Determining the position of pick holders on the side surface of the working unit of the cutting machine in the robotic technology of their assembly

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Determining the position of pick holders on the side surface of the working unit of the cutting machine in the robotic technology of their assembly

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Abstract. One of the important issues related to the robotization of the manufacturing process of cutting machine working units is to determine the degree of movement of pick holders positioned by the industrial robot to the side surface of the cutting drum/head. This article examines the possibility of using vision system for the purpose of measuring the distance between the pick holder base and the side surface of the working unit of the cutting machine. Based on the boom-type roadheader cutting head, a mathematical measurement model has been formulated and a measurement procedure algorithm has been developed. Tests of the proposed measurement method with the use of a single camera were carried out at a test station. The station is equipped with the KUKA KR 16-2 industrial robot working together with the VisionTech vision system. This work contains examples of measurement results for three pick holders positioned differently in relation to the side surface of the cutting head. Based on distance measurement between the respective elements with the use of the 2D vision system along one line of known direction and position, a prediction of the distance distribution along the whole surface of the pick holder base has been made.

1. Introduction

Rock mining in mineral resource mining industry, apart from economically unjustified cases, is carried out mechanically. Usually in hard coal mines, longwall shearers are used for deposit mining and roadheaders are used for making underground roadways. These machines are equipped with working units, on which the picks are mounted in their holders. These picks cut the rock. The number and arrangement of picks differ depending on the mechanical properties of the processed rock.

The efficiency of the process depends primarily on the stereometry of the cutting drum/head – their dimensions, number of picks and their arrangement and positioning [1]. To provide optimal mining conditions, cutting drums/heads are designed in such a way, as to take into account conditions in which longwall shearers or roadheaders will operate. The process of designing the arrangement of picks is computer-aided by means of dedicated tools. Based on input data, these tools allow for quick generation of picks layouts located on the side surface of the cutting drum/head, and for the numerical analysis of the mining process for the technical solution being designed [2, 3]. The stereometry optimization for this type of working units, as well as the simulation of the operation process is carried out with the use of different numbering methods [4 – 8]. However, even the most optimal arrangement of picks will not allow for achieving expected results if it is not faithfully reproduced at the manufacturing stage [9]. Thus, the process of pick holders positioning on the side surface of the cutting drum/head is aimed at

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robotization. Robotization will ensure high accuracy and repeatability of the process of pick holders positioning according to the project design [10].

An important issue in terms of robotization of the pick holders positioning process on the cutting drum/head of the roadheader is to identify the position of the pick holder base in relation to this side surface. As regards to the possibility of welding pick holders to the side surface of the cutting drum/head, it is essential to determine the distance of surfaces of elements being joined [11]. This applies particularly to cutting heads of roadheaders, in case of which the flat surface of the pick holder base must be joined with the side surface of the solid of revolution (body of the cutting head) with large curvature. Due to spatial position of pick holders, very rarely the pick holder base is tangential to the side surface of the cutting head. Measuring the distance of the aforementioned surfaces for a set position and positioning of a particular pick holder is the basis for assessing the possibility of making a positional weld. In case of lack of conditions for making the welded connection mentioned above, the data obtained from this type of measurement can be used as the basis for automatic correction of the pick holder position by the positioning robot [12].

The measurement of the position of pick holders on the side surface of the cutting drum/head has also another aspect. In this way, it is possible to protect the robotized station against emergency states caused by a collision of the positioned pick holder with the side surface of the cutting machine working unit. The problem of collisions is analyzed at the stage of preparing the technology of mounting pick holders (developing the control program for the robot). However, there is a risk of collision if the actual shape of the side surface of the cutting machine working unit deviates from the nominal shape. This can be the case when these elements are regenerated during an overhaul process.

2. Method of identifying the position of the pick holder on the side surface of the working unit of the cutting machine

The spatial position of the pick holders of the cutting machine results from the values of geometrical parameters which describe the arrangement and positioning of the system: pick – pick holder. For each pick holder, the values of six parameters are determined at the design stage, according to the applied method of dimensioning. The arrangement in the pick holder space results from the position of the tip of the associated pick. It is unambiguously defined in the cylindrical reference system by coordinates r, z, θ (figure 1a). The spatial orientation of the pick holders is determined by three angles in the local Cartesian reference system: ε, δ, Θ (figure 1b). There are several ways to define the position of the pick holders in space, which are equivalent to each other and it is possible to switch from one writing convention to another [13].

For the set values of stereometry parameters, the pick holder occupies a specific position in relation to the side surface of the working unit of the cutting machine. Due to the shape of pick holders used in such machines, the identification of the position of the pick holder on the side surface of the working unit of the cutting machine is reduced to determining the position of the flat surface of their base in relation to the surface of the side surface of the working unit at the place of its assembly. In order to measure the distance of the above mentioned surfaces, a vision method based on the use of the KUKA VisionTech system was applied [14]. Further consideration will relate to the cutting head of the boom-type roadheader, on which the developed measurement method has been tested. However, the presented method of measurement can be applied in the case of working units of other cutting machines, e.g., cutting drums of longwall shearers or milling drums.

