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ACCURACY OF WORK TOOL POSITION MEASUREMENT BY MEANS OF A DRILLING MONITORING SYSTEM

The article presents examples of test results of an innovative, optical system of tool location identification in a workspace. This system was developed and produced as part of the research carried out in cooperation with KGHM Polska Miedź S.A. The article contains a general description of the system, basic components and the scientific basis underlying the development. The technical parameters of the system are also indicated as well as the ranges of required accuracy of the tool location determination, the achievement of which was a condition for the admission of the project to the implementation stage for operation. Based on the results of tests carried out both on the surface and in underground operation conditions, the project assumptions were confirmed and the system's accuracy ranges were determined. The very promising results obtained clearly indicate the validity of continuing work on the development of the tool location identification system in a wider range of machines.

1. INTRODUCTION

The commonly used system for identifying the position of the work tool in the machine workspace is based on the identification of angles and instantaneous displacements in the kinematic pairs of the positioning system and is fully suitable for use in machines with short and rigid kinematic systems, not operating in difficult environmental conditions. Systems of this type are successfully used in processing machines. The research on the development of systems based on the indicated configuration focuses mainly on the development of new control systems, error identification and work optimization [1-3, 4]. However, the applications of these position monitoring systems in other machines, for example, in work machines used in the mining industry have revealed some disadvantages of this type of solution. At the same time, in the mining industry, the research has been carried out on the implementation of monitoring systems for individual components, systems, as well as components and machines as a whole [5, 6]. These actions opened the possibility to undertake a study on a new type of tool position identification system that was supposed to be compact and resistant to external conditions. Owing to the cooperation

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undertaken by KGHM Polska Miedź S.A. and Wrocław University of Science and Technology, a research project was carried out, as a result of which a prototype of a new work tool position identification system was developed. The tests of the system were performed both on the surface and in the conditions of the underground mine. This article presents the results of these tests, with the focus on the obtained results of accuracy and repeatability of the measurements.

2. THEORETICAL ANALYSIS OF THE PROBLEM

In the industrial practice, in order to determine the position of the object at the end of the kinematic chain, the method of transforming the reference system based on indirect systems related to kinematic pairs is most commonly used (Fig. 1a). In practice, this means that it is necessary to determine the angles of rotation and momentary displacement in each kinematic pair of the chain, which involves the use of transducers in a number not less than the number of kinematic pairs in the system. This assumption holds for the description of the kinematics of industrial robots by means of the sequent transformations of the coordinate system [7, 8].

The application of the tool position identification systems, based on the principle described above, in heavy-duty machine boom systems is often associated with a significant reduction in the reliability. This is due to the necessity to install a large number of transducers on the work system, power and signal lines associated with them, and plastic deformation of the kinematic system elements. The above problems occurred and were identified directly during preliminary tests of the tool position identification system mounted on a self-propelled drilling vehicle operating in underground copper mines, which was the reason for undertaking work on a new alternative technical solution for the tool position identification system.

Work on the project began with an analysis of the theoretical possibilities for determining directly the location of objects in space on the basis of geometric axioms (Fig. 1b). It has been assumed that the function of the reference system will be served by the base point associated with the machine having uniquely oriented coordinate system. Determining the position of a solid element in space requires determining the position of three points which belong to it and are not located on the same straight line, in a manner analogous to determining the position of a plane in space (Fig. 2). This assumption leads to the conclusion that in order to determine the position of a rigid body in space, a plane should be connected rigidly with the solid body in defined geometrical relations. The determination of the position of the solid body is then possible by simultaneously identifying the position of the plane and the mutual position of the plane and the rigid body. In the general case, it is therefore necessary to specify nine parameters, three for each point, relative to the unambiguously defined base point, while also taking into account the location of each defined point with respect to other points. The mathematical description of the location identification process in accordance with these assumptions is based on the following transformations [9]:

- Determining the location and the binding of the coordinate system related to the machine (determining the base point 0 and the position of the coordinate axes X_B, Y_B, Z_B),
- Identification of the position of three points in space by means of the radius vector (r_i) and two angles of deflection–polar (α_i) and azimuthal (β_i),
- Transformation of point parameters from a spherical system to a Cartesian system according to mathematical relationships:

$$\begin{cases} x_i = r_i \cdot \sin\alpha_i \cdot \cos\beta_i \\ y_i = r_i \cdot \sin\alpha_i \cdot \sin\beta_i \\ z_i = r_i \cdot \cos\alpha_i \end{cases} \tag{1}$$

