS sensor positions relative to excavator vertical axis – bucket-wheel boom joint distance from excavator axis in upper position	l_3		13.29	
GPS sensor lengthwise positions – distance from excavator lengthwise plane				0,01
Ball bearing slewing ring head above undercarriage bottom edge	Z_{KD}		6.8	–0.02

3. Establishing key bucket-wheel excavator geometric parameters

Key bucket-wheel excavator geometric parameters were derived from the 3D vector model by means of the Microstation V8 software and with the help of auxiliary dimension-giving elements added to the vector model.

The abbreviation IRC is a marked sensor of the Incremental Rotary Encoder. Movement of the wheel boom causes movement of its joint (IRC) on the beam, which records the number of encoder pulses. The number of pulses can be subsequently translated along the length of the extended boom using an impulse conversion constant.

Geometric parameters were referred to by the following machine features (Sládková *et al.* 2011; Staňková, Černota 2010; Vrubel *et al.* 2007) (Fig. 6):

- GPS receiver locations;
- Bucket-wheel;
- Centre of the ball-bearing slewing ring;
- Bucket-wheel boom hoisting direction;
- Boom travel rails;
- IRC (incremental sensor positions);
- Undercarriage bottom edge.

GPS sensor vertical distance Z_{GPS} indicates excavator lengthwise tilt. What is needed is the GPS sensor vertical distance Z_{GPSo} relative to the excavator in absolutely horizontal position.

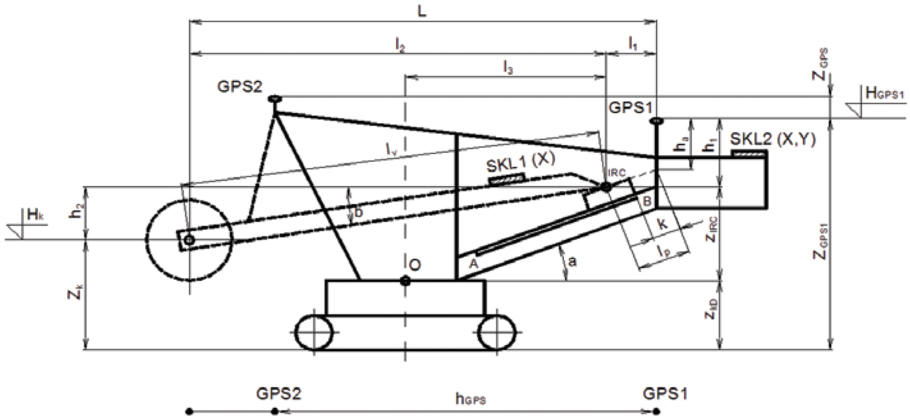

Fig. 6. Bucket-wheel excavator sketch

4. Data evaluation

A suitable mathematical model is required to calculate the 3D position of the centre of the bucket wheel from the data described in the previous section. The definition of the bucket-wheel position is based on GPS sensor data. The formula definitions are based on Figure 6 (Weiss, Gašinec 2005).

– The parameters to calculate include:
– Bucket-wheel geodesic head;
– Bucket wheel-to-machine axis horizontal distance;
– Bucket-wheel horizontal incline from vertical plane running through GPS1;
– 3D bucket wheel position.

All variables and some constant parameters will change with the slewing motion while excavator superstructure is off horizontal, i.e. almost every time. This is why the impact of excavator tilt on length projections in the horizontal and vertical planes must be accounted for. Let us now carry out a rough calculation of what the tilt impact on the lengths is. Different excavators feature different max values of lengthwise and crosswise working tilt determined by individual design. For max tilt values in selected excavators see Table 2.

Table 2. Geometric parameters

Type of Excavator	Lengthwise tilt	Cross tilt
K 10000	1:14.3 = 7%	
KU 800	7%	
K 2000	5.6%	
K 800 N	3%	
KU 300	14%	5%

The 3% tilt in case of K 800/N1/103 corresponds to an angle of 1.72°. The excavator superstructure design does not allow bigger tilts without compromising machine stability. Let us calculate the maximum inclinations for the superstructure axis and for its perpendicular plane for maximum allowable tilt:

a) Horizontal inclination:

Difference between maximum distance of bucket wheel from GPS1 sensor in horizontal plane and at maximum tilt of superstructure axis. The result is 0.025 m.

b) Vertical inclination:

GPS1 sensor shift from the horizontal plane at maximum tilt perpendicular to superstructure axis relative to the plane of travel. The result is 0.011 m.