Since the vision system uses information about the position and orientation of the robot tool, it is necessary to switch from the associated coordinate system ($X_TY_TZ_T$) to the coordinate system associated with the base of the pick holder ($X_PY_PZ_P$) (figure 2) [15]. The transformation matrix of the $X_TY_TZ_T$ gripper coordinate system to the $X_PY_PZ_P$ pick holder base coordinate system has the following form:

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$$A = Trans(l_u - \Delta X_N, 0, 0) \cdot Trans(0, -l_T, 0) \cdot Rot(Z, -\alpha_u) \cdot Trans\left(0, -\frac{b}{2}, 0\right) \cdot Rot\left(Y, \frac{\pi}{2}\right) \cdot Rot\left(Z, \frac{\pi}{2}\right) \quad (1)$$

where:

b – length of the longer side of the pick holder base,
l_T – height of the pick holder measured on its rear surface,
l_U – length of the pick holder,
ΔX_N – distance between the face surface of the pick holder and the TCP point of the robot tool, measured along the axis of the slot in the pick holder,
α_U – the angle of inclination of the socket axis in the pick holder in relation to its base,
Trans(), *Rot()* – respectively: a homogeneous translation and rotation matrix.

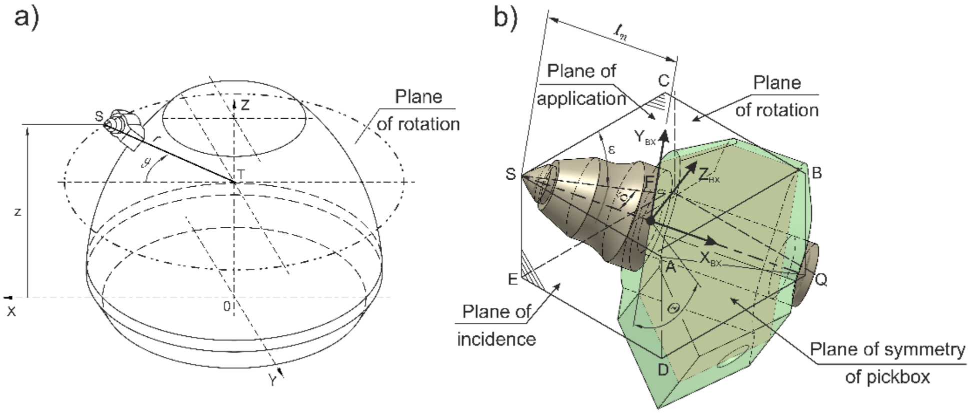

Figure 1. Parameters describing the spatial arrangement and positioning of pick holders in space [10].

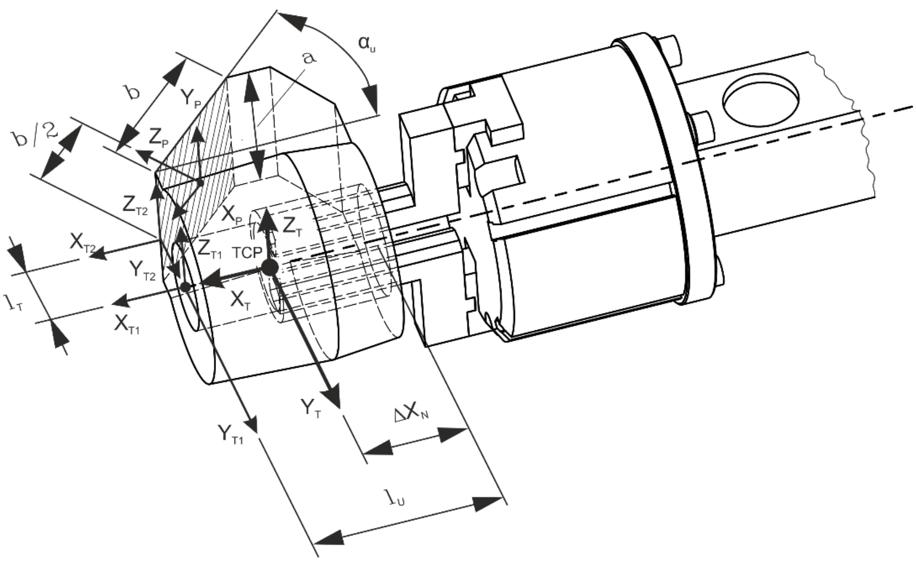

Figure 2. Transformation of the coordinate system of the tool (gripper) into a coordinate system related to the pick holder base.

In the measurement method under consideration, the shortest distance between the plane of the pick holder base and the surface of the side surface of the cutting head in the environment in which the particular pick holder is to be located, is sought for. In order to measure the desired distance it is necessary to take measurement photos from two different photo stations (two camera positions).

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Measuring the distance between the base of the pick holder and the side surface of the cutting head from one camera position is not possible due to the complicated shape of the cutting head. Moreover, you can only determine the distance between elements in two dimensions based on a photo taken from one camera setting. To get information about the distance in space, you need at least one more photo taken with a different camera setting (position) [16].

Four positions of the camera in relation to the center of the rectangle representing the base of the pick holder have been considered (the hatched area in figure 2). These positions are marked in figure 3 with letters A, B, C and D. Photo stations are located at the same distance from the base of the pick holder – on one side and on the other. The Cartesian coordinate system of the camera is oriented in such a way that the X_K axis coincides with the optical axis of the camera, while the Y_K and Z_K axes form a plane parallel to the background plane (light-sensitive matrix of the camera). The starting point of the coordinate system is related to the camera optics.