- Identification of the matrix of the plane defined by three points in space (P_1, P_2, P_3):

$$\begin{vmatrix} x & y & z & 1 \\ x_{P1} & y_{P1} & z_{P1} & 1 \\ x_{P2} & y_{P2} & z_{P2} & 1 \\ x_{P3} & y_{P3} & z_{P3} & 1 \end{vmatrix} = 0 \tag{2}$$

- Determination of the slope of a normal line in relation to the identified plane:

$$A = \begin{vmatrix} y_1 & z_1 & 1 \\ y_2 & z_2 & 1 \\ y_3 & z_3 & 1 \end{vmatrix} \quad B = \begin{vmatrix} z_1 & x_1 & 1 \\ z_2 & x_2 & 1 \\ z_3 & x_3 & 1 \end{vmatrix} \quad C = \begin{vmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{vmatrix} \tag{3}$$

- Determination of the inclination angle of the identified plane in relation to the planes normal to the Z_B axis (A_H, B_H, C_H) and the Y_B axis (A_V, B_V, C_V):

$$\varphi_H = \arccos\frac{A \cdot A_H + B \cdot B_H + C \cdot C_H}{\sqrt{A^2+B^2+C^2} \cdot \sqrt{{A_H}^2+{B_H}^2+{C_H}^2}} \tag{4}$$

$$\varphi_V = \arccos\frac{A \cdot A_V + B \cdot B_V + C \cdot C_V}{\sqrt{A^2 + B^2 + C^2} \cdot \sqrt{{A_V}^2 + {B_V}^2 + {C_V}^2}} \tag{5}$$

- Assuming that the directional coefficients A_H, B_H, A_V and C_V equal 0, and the coefficients C_H and B_V equal 1, the equations are simplified to the form:

$$\varphi_H = \arccos \frac{C}{\sqrt{A^2 + B^2 + C^2}} \tag{6}$$

$$\varphi_V = \arccos \frac{B}{\sqrt{A^2 + B^2 + C^2}} \tag{7}$$

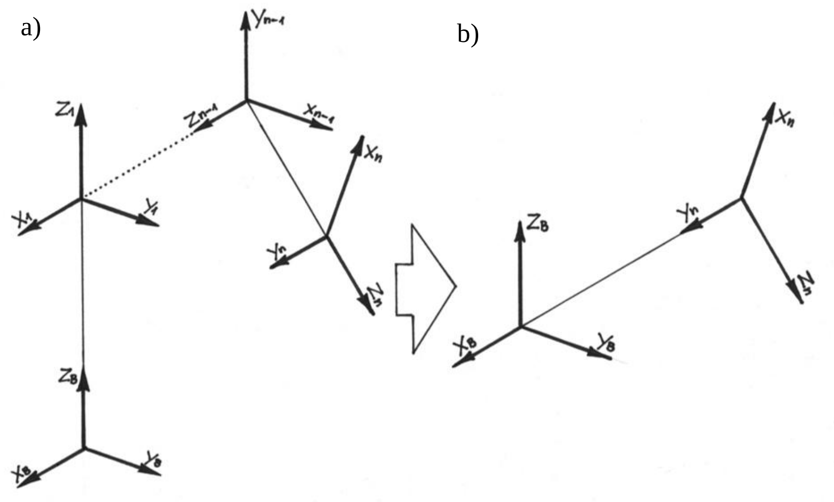

Fig. 1. Transformation of the reference system in order to determine the position of the coordinate system associated with the tool (n) relative to the basic coordinate system (*B*): a) – method based on subsequent transformations, b) – direct method

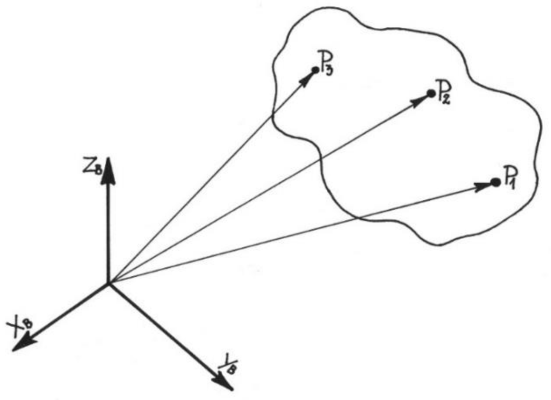

Fig. 2. Determination of the location of the rigid body in space based on the identification of the position of three unambiguously determined points not lying on the same straight line

The unambiguous description of the theoretical assumptions behind the researched solution made it possible to move to the system design stage. At this stage of the work, the margin of measurement errors was not determined. However, it was assumed that the system should ensure displacement measurements with accuracy at the level of at least ±5 cm and angle measurement with accuracy at the level ±1° when installed on the boom work system of a drilling rig.