The resulting differences are not very big, but the horizontal inclination will be taken account for in the following four scenarios of relative positions of the bucket-wheel boom and the excavator:

I. Bucket-wheel excavator in horizontal position.

II. Bucket-wheel excavator inclined with bucket wheel below horizontal plane intersecting IRC centre ($|\gamma| < |\beta|$).

III. a) Bucket wheel below horizontal plane (sign β = sign γ).

b) Bucket wheel above horizontal plane (sign β = –sign γ).

Regarding calculation formulas, the present article will only show formulas with input data and after derivation of formulas. The input data descriptions are based on Table 1.

4.1. Option I – Bucket wheel excavator in horizontal position (Fig. 6)

The following calculation is based on Figure 6 and Table 1.

γ – excavator tilt in horizontal plane.

$$\gamma = SKL2 = 0°.$$

β – SKL1 inclinometer angle reading; absolute value will be used:

$$\beta = \left|SKL1\right|.$$

α – bucket-wheel boom travel tilt angle.

$$\alpha = 19{,}151°.$$

l_1 – horizontal distance between GPS1 and bucket-wheel boom joint in deliberate position.

$$l_1 = l_p \cdot \cos\alpha.$$

l_p – distance between IRS centre with point of intersection on GPS1 vertical and between a parallel line to the beam running through IRC centre.

$$l_p = l_{p0} + IRC \cdot \frac{12{,}03}{40\,423}. \quad (1)$$

l_2 – horizontal distance between IRC and bucket-wheel axis.

$$l_2 = l_v \cdot \cos\beta,$$

L – bucket-wheel axis distance from GPS1,

$$L = l_1 + l_2,$$

$$L = l_p \cdot \cos\alpha + l_v \cdot \cos\beta. \quad (2)$$

Let us substitute l_1 *a* l_2 and make adjustments,

$$L = \left(l_{p0} + IRC \cdot \frac{12{,}03}{40\,423} \right) \cdot \cos\alpha + l_v \cdot \cos\beta. \quad (3)$$

The Z coordinate of bucket-wheel centre comes from:

$$ZK = Z1 - \left(h_1 + h_2 \right), \quad (4)$$

$$Z1 = Z_{GPS1}.$$

$$h_1 = h_a + l_p \cdot \sin\alpha, \quad (5)$$

$$h_1 = 1{,}804 + \left(7{,}575 + IRC \cdot \frac{12{,}03}{40\,423} \right) \cdot \sin\alpha,$$

$$h_2 = l_v \cdot \sin\beta. \quad (6)$$

By substituting we obtain a general formula for the Z coordinate of the bucket-wheel centre as follows:

ZK – geodesic head of bucket-wheel axis.

Z – coordinate of bucket-wheel centre.

$$ZK = Z1 - h_a - \left(l_{p0} + IRC \cdot \frac{12{,}03}{40\,423} \right) \cdot \sin\alpha - l_v \cdot \sin\beta. \quad (7)$$

4.2. Option II – Bucket–wheel excavator not in horizontal position with bucket wheel below horizontal plane intersecting IRC centre (|γ| < |β|) (Fig. 7)

Now the L value is required to calculate the X and Y coordinates.

L – bucket-wheel axis distance from GPS1,

$$L = l_p \cos\left(\alpha + \gamma\right) - h_a \sin\gamma + l_v \cos\beta. \quad (8)$$

$$ZK = Z1 - h_a \cos\gamma - l_p \sin\left(\alpha + \gamma\right) - l_v \sin\beta. \quad (9)$$

4.3. Option III Bucket-wheel excavator in inclined positions, III. a), III. b)

$$L = h_a \cdot \sin\gamma + l_p \cdot \cos\left(\alpha - \gamma\right) + l_v \cdot \cos\beta. \quad (10)$$