Based on the conducted analyses, it was found that during the measurement the camera should be positioned in a specific way in relation to, simultaneously, the pick holder and the side surface of the cutting head. For one of the two camera settings (figure 4 – position B or D) there should be visible elements between which the distance is measured. The optical axis of the camera should be contained in the plane of the pick holder base and pass through its center. At the same time, this axis should be contained in the plane passing through the side surface center of rotation of the cutting head and the center point of the pick holder base for which the measurement is made (figure 4 – Plane 1). For the second camera setting (figure 4 – position A or C), its optical axis is contained in the plane of the pick holder base and passes through its center. Additionally, this axis is contained in a plane perpendicular to the axis of rotation of the side surface of the cutting head (figure 4 – Plane 3).

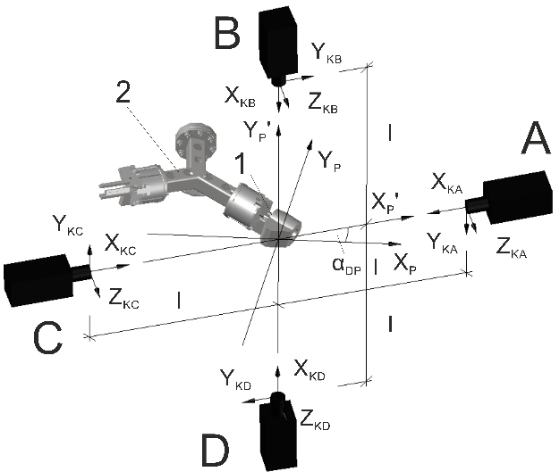

Figure 3. Considered positions of the camera in relation to the pick holder base during the acquisition of measurement photos.

The position of the camera at individual photo stations in the coordinate system related to the base of a particular pick holder ($X_PY_PZ_P$) is described by the transformation matrices:

$$\begin{cases} B_1 = Rot(Z,\alpha_{DP}) \cdot Rot(Z,\pi) \cdot Trans(-l_K,0,0) & (2) \\ B_2 = Rot(Z,\alpha_{DP}) \cdot Rot\left(Z,\frac{\pi}{2}\right) \cdot Trans(-l_K,0,0) & (3) \\ B_3 = Rot(Z,\alpha_{DP}) \cdot Trans(-l_K,0,0) & (4) \\ B_4 = Rot(Z,\alpha_{DP}) \cdot Rot\left(Z,\frac{3\pi}{2}\right) \cdot Trans(-l_K,0,0) & (5) \end{cases}$$

where:

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l_K – distance between the beginning of the pick holder base coordinate system ($X_PY_PZ_P$) and the beginning of the camera coordinate system ($X_KY_KZ_K$),

α_{DP} – angle between the X_P axis of the coordinate system related to the base of a particular pick holder and the straight which is a common part of the plane of the pick holder base (figure 4 – Plane 2) and a plane perpendicular to the axis of rotation of the side surface of the cutting head (figure 4 – Plane 3).

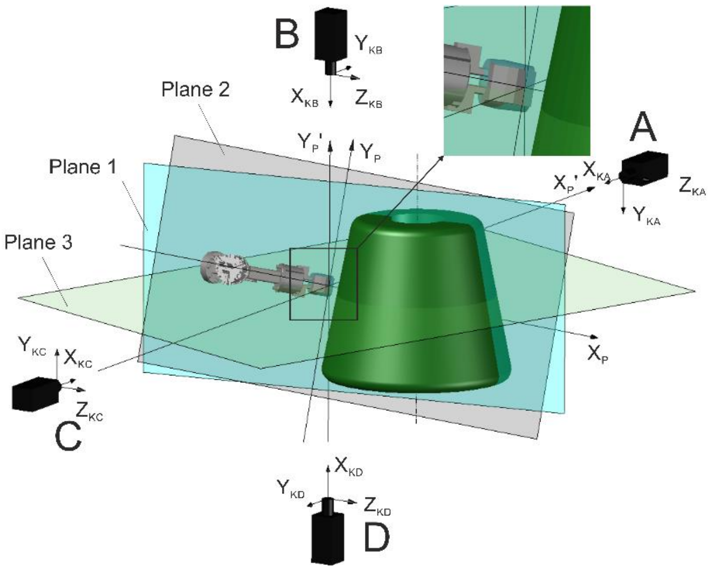

Figure 4. Spatial orientation of the camera in relation to the pick holder and the side surface of the cutting head during the acquisition of measurement photos.

The VisionTech vision process programming tool allows you to determine the distance between any points visible in the camera image. In the measurement task under consideration, it amounts to determining the distance between the points of the line segment representing the pick holder base and the points of the side surface edge of the cutting head, visible in the photo. This measurement is made along a line perpendicular to the pick holder base (figure 5). The line does not have to intersect the pick holder base at the right angle, but it should coincide with the direction of movement of the pick holder to the side surface of the cutting head (the direction of gripper advance). During data processing, first, the pick holder is located in the photo. Then, for a particular pick holder, depending on whether the photo was taken from the camera position: (A or C) or (B or D), a line representing the outline of the cutting head is searched for (figure 6).