3. PROTOTYPE VERSION OF THE SYSTEM

Based on the theoretical foundations specified in the previous chapter, a research on a prototype version of the monitoring system was started (Fig. 3, Fig. 5) [10, 11]. As the first task, a light beam emitting unit was developed and assembled. The beam emitter was a laser beam generator, which had a wavelength λ = 650 nm, a clearly visible spot and was a part of an industrial laser rangefinder equipped with a signal output compatible with the CAN data transmission protocol. The light beam emitting unit was mounted on a support unit which allowed changing the incidence angles of the laser beam in two perpendicular planes (Fig. 7).

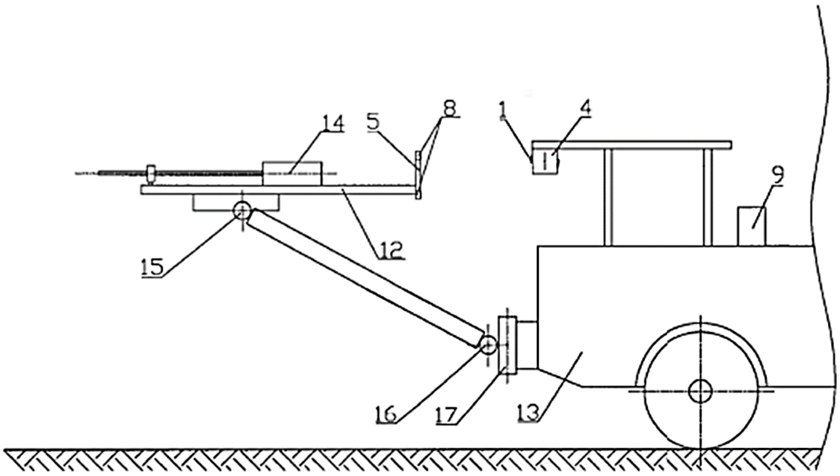

Fig. 3. A selected version of the drilling monitoring system in the mine face (drawing from the patent application, selected descriptions) [12]: 1 - laser beam emission unit, 4 - support assembly, 5 - photodetector unit, 8 - photodetector matrices, 9 - control and recording device, 12 – drilling rig frame, 13 - drilling rig, 14 - drill

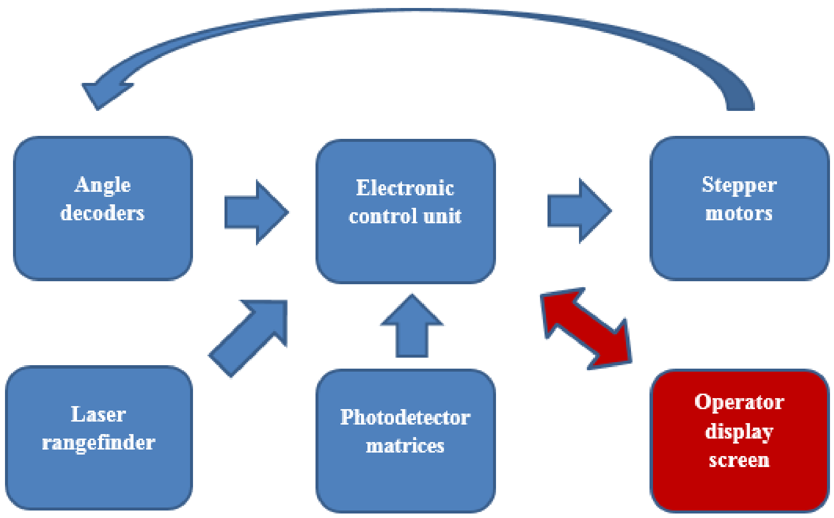

Fig. 4. Elements of the control and automatic regulation system along with the directions of signal transmission of the position identification system