III. a) Bucket wheel below horizontal plane (sign β = sign *γ*) (Fig. 8.).

The Z coordinate calculation will be different for position 1 with the bucket wheel below the horizontal plane and sgn β= −sgn *γ*. Thus:

$$ZK = Z1 - h_1 - h_2. \quad (11)$$

$$ZK = Z1 - h_a \cdot \cos\gamma - \left(l_{p0} + IRC \cdot \frac{12{,}03}{40\,423} \right) \cdot$$

$$\sin\left(\alpha - \gamma\right) - l_v \cdot \sin\beta. \quad (12)$$

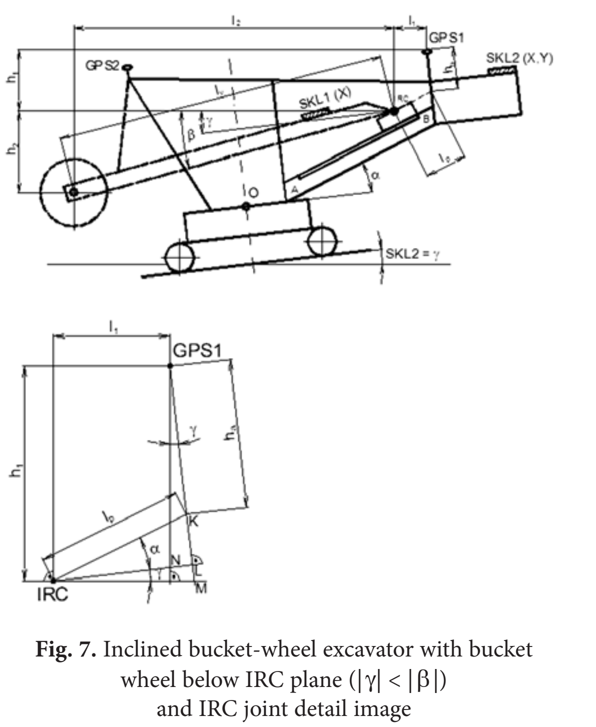

Fig. 7. Inclined bucket-wheel excavator with bucket wheel below IRC plane (|γ| < |β|) and IRC joint detail image

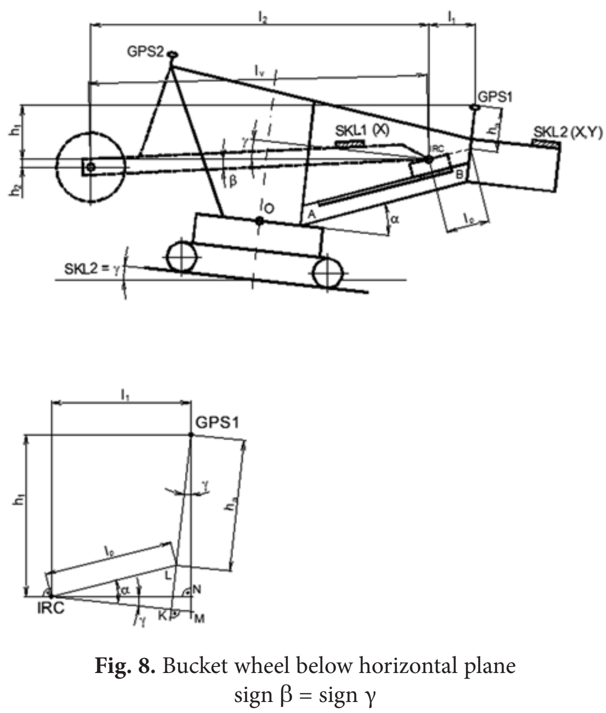

Fig. 8. Bucket wheel below horizontal plane sign β = sign γ

Bucket-wheel boom detail.