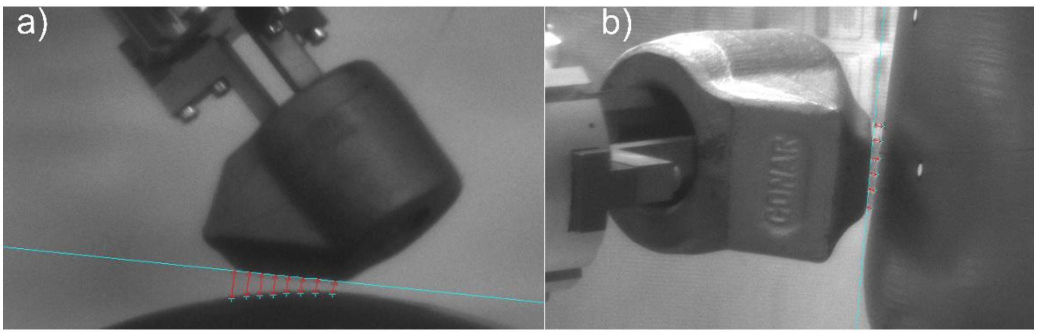

Figure 5. Determined distances between the pick holder base and the side surface of the cutting head on the basis of a photo taken by the camera from: a) position B; b) position C.

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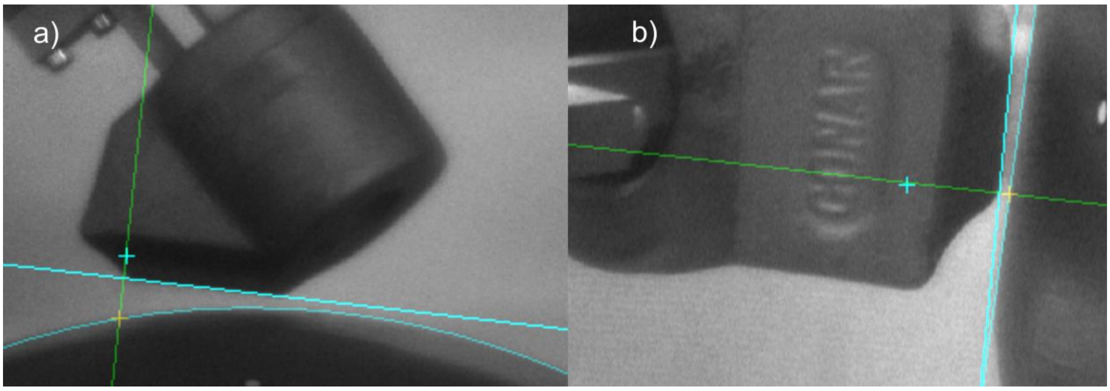

Figure 6. The way of finding the pick holder and the side surface of the cutting head in the photo taken from: a) position B; b) position C.

The shortest distance between the outline of the pick holder and the outline of the side surface of the cutting head is determined based on the photo from position B or D (figure 7a). However, the outline of the pick holder in the image may overlap the contour of the side surface of the cutting head. Then, the largest distance between the edge of the pick holder base and the outline of the cutting head is searched for (figure 7b). However, the point of the pick holder base, for which this distance has been determined, must be located within the outline of the base. This is a necessary condition for measuring the distance between the pick holder base and the side surface of the cutting head based on the image captured from position A or C (figure 7c). The shortest distance between the pick holder base on the side surface of the cutting head can be determined based on the photo from this camera position.

As a result of the analysis of the obtained digital images from the camera position A or C, we obtain the distribution of distances of the considered elements along the Y_P' of the coordinate system related to the pick holder base (figure 8). On the other hand, based on the image from the camera position B or D, we obtain information about the position of the straight ***p***, along which the distance between the pick holder base and the side surface of the cutting head is the shortest. The straight ***p*** is parallel to the Y_P' axis and is described by equation (6):

$$p = \begin{bmatrix} k_X \cdot x_p \cos\alpha_{DP} - k_X \cdot t \sin\alpha_{DP} \\ x_p \sin\alpha_{DP} + t\cos\alpha_{DP} \\ 0 \\ 1 \end{bmatrix} \quad (6)$$

where:

α_U – angle between the longer side of the pick holder base and the diagonal of this base:

$$\alpha_u = arctg\left(\frac{\overline{P_{P1}P_{P2}}}{\overline{P_{P1}P_{P4}}}\right) = arctg\left(\frac{a}{b}\right) \quad (7)$$

c – length of the diagonal of the pick holder base:

$$c = \sqrt{a^2 + b^2} \quad (8)$$

a – length of the shorter side of the pick holder base (see figure 2),
b – length of the longer side of the pick holder base,
k_X – length change coefficient of the longer side of the pick holder base:

$$k_X = \frac{c}{b} \cdot \sin\left(\alpha_{dp} + \alpha_u\right) \quad (9)$$

t – parameter: $t \in (-\infty, +\infty)$.

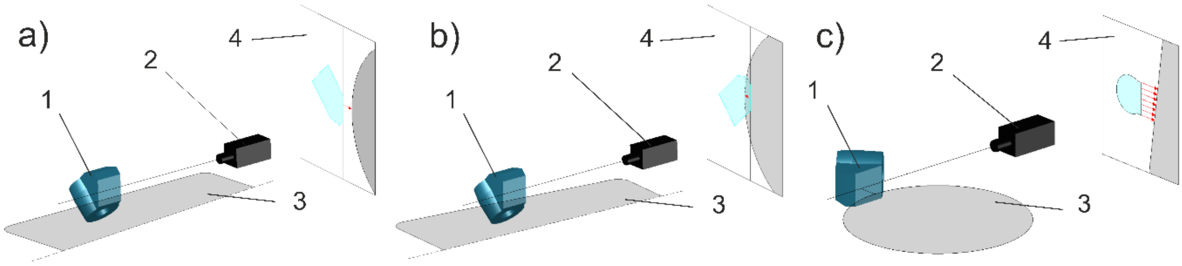

Figure 7. Identification of the distance between the pick holder base and the side surface of the cutting head based on photos from: a) and b) position B, c) position A: 1 – pick holder, 2 – camera, 3 – cross-section of te cutting head, 4 – acquisitioned photo.

