Measurement of the pick holders position on the side surface of the cutting head of a mining machine with the use of stereoscopic vision

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Abstract. The efficiency of rock cutting with mining machines is largely determined by the arrangement of picks, i.e. the number and their arrangement on the working unit of the mining machine. Not only the correct selection of the pick system for given conditions at the design stage is important, but also ensuring compliance with the design of the finished product. Strives, among others therefore, for robotisation of the process of manufacturing cutting heads/drums. From the point of view of the robotisation of the pick holders welding process, it is necessary to assess in real time the position of the pick holders relative to the side surface of the cutting head body. A convenient way is to use contactless measurement methods based on vision systems. The article presents a method of determining the position of pick holders relative to the side surface of the cutting head body of a roadheader, during their positioning, using a 3D vision system. Data processing was carried out in the Matlab software using the libraries of the Computer Vision Toolbox. A mathematical model describing the transformation of images recorded by cameras has been presented. On the basis of this model, the distribution of distances between the pick holder base points and the side surface of the cutting head was determined for a given pick holder setting. The developed measurement method was tested on an experimental stand built in the Laboratory of robotics of the Department of Mining Mechanization and Robotisation at the Silesian University of Technology.

1. Introduction

To ensure high accuracy and repeatability in the manufacturing of cutting heads/drums of mining machines, robotisation of this process is sought [1, 2]. Cutting heads/drums consist of a body and pick holders welded to the side surface of this body, in which the picks are placed. The spatial position of the pick–pick holder system is determined by the values of six parameters determined at the design stage. The bodies of the cutting heads of roadheaders and cutting drums of longwall shearsers are commonly recovered in the overhaul process. Their dimensions often don’t match the nominal values. Control of the process of pick holders positioning in robotic technology determines the need to develop a method that allows on–line monitoring and measuring the distance between the pick holder base and the side surface of the cutting head at the place of its assembly, while the robot arm travels to the target position resulting from the position of the given pick holder.

Having information about the spatial location of the cutting head side surface points and the pick holder base points, it is possible to determine the position of the pick holder relative to the body of the cutting head (cutting drum). When the actual shape of this body deviates from the nominal, it will
be possible to adjust the position of the pick holder to eliminate the risk of collision of the pick holder with the cutting head body and ensure its welding.

The method presented in this article allows the distance between the pick holder base and the side surface of the cutting head to be measured at any point of the pick holder base. It is based on the analysis of measurement photos obtained from the cameras of the KUKA VisionTech vision system. These photos are processed by the Computer Vision Toolbox in MatLab software. It is also possible to use other tools, such as the OpenCV library [3] or the LabView software.

2. The method of determining the distance between the pick holder base and the side surface of the cutting head using stereoscopic vision

There are many possibilities to obtain a stereoscopic effect [4]. Three dimensional vision is based on it. If a point is recorded on at least two photos taken from different positions, it is possible to clearly determine its coordinates in space [5]. Depending on the possess input data, there are different ways to determine these coordinates [6].

The starting point of the measurement process is the camera or cameras calibration. It is done in order to obtain matrix of camera internal parameters [7]. The camera's internal parameters determine the optical properties of the lens, its radial and tangential distortions. The coordinates of the image center (projection center) are also determined. There are several ways to calibrate cameras, e.g. using a calibration plate. In use are methods such as: Direct Linear Transform, Tsai, Zhang, Heikkil, Bouguet and many more [8]. Calibration of cameras can be done on the basis of one or many photos. Some methods include radial and tangential distortions, and some do not. Regardless of the method used, the results are quite similar. In the developed measuring method the Zheng method was used. This is the default method implemented in the MatLab software, which uses the default calibration plate (Figure 1a). To calibrate the cameras, eleven photos were taken at various positions relative to the calibration plate (Figure 1b).