Changing the angle of laser beam incidence is the result of coupling the axis of rotation with the combined drive and recording system, which consists of two stepper motors and two angle transducers (Fig. 4). As a result, the direction of the laser beam is explicitly defined and controlled. The use of a laser rangefinder ensures simultaneous execution of continuous laser beam length measurements. A dedicated mechanical element was designed and mounted on the frame of the drill in order to enable rigid attachment of photodiode matrices acting as photodetector surfaces activated by the laser beam. The central photodiode was indicated in the software as the central area of the photodetector surface, and lighting it by the laser beam corresponded to the indication of the base point of the coordinate system of the photodetector surface. It has been assumed that the number of photodiode matrices cannot be less than three in order to ensure that the position of the object in space is fully identified. However, to improve the accuracy of the measurement, their number had to be increased to four in order to increase operating area of the system in the side directions (Fig. 6).

Fig. 5. The face drilling monitoring system installed on the drilling rig, shown during surface tests:
1 - laser beam emitting unit, 2 - photodetector matrices unit, 3 - control system with display

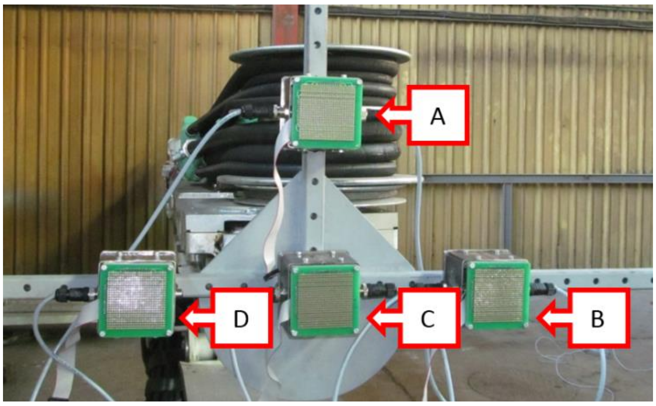

Fig. 6. Photodetector unit mounted on the frame of the drill, visible four photodetector matrices (A, B, C, D), and mounting holes enabling the change of the relative position of the matrices

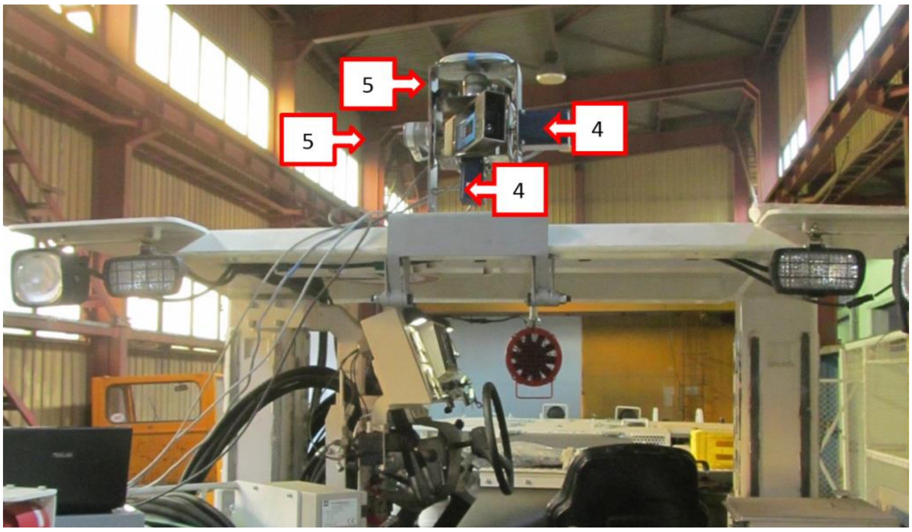

Fig. 7. Laser beam emitting unit mounted on the roof of the operator's cabin: 4- stepper motors, 5 - angle encoders

The control system performed three independent work algorithms. The first of them was responsible for identifying the location of the detectors' matrices after the system was started. The second control algorithm was responsible for performing the process of tracking the central photodiode of the central matrix during the movement of the work system (Fig. 8). This effect was achieved by identifying the activated diode of the real-time tracked matrix and based on the known location of the diode on the matrix, determining the direction of angle changes of laser beam. The system operating in this mode enabled real-time measurements of the displacement of the central matrix. The third control algorithm was manually triggered by the operator when the work tool system of the machine was stopped. The algorithm implemented an automatic procedure for measuring the angular position of the matrix system by identifying the position of the central photodiode of the three selected matrices, depending on the momentary position of the central matrix.