The distance distribution of the considered elements along the straight ***p*** is limited to the line segment $\overline{P_1P_2}$. Meanwhile, the distribution obtained on the basis of the photo may include a longer line segment (in figure 8 this is the section $\overline{P_3P_4}$). This is due to the fact that the coordinate system related to the pick holder base ($X_PY_PZ_P$) is rotated with respect to the $X_P'Y_P'Z_P'$ coordinate system by an angle of α_{DP}. As a result, the line segment length $\overline{P_3P_4}$ is equal to the length of the diagonal projection of the pick holder base (line segment $\overline{P_{P1}P_{P3}}$) on the Y_P' axis.

As a result of rotation of the $X_PY_PZ_P$ coordinate system, the $X_P'Y_P'Z_P'$ coordinate system is obtained. Line segments which are found in images and represent the contour of the pick holder base, change their length. This change is described by the k_X coefficient (scaling coefficient) in the direction of the X_P' axis. The coefficient describes the length ratio of the longer side of the base to the length of the line segment captured in the image processed by the vision system. When the α_{DP} angle is known, it is possible to calculate the length of this line segment.

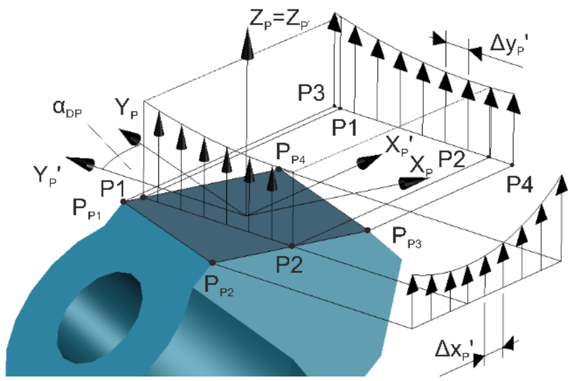

Figure 8. Graphic interpretation of the model for measuring the distance between the pick holder base and the side surface of the cutting head.

Depending on the distance between the straight ***p*** and the camera, the measurement results obtained from the analysis of the photo from the position A or C will be different. The distance at which the camera was calibrated corresponds to the distance between the center of the pick holder base (point O in figure 9) and the camera. If the straight ***p*** does not pass through the point O, the actual distance between the measured elements along the straight ***p*** is calculated using the intercept theorem (figure 9):

$$W = \frac{l \cdot W_O}{l + x_{P'}} \tag{10}$$

where:

l – distance between the camera and the center of the pick holder base,

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x_P' – distance of the straight ***p*** from the center of the pick holder base,
W_O – measurement result obtained based on a photo from the camera position A or C,
W – the actual distance between the pick holder base and the side surface of the cutting head.

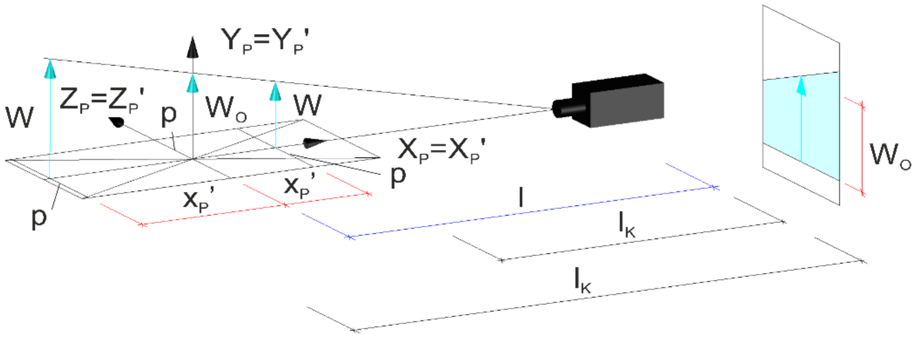

Figure 9. Determining the actual distance between the pick holder and the side surface of the cutting head depending on the position of the straight **p.**

The algorithm of the measurement procedure using the presented method consists of nine stages (figure 10). The camera position is determined based on information obtained from the robot's control system on the position and orientation of the holder in space. The camera is then moved to position A or C, then to position B or D and it captures the measurement photos. The position of the camera (A or C) and (B or D) results from the visibility, at its given position, of the contact area of the pick holder base with the side surface of the cutting head. After the acquisition of measurement photos, they are analyzed. First of all, it applies to a photo taken from the camera position B or D. If the desired distance between the pick holder and the side surface of the cutting head is between these elements, then the equation of the straight **p** is determined. Then, the analysis of the second measurement photo (from the camera position A or C) is performed. If the straight **p** passes through the center of the pick holder base, the measurement result is obtained directly. If the straight does not pass through the point O, the actual distances between the pick holder base and the side surface of the cutting head along this straight are determined.