![Figure 1. Calibration table (a) and camera position relative to the calibration table during calibration (b): 1 – calibration plate, 2 – camera set (colored segments marked with numbers from 1 to 11 show the position of the camera set base relative to the calibration plate).](image)

To get a stereoscopic effect it is not necessary to use two cameras [9]. Algorithms implemented in computer tools allow 3D visualization of points visible on downloaded images without knowledge of the external parameters of the camera system [10]. The external parameters of the camera system determine the offset and rotation of the cameras relative to the coordinate system associated with the observed scene. Using the appropriate functions and based on certain corresponding points in both images, it is possible to build a spatial model of the photographed scene. Nevertheless, having
knowledge about the external parameters of cameras, this reconstruction is easier and more accurate [11, 12]. Different calibration methods require different numbers of measuring points needed for calculations. They are used among others: sevenpoint algorithm, eightpoint algorithm, Ransac, or LMedS algorithm [13]. As a result of their operation we get the values of matrix elements that determine the relationship between the points recorded in the pictures. Camera calibration is enabled by computer tools. The basic method in the MatLab software is the eightpoint algorithm.

With an industrial robot at its disposal, it is possible to acquire subsequent measurement photos with one camera, by changing its position in space using a robot [14]. Then you can get the same effect as using two cameras.

If two cameras are used, knowing their external and internal parameters, using triangulation, you can determine the spatial coordinates of the corresponding points on the pair of analyzed photos [15]. If the camera layout is canonical, then a disparity map can be computed based on the camera’s internal and external parameters [16, 17]. It illustrates the difference in pixel position between a pair of stereo images [18]. The spatial model built on the basis of the disparity map includes the scene recorded in the pictures.

In order to determine the distance between the side surface of the cutting head body and the base surface of a given pick holder, it is necessary to determine the shape of the cutting head side surface in the immediate vicinity of the considered pick holder. This is done on the basis of the location of markers applied to the side surface of the cutting head body [19]. During the bench tests, these markers were in the form of grids of dots printed on a sheet of paper (Figure 2a). This card was glued onto the body of the cutting head in the place where the pick holder base will be located after placing it with the robot arm. An alternative and more practical solution is projection of the dot grid with a projector or laser [20] (Figure 2b). Due to the fact that the pick holder base is flat, to determine its position in space it is sufficient to determine the coordinates of three of its four corners.

![Figure 2. Markers applied to the body of the cutting head: a) in the form of a grid printed on a sheet of paper, b) displayed with a laser.](image)

![Figure 3. Canonical camera arrangement (a) and converging camera arrangement (b).](image)

Two digital cameras, which are part of the vision system, were used in the bench tests. The use of two cameras speeds up the acquisition of measurement data. Despite the fact that they are the same cameras from the same manufacturer, the photos recorded by these cameras may be of different quality. This makes it difficult for the software to find the corresponding points in the images. Various techniques to improve photo quality come to the rescue, such as: segmentation, contrast equalization methods, line filters, morphological operations, or histogram equalization methods [21].

Due to the mutual arrangement of cameras, they can work in a canonical (parallel) or convergent arrangement [22]. Because two narrow-angle cameras were used in the research and the areas that
were photographed are small, a converging camera arrangement was used (Figure 3b). In the case of a canonical system (Figure 3a), these cameras would have to be far away from the photographed objects during image acquisition to ensure an adequate ratio of base length (distance between cameras) to the distance from the photographed objects [23]. When the cameras are close to the photographed object, it is reproduced with a higher resolution. For this reason, markers applied to the cutting head side surface should be as small and densely spaced as possible, which increases measurement accuracy. As a result of applying a convergent camera system, we get two photos of objects of interest to us rotated relative to each other. Similarly to the method described in the work [24], cameras should be placed in an appropriate manner relative to the base of the pick holder and the side surface of the cutting head body during the acquisition of measurement photos.

