Developing Method of Automatic Gaps Finding in Workpieces Models Obtained by Means of Vision Systems

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***Abstract*—This paper deals with the concept of fully automatic processing of large scale detail or workpieces by help of multilink industrial manipulators. This concept is based on using different vision systems for determining position and orientation of details in working area. These systems are installed inside robotic cell or directly on the industrial robot. The higher the quality of the obtained models of details, the more efficiently the robot will be able to process them. That is why the main attention is paid to the method of gaps finding in the workpiece point clouds, because it can sufficiently rise the quality of technological operations in automatic mode.**

***Index Terms*—vision system, industrial robot, point cloud, gaps finding, automatic mode, industry**

I. INTRODUCTION

One of the perspective application of industrial robots (IR) in the industry is their use in the technological processes of machining of various details and products in fully automatic mode. There are a lot of publications where the following tasks have already been solved: the trajectories of the IR working tool forming with use of the vision systems (VS) [1-3], the creation of force-position systems for providing mechanical efforts to the processed object during accurately tracking the surfaces when the workpieces and products are rigid. But if these details are made of composite materials, they are flexible, and especially have a complex spatial form, then their machining is associated with significant problems [4-6].

For the processing of these details, various automated complexes are already widely used [7, 8]. However, these complexes are intended for use of expensive five-coordinate machines with computer numerical control, expensive large-scale equipment designed for rigid fixation of workpieces, and complex control measuring machines. These devices provide rigid and accurate fixation in strict accordance with their CAD-models. Moreover, at force cutting an additional deformation of some parts of these details is possible, leading to defects.

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In connection with the noted it is expedient to replace the described technology, completely eliminating the use of expensive fixing devices and five-axis CNC machines from the technological process. To solve this problem with the use of simple and cheap universal positioning-fixing devices, it is necessary to apply the IR with VS and higher level intellectual control. This approach uses two basic principles:

- fast fixing of any workpieces in a simple universal tooling with possible deformation of their geometric form;
- automatic generation and correction of the control program during the IR operation on the basis of information received from the VS.

At fast fixing of flexible workpieces in a simple universal device, they usually don't correspond to their CAD-models. In this case, it is required to quickly create a new model of deformed workpiece, compare it with the reference CAD-model, and on the basis of this comparison, form a control program for IR. It is possible to solve the specified problem using stereoscopic VS [5], capable to obtain accurate data on the current spatial location of any processing surface on complex details. Therewith the control program can be formed either before or during the movement of the IR.

Modern VS allows to obtain exact positions and spatial orientations data of these workpieces. For creating of their three-dimensional models, the optical and laser scanners can be used. Stereoscopic cameras are used to identify the locations of objects in a changing working environment in real time.

As experiments shown, the point clouds obtained after each scan, in addition to noise, also contain gaps in some sections of the workpieces surface (see Fig. 1). It is connected with their different spatial location, different illumination, glares and scanning errors. At large number of gaps, the workpieces models are unsuitable for further use in the process of forming trajectories of the IR working tool. Therefore, even before the use of these models it is very important to automatically evaluate their quality (the presence and size of gaps), and, if necessary, to carry out repeated scanning of the required parts of the workpieces.

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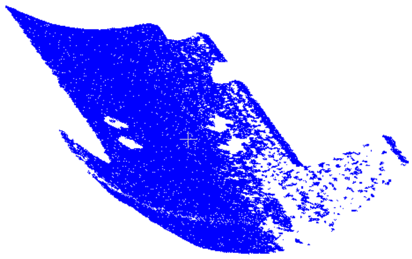


Figure 1. An example of point cloud with gaps

As a result, the problem of developing the method for determining of gaps in the point clouds obtained after scanning the workpiece is considered. Also check of the operability and efficiency of proposed algorithm is performed.