3. Test station

Tests of the developed measurement method were carried out at the Robotics Laboratory of the Faculty of Mining and Geology at the Silesian University of Technology (figure 11a). In this study, the MXG 20 digital camera was used. It is dedicated to vision systems operating with KUKA robots. The camera was connected to the control system of the KUKA KR 16-2 pick holders positioning robot (figure 11a – item 1) through a switch (figure 11b) installed in the robot's control cabinet. The robot is mounted on the KL 250-3 linear unit (2). The side surface of the cutting head (4) is attached to the PEV-1-2500 positioner disc (3) so that it can be rotated around the vertical axis to the desired position. The KR 16-2 robot is equipped with a pneumatic gripper (5) used to position picks taken from the storage in a preset position within the side surface of the cutting head (4).

In the first stage, the research was carried out with the use of a stationary camera mounted on a tripod (figure 12a and b). In the second stage, the vision system camera was mounted on the gripper (5) of the pick holders positioning robot, by means of a special bracket (figure 12c). The construction of this bracket allows you to change the position of the camera in relation to the photographed object. This allows you to acquire measurement photos from two different photo stations.

4. Sample measurement results

Using the vision system and the developed method, the position of three selected pick holders in relation to the side surface of the cutting head was measured. Each holder has a different position and orientation (table 1). The distances of the pick holder base from the side surface of the cutting head were determined based on information about the position of the TCP point of the positioning robot tool and the orientation of the $X_TY_TZ_T$ coordinate system related to it, the analysis of the photos and numerical calculations. Figure 13 shows distributions of these distances. These distances are the same as the z_p coordinate of side surface points of the cutting head corresponding to the points of the pick holder base with set coordinates (x_P, y_P) in the $X_PY_PZ_P$ reference system.

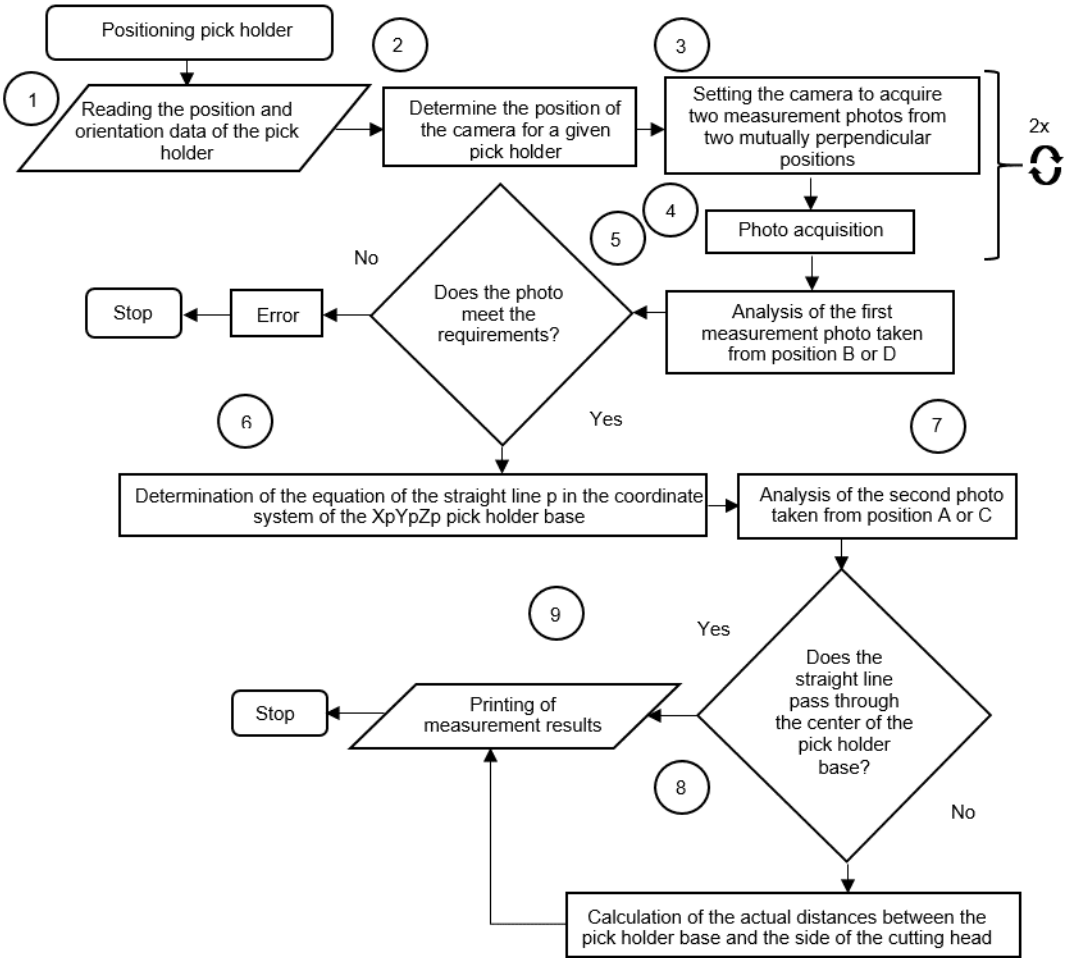

Figure 10. Algorithm of the measurement procedure.

Since in the measurement results we obtain only the shortest distances between the considered elements (in the cross-sectional plane marked with a pink line), the distance prediction at other points of the pick holder base was carried out. It was based on the analytical determination of the distance between the pick holder base plane and the side surface of the cutting head. It was assumed that the side surface has a nominal shape created as a result of a rotation of a generator with a known equation around its axis of rotation (Z axis – figure 1a).