The measurement using the stereo vision system is carried out during the positioning of the pick holder relative to the side surface of the cutting head body. During the approach with the pick holder to the side surface, measurement photos are acquired. The advance direction of the gripper built on the robot arm, holding the positioned pick holder, is perpendicular to the pick holder base. Because the robot control system uses the position and orientation of the tool coordinate system ($X_T Y_T Z_T$) when positioning the pick holders, it must be transformed into the coordinate system associated with the pick holder base ($X_P Y_P Z_P$).

Two camera settings were considered in relation to the photographed objects – upper (marked as "U") and bottom (marked as "B") (Figure 4). Photographic stands are located on two opposite sides of a given pick holder in such a way as to ensure that cameras record all points of interest. Axes: $X_U$ and $X_B$ of the coordinate system associated with the vision system for its individual settings coincide with the plane extending between the axis of rotation of the cutting head and the center of the pick holder base (plane 1). If all the points cannot be found on the recorded photos from the upper position, the robot control system positioning the vision system can set the cameras in the bottom position. Determination of the position and orientation of the vision system in space for individual photogrammetric stations is possible based on composite homogeneous transformation matrices:

- upper setting: \[ B_U = \text{Rot}(Z, \alpha_{DP}) \cdot \text{Rot}(X, -\frac{\pi}{2}) \cdot \text{Rot}(Y, \beta_{DP}) \cdot \text{Trans}(0, 0, -l) \] (1)
- bottom setting: \[ B_B = \text{Rot}(Z, \alpha_{DP}) \cdot \text{Rot}(X, \frac{\pi}{2}) \cdot \text{Rot}(Y, \beta_{DP}) \cdot \text{Trans}(0, 0, -l) \] (2)

Figure 4. Camera settings during the acquisition of measurement photos: a) relative to the pick holder base, b) relative to the side surface of the cutting head body: 1 – gripper, 2 – pick holder, 3 – cameras in the upper position (located from the front side of the cutting head), 4 – cameras in the bottom position (located from the base of the cutting head), 5 – side surface of the cutting head body.
where:
- $\alpha_{DP}$ – angle between the axis $X_P$ coordinate system associated with the base of the given pick holder and axis $X'_P$ coordinate system $X'_P'Y'_P'Z'_P'$, being part of the common plane of the pick holder base (plane 2 in Figure 4b) and the plane perpendicular to the axis of rotation of the cutting head's side surface (plane 3 in Figure 4b),
- $\beta_{DP}$ – angle between the pick holder base and the camera’s optical axis,
- $l$ – distance of the origin of the vision system coordinate system from the origin of the coordinate system of the pick holder base ($X_PY_PZ_P$).

Because the spatial coordinates of the markers obtained as a result of measuring photos processing in the Matlab software are specified in the coordinate system associated with the left camera ($X_LY_LZ_L$), to obtain the coordinate values of these points in the coordinate system for the base of the pick holder, we must first transform the coordinate system into the system coordinates associated with the vision system ($X_UY_UZ_U$ or $X_BY_BZ_B$) (Figure 5). The camera coordinate system is so oriented that the Z axis coincides with the optical axis of the camera. The X and Y axes form a plane parallel to the background plane (CCD image sensor). To make such a transformation, the position vector of each measuring point should be multiplied by a homogeneous composite transformation matrix $C$:

$$C = \text{Rot}(Y, \alpha_U) \cdot \text{Trans}(-l_X, 0, -l_Z)$$

where:
- $\alpha_U$ – the angle contained between the optical axis of the cameras and the $Z_U$ axis (or $Z_B$ axis) of the coordinate system associated with the vision system,
- $l_X$ – distance of the origin of the coordinate system associated with the left camera optical system from the origin of the coordinate system $X_UY_UZ_U$ (or $X_BY_BZ_B$) cameras along the axis $X_U$ ($X_D$),
- $l_Z$ – distance of origin of the coordinate system $X_UY_UZ_U$ (or $X_BY_BZ_B$) from the origin of the left camera coordinate system measured along the axis $Z_U$ ($Z_B$).