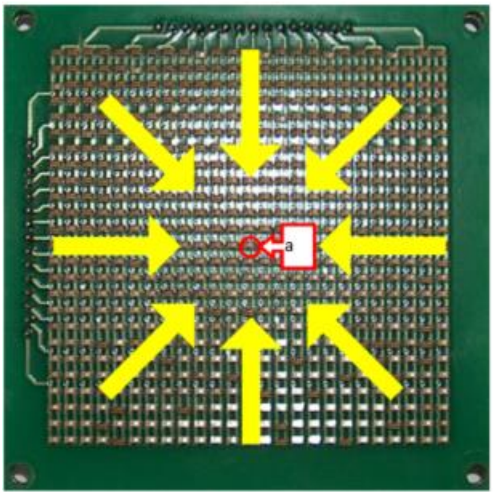

Fig. 8. Sample photodiode matrix with marked diode which was selected in the control logic as central (a), including marked directions of laser ray movement depending on place of its incidence

The results of the measurements were displayed in real time on the screen placed in the operator's cabin. On the basis of the measured and displayed quantities, the operator could control displacement of the drilling rig work tool according to the drilling plan and was able to make possible corrections of the position of the drill frame during its setting before making the hole.

4. TESTS OF THE SYSTEM

The purpose of the tests was to preliminarily determine the accuracy of the measurements of the object location in space made with the help of the monitoring system and to determine the possibility of its use in the working conditions prevailing in the mine face. The absolute error of the displacement measurement results was a function of the following variables and parameters:

$$\Delta i = F(P_d, D_l, A_d, R_l, \Delta R_l, \Delta\alpha_i, \Delta\beta_i) \tag{8}$$

P_d - size of the active area of the tracked photodiode,
D_l - diameter of the laser beam,
A_d - the percentage of the photodiode active area, whose illumination with the laser beam causes its activation (the size depends on the incidence angle of the beam),
R_l - laser beam length,
ΔR_l - absolute error of the laser beam length measurement,
$\Delta\alpha_i$ and $\Delta\beta_i$ - absolute error of measurement of laser beam deflection angles.

In the case of measuring three points which enable the determination of the angular position in the space, measurement errors proved to influence positioning accuracy depending on the parameter of the actual distance between the defining points (Δd). Due to the complexity of the mathematical description of errors, empirical determination of their values was made. For this purpose, the repeatability of the measurement results was checked and verified against the values determined by means of measuring instruments. The test series were carried out in a wide range of variable parameters, and the exemplary series of results are presented in this article. During the tests, the accuracy of displacement measurement was determined first. The verification was carried out by specifying the actual change in the height of the central point of the central matrix during the lifting of the work system.

The next stage of the tests was performed in order to find the dependence between the accuracy of angle measurements, which determine the angular position of the object, and the spacing of the photodiode matrices. The measurements were performed in the horizontal and vertical planes associated with the coordinate system of the laser beam emitting unit, which were identical to the planes containing the longitudinal and transverse axis of the drilling rig. The series of tests covered frame angle measurements in the vertical plane containing the longitudinal axis of the machine. The standard deviation of a series of five repetitive measurements of the swing angle was determined. Figure 9 shows an example of the dependence of standard deviations of a series of results as a function of the spacing of matrices.