In case of holder no. 1 (figure 13a), the distance between the pick holder base and the side surface of the cutting head ranges from 8 mm to 43 mm. Due to the position of the pick holder (on the part of the head from the gearbox side) the distance measured at points located on one of its diagonals changes in a small degree (it is about 20 mm). In case of points located on the other diagonal, this distance takes values from the above mentioned range. The pick holder is closest to the side surface in the corner of its base from the face surface side (at point P_{P4} – see figure 8). The average distance between the base of the considered pick holder and the side surface of the cutting head was 22 mm.

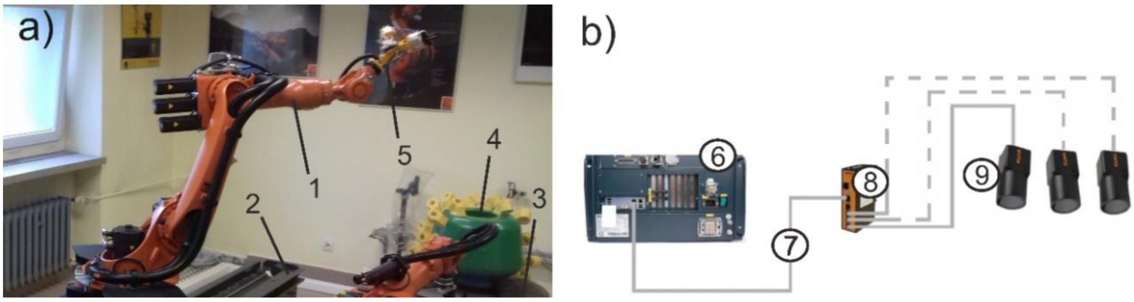

Figure 11. Experimental station at the Robotics Laboratory of the Faculty of Mining and Geology (a) and the schematic diagram of connecting the camera to the robot's control system (b): 1 – KUKA KR 16-2 robot, 2 - KL 250-3 linear unit, 3 – PEV-1-2500 positioner, 4 – side surface of the cutting head, 5 – gripper, 6 – control system, 7 – connecting cable, 8 – switch, 9 – camera.

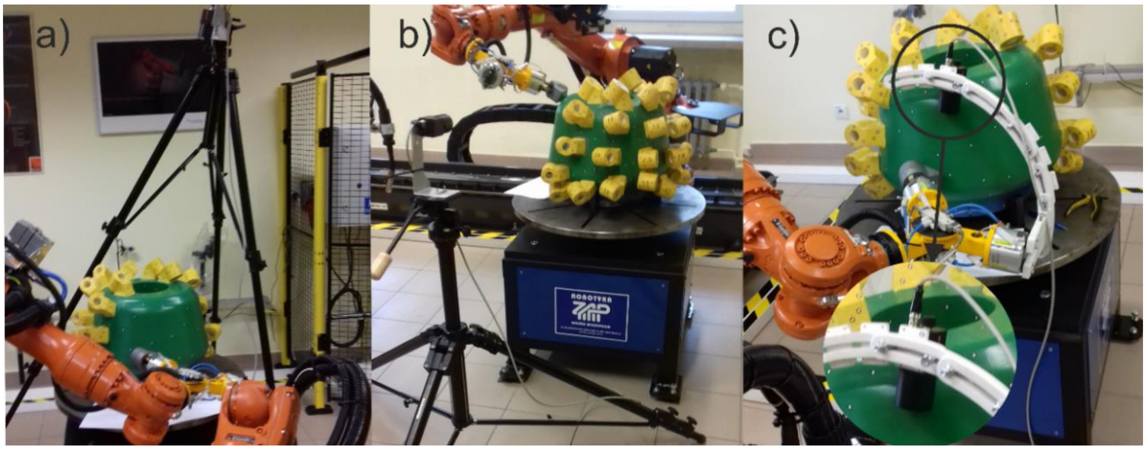

Figure 12. The way of placing the camera when taking measurement photos: a), b) stationary camera mounted on a tripod, c) mobile camera mounted on a bracket attached to the robot's gripper.

Table 1. Position and orientation of each pick holder.

Number of pick holder	x_T (mm)	y_T (mm)	z_T (mm)	A (deg)	B (deg)	C (deg)
1	282.88	-88.02	134.77	-152.49	-7.13	-159.92
2	285.26	-52.01	-169.33	-148.63	-2.26	-169.33
3	229.41	-70.53	-164.49	-138.50	22.90	-164.49

Designations: x_T, y_T, z_T – coordinates of the robot tool’s TCP point when positioning a particular pick holder, A, B, C – angles representing orientations of the $X_TY_TZ_T$ coordinate system axes.

The pick holder no. 2 is located on the conical part of the side surface of the cutting head. The position of the pick holder makes the shortest distances between its base and the side surface of the cutting head also apply to points located close to the corner of the base, in the front part of the pick holder (P_{P3}) – figure 13b. However, these distances are much smaller in comparison to the pick holder no. 2, as they are in the range from 2 mm to 6 mm. The average value of the tested distance is 3 mm.

In the case of pick holder no. 3, located on the front side of the cutting head, the points of the pick holder base which are closest to the side surface of the cutting head are located in the central part of this base (figure 13c – pink line). In this case, the distance is between 2 mm and 10 mm, and the average value is about 6 mm.