In the second stage, the vision system coordinate system ($X_UY_UZ_U$ or $X_BY_BZ_B$) is transformed into the coordinate system of the pick holder base ($X_PY_PZ_P$). It is described by the following composite homogeneous transformation matrices:

- for upper setting of the vision system:
  $$D_U = \text{Trans}_1(0,0, l) \cdot \text{Rot}_1(Y, -\beta_{DP}) \cdot \text{Rot}_1 \left(X, \frac{\pi}{2} \right) \cdot \text{Rot}_1(Z, -\alpha_{DP})$$

- for bottom setting of the vision system:
  $$D_B = \text{Trans}_2(0,0, l) \cdot \text{Rot}_2(Y, -\beta_{DP}) \cdot \text{Rot}_2 \left(X, -\frac{\pi}{2} \right) \cdot \text{Rot}_2(Z, -\alpha_{DP})$$

![Figure 5. Relations between coordinate systems associated with cameras ($X_LY_LZ_L$ and $X_BY_BZ_B$) and the coordinate system of the vision system in the upper position ($X_UY_UZ_U$).](image)
As a result, the components of the position vectors of each measuring point are determined in the coordinate system associated with the pick holder base \((X_P Y_P Z_P)\):

\[
[x_{p_i}, y_{p_i}, z_{p_i}, 1]^T = \begin{pmatrix} C \cdot D_G \cdot [x_{L_i}, y_{L_i}, z_{L_i}, 1]^T \\ C \cdot D_D \cdot [x_{L_i}, y_{L_i}, z_{L_i}, 1]^T \end{pmatrix} \quad \text{for } i = 1, ..., N,
\]

where the coordinate \(z_p\) is the distance measured in the advance direction of the gripper's during the positioning of the pick holder (Figure 6). All points that are found within the pick holder base are considered, i.e. those whose \(x_p\) and \(y_p\) coordinate values are within the rectangle representing the pick holder base.

Figure 6. Location of markers: a) in the coordinate system associated with the left camera \(X_L Y_L Z_L\), b) in the coordinate system related to the pick holder base \(X_P Y_P Z_P\), c) located within the pick holder base in the coordinate system associated with the pick holder base.

If there is no data on the position of the vision system during the acquisition of measurement photos, we can specify the values of the marker coordinates in the coordinate system associated with the base of the pick holder based on information about the location of the characteristic points of this base. For this purpose, the coordinate system associated with the left camera \((X_L Y_L Z_L)\), in which the coordinate values of the measuring points are defined, should be transformed into the coordinate system associated with the pick holder base \((X_P Y_P Z_P)\). It comes down to the translation of the camera coordinate system to the point of the pick holder base with known coordinates (e.g. one of the corners). The components of the translation vector are equal to the coordinates of this point. Then we rotate this coordinate system so that the axes of the X and Y system are parallel to the edge of the pick holder base.

3. Measuring stand

The developed measurement method was tested in the Laboratory of robotics of the Department of Mining Mechanization and Robotisation of the Faculty of Mining, Safety Engineering and Industrial Automation at the Silesian University of Technology (Figure 7). Pick holders taken from the storage are positioned using a KUKA KR 16–2 robot (1) located on the KL 250–3 linear unit (2), relative to the side surface of the cutting head (4) placed on the rotary table of the positioner PEV–1–2500 (3). For the purposes of testing, the cameras (9) were placed on a tripod with a special design bracket (10) – Figure 7b. KUKA MXG20 cameras (9) are connected to the robot control cabinet (6) with a switch (8). Measurement photos are taken from the robot’s memory and processed on a computer with MatLab software installed along with appropriate toolboxes. In the developed measurement program, pairs of photos are processed, resulting in the spatial coordinates of the points representing the pick holder base and the side surface of the cutting head body within its place of assembly.
The set of spatial coordinates of markers located on the side surface of the cutting head body is obtained as a result of processing and analyzing measurement photos. For this purpose, functions and procedures implemented in the measurement program from the Computer Vision Toolbox are used. Each of these functions is responsible for a certain process. The \texttt{imadjust} function adjusts the intensity of the raw image (Figure 8), which changes the contrast so that the pixels clearly stand out in the image (Figure 9). Based on the camera calibration data, the \texttt{undistortimage} function removes distortions from downloaded images, resulting from optical distortions. Corresponding measuring points in the pictures are adjusted using the \texttt{cpselect} function. Basis on the position of the measuring points in the pictures and the values of external camera parameters, the \texttt{triangulate} function determines the values of the spatial coordinates of the measuring points in the coordinate system associated with the left camera (\(X_L, Y_L, Z_L\)). Then, using the formulas (3) – (6), the coordinate values of these points are determined in the \(X_P, Y_P, Z_P\) coordinate system.