II. Developing of Method of Gaps Finding in the Obtained Models of Workpieces

The quality indicator of the obtained model is the average density ρ of points in the cloud, that is the number of points per unit surface of the model. If this density for a particular section of the model is less than a given value ρ^*, then a gap is supposed, also there is a need to rescan the specified site.

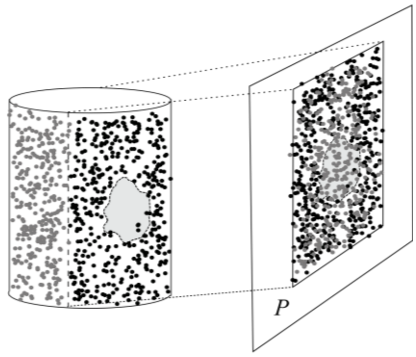
The calculation of ρ for the cloud describing the workpiece surface, is a complicated task, because the points of the cloud are not connected to each other. The location and orientation of the workpiece surface is unknown in advance. Furthermore, to determine the cloud boundary in three-dimensional space, as well as the shape and area of the considered part of the workpiece surface, it is required large computational and time resources. Therefore, instead of accurate calculating the value ρ, its estimation will be calculated by using not the obtained cloud **M**, but its projection onto a certain plane *P*. In this case, a study of the simpler plane figure will be carried out, instead of the analysis of three-dimensional surface. But there is a problem of determining the quality of the scanned surface.

The essence of this problem can be explained if the workpiece has a cylinder form whose surface is scanned with help of the VS (see Fig. 2a). After scanning the points cloud describing the surface of this cylinder is formed. There is one gap on one of the scan. In Fig. 2a the plane *P* is shown. According to the proposed approach all points will be projected (perpendicularly). These points can be divided into two groups. The nearest to the plane *P* (black points in Fig. 2a), and those that are on its far side (gray points in Fig. 2a).

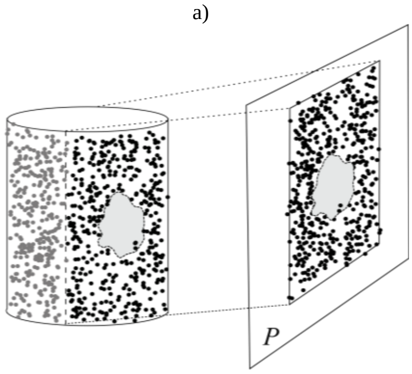
Fig. 2a shows that the plane *P* is located opposite the gap. After projecting all points of the cloud to the plane *P*, this gap will not be detected, because it will be filled with points (see gray points in Fig. 2a).

These cloud points are locating on the far side of the cylinder (distant from the plane), which was scanned successfully (with a large value of density ρ).

To solve this problem, the gray points of the cloud should not be projected on the plane *P*. In this case, the the gap will be well seen on the plane *P* (see Fig. 2b).



a)



b)

Figure 2. Projection of point cloud on a plane P without removing (a) and with removing (b) points corresponding to the invisible side of the workpieces

However, for many workpieces it is often impossible to select a single plane, project all points, and define the quality of this scan. To solve this problem, it is necessary to use several planes and analyze several projections of the points to these planes. They should be differently oriented relatively to the workpiece. It will allow to find unambiguously the gaps in the obtained point cloud. These planes are experimentally selected in advance in the base IR CS during tuning a technological process for each type of the workpiece. If the workpieces consist of flat surfaces, then the number of planes used to projection is significantly reduced.

Thus, the proposed method of automatic quality check of three-dimensional models of workpieces on existence of gaps consist of three main stages:

- projection of the resulting point cloud describing the workpiece into several differently located planes in the base IR CS;
- remove points which "is invisible" from the corresponding plane from the projections;
- splitting each projection into rectangular sections, calculating the density of points for each section and search of section with a low density of points.

III. The Implementation of the Method of Checking the Quality of the Obtained Model

In the first step the cloud, consist of N points, is projected onto several planes $P_j, j=\overline{1,N_p}$ with a predetermined orientation in IR CS, where N_p is the number of planes on which all N points of the cloud are projected. The procedure of projecting the specified cloud is schematically shown in Fig. 3.