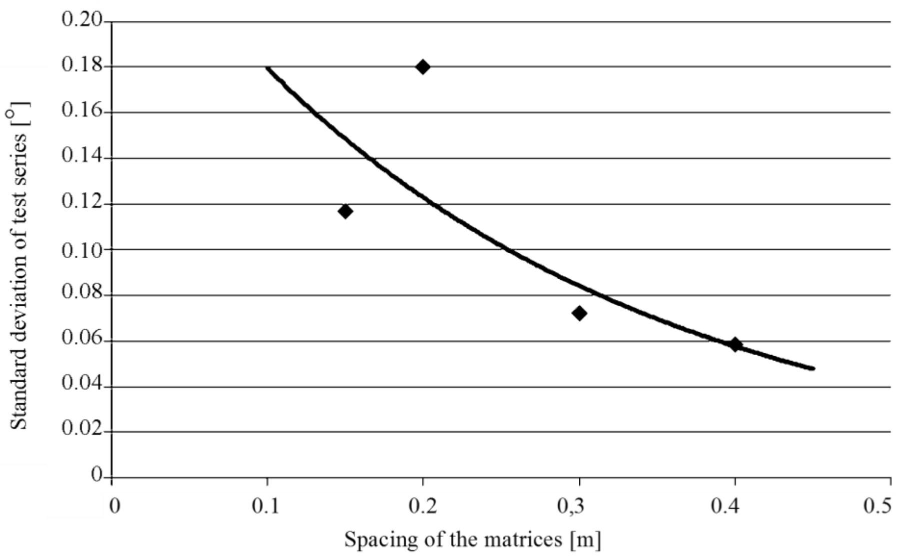

Fig. 9. Standard deviations of the measurement series of a drill frame swing angle in the horizontal plane as a function of the matrices spacing

Table 1. Selected results of drilling rig frame swing angle measurements in the horizontal plane

Spacing of the matrices [m]	0.2				
Test number	1	2	3	4	5
Angular position acc. to the monitoring system [°]	31.18	31.18	31.04	31.53	31.3
Average value of the angle acc. to the monitoring system [°]	31.222				
Standard deviation of the normal distribution [°]	0.18				

The obtained results fully met the expectations regarding the system measurement accuracy and enabled the construction of the second, industrial version of the system. Based on this version, the next series of the measurement accuracy tests were carried out, extended with full range tests measuring the repeatability of the obtained results. The selected results of these tests are presented in Tables 1, 2 and 3. The standard deviation values of the test results presented in the tables were rounded to the second significant digit.

The analysis of the measured values obtained during the tests (Table 2) revealed a high repeatability of the obtained results. The level of standard deviation for radius length measurements during the entire experiment, with different positions of the working system taken into consideration, did not exceed 1 mm. It was additionally found that during the measurement series, the recorded values of beam radius angles were not characterised by normal variables. The value of the angle β tended to change in time in one direction, which could be the result of a slight and imperceptible lowering of the work system under its own weight. Due to the above, the obtained results may be underestimated in relation to the accuracy and repeatability of measurements obtained by the system (Table 3).

The performed tests clearly indicate that the system has the ability to determine the location with an accuracy of less than 10 mm and an angular position with an accuracy of less than 1 degree in the whole working area of the work system when drilling in the mine face. Moreover, the results of the actual tests showed that the stability and measurement repeatability greatly exceed the requirements. The obtained results indicate the possibility for a wider use of the developed system in applications requiring direct identification of the location of objects in relation to each other.

Table 2. Selected test results of repeatability of the location identification of one central point of matrix No. 2 with a supported work system

Test number	R_B [mm]	α_B [°]	β_B [°]
1	3172.9	-4.21	-0.15
2	3172.9	-4.23	-0.16
3	3172.8	-4.21	-0.16
4	3172.9	-4.21	-0.19
5	3173.0	-4.21	-0.19
6	3173.0	-4.19	-0.21
7	3172.7	-4.19	-0.22
8	3172.6	-4.19	-0.23
9	3172.5	-4.23	-0.25
10	3172.2	-4.18	-0.24
Average measured value	3172.75	-4.205	-0.20
Standard deviation	0.26	0.02	0.04

Table 3. Selected results of location identification repeatability measurements of the center points of the three matrices with a stopped work tool system

Matrix number	A	B	C
Number of tests	10		
Average radius value [mm]	3173.1	3172.75	3164.29
Standard deviation [mm]	0.34	0.26	0.21
Average angle value α_i [°]	-0.023	-4.205	0.08
Standard deviation [°]	0.01	0.02	0.04
Average angle value β_i [°]	4.307	-0.2	-0.108
Standard deviation [°]	0.04	0.04	0.04

5. SUMMARY

The tests of the drilling monitoring system, which is the outcome of the described research and development works, have shown that the achieved accuracy of the position measurement has met the requirements with some surplus. Additionally, the tests of the system have demonstrated that the new technical solution has a high level of accuracy and measurement repeatability. These conclusions indicate the validity of continuing the development work in the area of full identification of object location in space based on the use of a laser beam. The physical features of the system – such as a small number of elements, the ability to be used as an auxiliary system without interfering with existing machine systems, insensitivity to the deformation of the work system and resistance to the impact of the external environment – combined with the obtained results allow the new solution to be applied in a significantly extended range of applications. The presented position identification system can be used in a whole range of work machines, in selected specialized production machines as well as in other branches of technology.

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