III. b) Bucket wheel above horizontal plane (sign β = –sign γ) (Fig. 9).

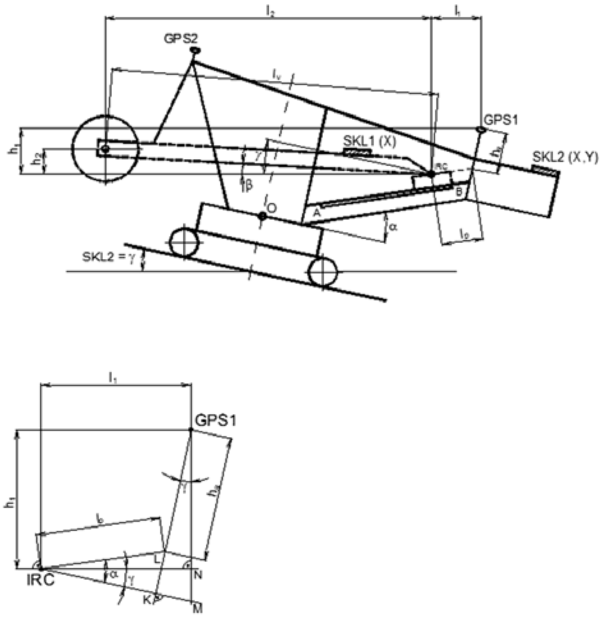

Fig. 9. Bucket wheel below horizontal plane sign β = sign γ

Bucket-wheel boom detail

In position 2, bucket wheel above horizontal plane and sgn β = –sgn γ, in absolute values |β| < |γ|, we get:

$$ZK = Z1 - h_1 + h_2 . \quad (13)$$

$$ZK = Z1 - h_a \cdot \cos\gamma - \left(l_{p0} + IRC \cdot \frac{12{,}03}{40\,423} \right) \cdot$$
$$\sin(\alpha - \gamma) + l_v \cdot \sin\beta . \quad (14)$$

4.4. Bucket-wheel centre *X* and *Y* coordinate calculation (Fig. 10)

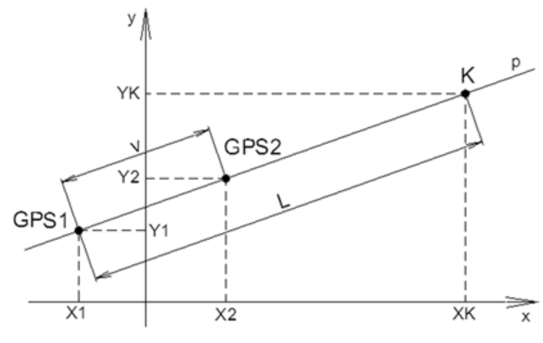

Fig. 10. GPS1, GPS2 and bucket-wheel K centre horizontal plan

The two sensors, GPS1 and GPS2, form a straight line represented by the following formula:

$$p : x = X1 + (X2 - X1) \cdot t,$$

$$y = Y1 + (Y2 - Y1) \cdot t,$$

GPS1: $t_1 = 0 : x = X1,\ y = Y1,$

for GPS2: $t_2 = 1 : x = X2,\ y = Y2,$

Distance GPS1 to GPS2:

$$v = |GPS1, GPS2| = \sqrt{(X2 - X1)^2 + (Y2 - Y1)^2} . \quad (15)$$

K is the bucket-wheel centre,

Bucket-wheel axis distance from GPS1:

$$L = |GPS1, K| . \quad (16)$$

Bucket-wheel centre parameter t_k comes from the following rule of proportion:

$$v \ldots t = t_2 - t_1 = 1,$$
$$L \ldots t_k = ?,$$

$$t_k = \frac{L}{v} . \quad (17)$$

Substituting the result in the p-line parametric formula, we get the *X* and *Y* coordinates of bucket-wheel centre *K* as follows:

$$XK = X1 + (X2 - X1) \cdot t_k . \quad (18)$$

$$YK = Y1 + (Y2 - Y1) \cdot t_k . \quad (19)$$

4.5. Proposed mathematical model

The mathematical model is based on geometric dimensions and on mathematical formulas shown in the preceding sections using the following input data:

– GPS1 receiver data;
– GPS2 receiver data;
– IRC incremental sensor data;
– SKL1 bucket-wheel boom mounted inclinometer;
– SKL2 support-frame mounted inclinometer;
– Excavator geometric data.

The output consists of the following bucket-wheel centre coordinates:

$$XK = X1 + (X2 - X1) \cdot t_k ,$$

$$YK = Y1 + (Y2 - Y1) \cdot t_k ,$$

$$ZK = Z1 - h_1 + h_2 .$$

5. Conclusions

A mathematical model describing bucket-wheel excavator movement in 3D space was built on the basis of 3D laser scanning and on additional data measurements. The mathematical model was processed by means of the MATLAB software. The exercise also aims at creating a useful technique for the surveying of bucket-wheel excavators. Such data will enable creating 3D visualisations of bucket-wheel excavator positions required to monitor the quality of extracted coal in real-time control of the excavation process.

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