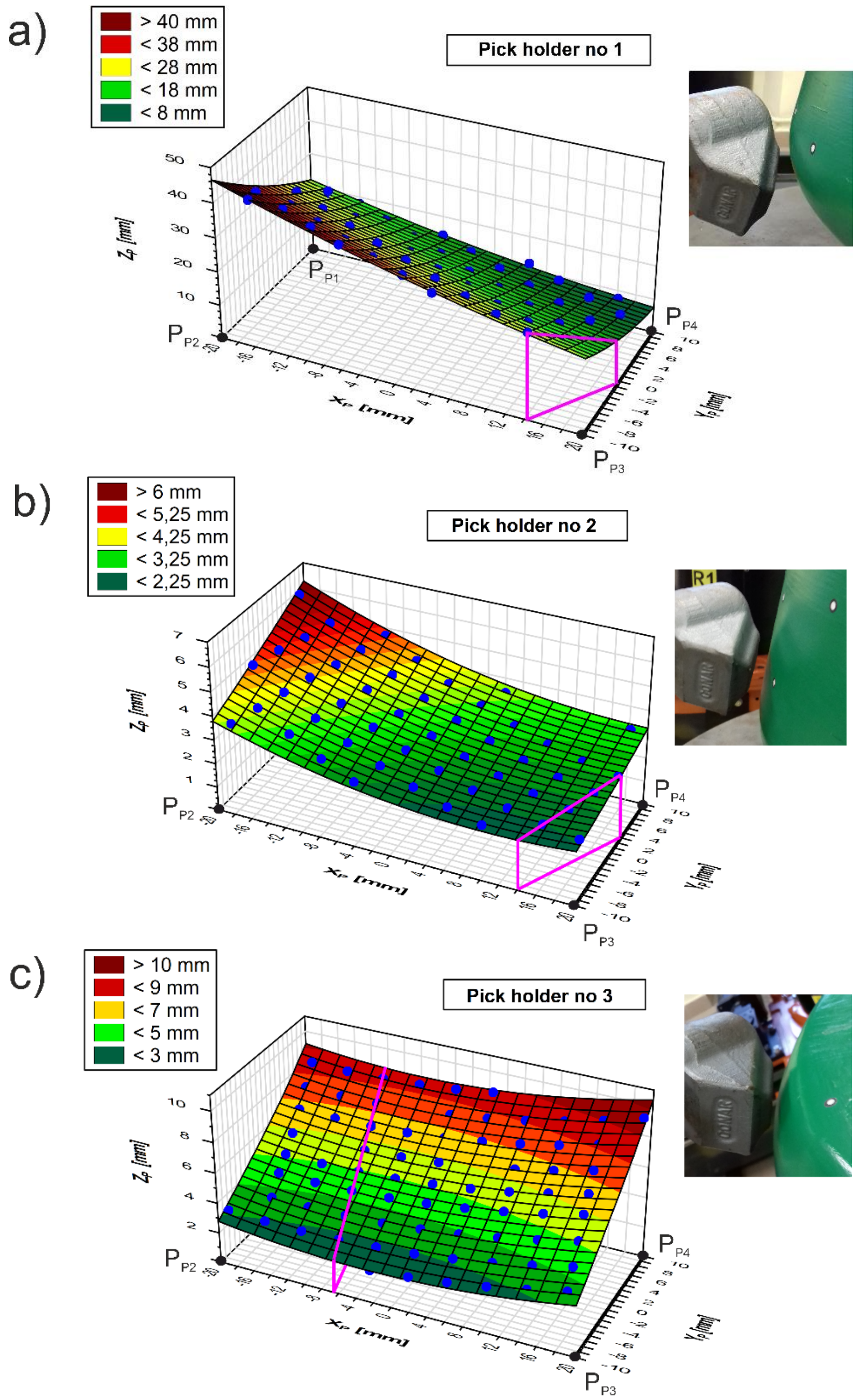

Figure 13. Graphic interpretation of measurement results for: a) pick holder no. 1, b) pick holder no. 2, c) pick holder no. 3.

5. Summary

The developed measuring method, based on the use of the vision system, allows to assess the correct positioning of the pick holder in relation to the side surface of the working unit of the cutting machine, from the point of view of the possibility of making a welded connection of these elements. It is dedicated especially for robotized production slots, where the working units of mining machines are to be manufactured, such as mining cutting machines, asphalt milling machines etc. The method presented here enables on-line monitoring of the position of pick holders in relation to the side surface of the working unit of the mining machine during their assembly. It also allows to avoid dangerous situations related to the collision of the assembled elements. This danger can occur especially if the actual geometry of the parts to be joined deviates from the nominal geometry. This can be the case, for example, when regenerated parts are used in the manufacturing process. On-line measurement of the distance between the base of the pick holder and the side surface of the working unit prevents stoppage of the robotized station in emergency mode and reduces the risk of damage to the robot.

The presented sample measurement results indicate the usefulness of the developed method for determining the position of pick holders on the side surface of the working unit of the cutting machine. Taking into account the results of the work carried out with the use of the 2D vision system and the limitations related to the possibility of determining desired distances on the measuring path over the entire surface of the pick holder base, further research will be directed towards the use of a 3D vision system based on the simultaneous use of two digital cameras. The KUKA VisionTech system used in these tests offers such possibilities, as well as the ability to automate the entire measurement process.

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