The developed method for measuring the position of the pick holders on the side surface of the cutting head body is based on the identification of measuring points (markers). The higher the density of points marked on a given area of the side surface of the cutting head body during acquisition of measurement photos, the more accurate its 3D model will be. Having the coordinates of the side surface points in the coordinate system associated with the pick holder base, we can determine the distance distribution between this base and the side surface of the cutting head body in the place where the pick holder is to be mounted. The distance between the pick holder base and the side surface between the measuring points can be determined using linear interpolation. The algorithm of the measurement procedure is shown in the Figure 10.

4. Results of bench tests
Using the proposed method, the distance between the pick holders base and the side surface of the cutting head body was measured. Figure 11 shows examples of measurement results. The position and orientation of the coordinate system associated with the robot's positioning tool considered pick holder during the measurement, describe the values of the gripper's TCP point: \(x_T = 1088\) mm, \(y_T = \)
1437 mm, $z_T = 951$ mm and angles defining the orientation of the robot tool coordinate system in the basic system: $A = 47$ deg, $B = 10$ deg, $C = 159$ deg. Following the algorithm of the measurement procedure (Figure 10), the distribution of the distance between the surface of the pick holder base and the side surface of the cutting head body was determined (Figure 11). These distances correspond to the coordinate values $z_P$.

![Figure 8](image1.png)  
**Figure 8.** Raw photos taken during measurements: a) image from the left camera, b) image from the right camera.

![Figure 9](image2.png)  
**Figure 9.** Application of the `imadjust` function – corresponding points are visible in the pictures: a) from the left camera, b) from the right camera.

The shortest distance between the surfaces considered is sought for. It determines how much the pick holder should be moved to the side surface of the cutting head body. This distance should correspond to the distance that the robot tool has to travel to set the pick holder according to the project design. In the case under consideration, the shortest distance is 35.1 mm. Due to the shape of the side surface of the cutting head body and the way the pick holder is positioned, the closest points are located within one of the corners.

**5. Summary**

The developed measuring method allows real-time determination of the distance distribution between the pick holder base and the side surface of the cutting head/drum body. This is particularly important in the case of re-use in the manufacturing process of the bodies of cutting heads/drums from which old pick holders have been removed. In this case, because the side surface of this body, if it is not subjected to regeneration aimed at restoring its nominal shape, is uneven. This is due to the remains of weld residues connecting removed pick holders and the defects created during their removal.
Figure 10. Algorithm of the measurement procedure.

Figure 11. Distribution of the distance between the pick holder base and the side surface of the cutting head body: 1 – measured values, 2 – values after moving the pick holder to the side surface of the cutting head body, 3 – direction in which the pick holder is moved to the side surface of the cutting head body (the direction of the robot tool advance).
In robotic technology for manufacturing cutting heads/drums, such a situation may lead to collision of the pick holders with the side surface of their body or prevent the assembly process (welding).

On-line measurement of the distance of the base of individual pick holders from the side surface of the cutting head/drum during robotic positioning lies at the basis of the adaptive control robot positioning the pick holders. It is possible on this basis to adjust the pick holder position so as to prevent the abovementioned situations during the manufacturing of these important, from the point of view of efficiency of the rock mining process, elements of mining machines.

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