First, the coordinates of the points of the source cloud $\mathbf{M}=\{m_i\}, i=\overline{1,N}$, defined in the base IR CS are recalculated to the coordinates specified in the right CS $X_p^jY_p^jZ_p^j$, associated with the projection plane P_j. Therewith the origin of this CS coincides with the origin of base CS, and axis X_p^j and Y_p^j are located in the plane of P_j. The specified recalculation of the coordinates of the points of the cloud **M** is performed using the transformation:

$$m_i^{*j}=\mathbf{R}_p^{*j}m_i,\ i=\overline{1,N},\ j=\overline{1,N_p}, \tag{1}$$

where $m_i=(x_i,y_i,z_i)^T$, $m_i^{*j}=(x_i^{*j},y_i^{*j},z_i^{*j})^T$ are coordinates of points of cloud **M** and their coordinates in CS $X_p^jY_p^jZ_p^j$, respectively; $\mathbf{R}_p^{*j}\in R^{3\times3}$ is a transformation matrix from base CS to CS $X_p^jY_p^jZ_p^j$; T is a transposition. The set of coordinates m_i^{*j} is the original **M** cloud in the CS $X_p^jY_p^jZ_p^j$.

To obtain the coordinates of the points m_i^{*j} projection on the plane P_j one should zero the coordinates z_i^{*j} of these points.

The second step consists in removing the points that are on the surface of the workpiece and invisible from the plane P_j. At the same time, before removing invisible points, it is necessary to ensure that the plane P_j does not cross the cloud **M**. Otherwise the projection of the specified cloud will consider the workpiece model from the inside with a previously unknown position. This will significantly complicate removing invisible areas. This situation may occur then the exact location of the workpiece is unknown in advance. For its occurrence indicates that the minimum $z_{\min}^{*j}$ and maximum $z_{\max}^{*j}$ values of the coordinates z_i^{*j} in the set of points m_i^{*j} have different signs. Therefore, for its elimination one should use the following expression:

$$\tilde{m}_i^{*j}=m_i^{*j}-(0,0,z_{\min}^{*j})^T, i=\overline{1,N},\ j=\overline{1,N_p}. \tag{2}$$

As a result, the points with coordinates $\tilde{m}_i^{*j}$ will be located above the plane P_j, except one that will lie on it.

After obtaining $\tilde{m}_i^{*j}$, one should specify a surface that separates the visible part of the **M** cloud from the invisible. It is assumed that this surface passes through the points that lie on the border of visibility, and their coordinates satisfy the conditions (see Fig. 4):

$$\begin{gathered}\tilde{m}_{B1}^{*j}=\min_{x^*}(\tilde{\mathbf{M}}_j^*),\ \tilde{m}_{B2}^{*j}=\max_{x^*}(\tilde{\mathbf{M}}_j^*),\\ \tilde{m}_{B3}^{*j}=\min_{y^*}(\tilde{\mathbf{M}}_j^*),\ \tilde{m}_{B4}^{*j}=\max_{y^*}(\tilde{\mathbf{M}}_j^*).\end{gathered} \tag{3}$$

where $\tilde{\mathbf{M}}_j^*$ is set of points $\tilde{m}_i^{*j}$.

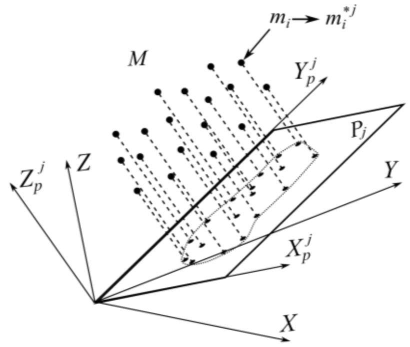


Figure 3. Projection of point cloud to the plane P_j

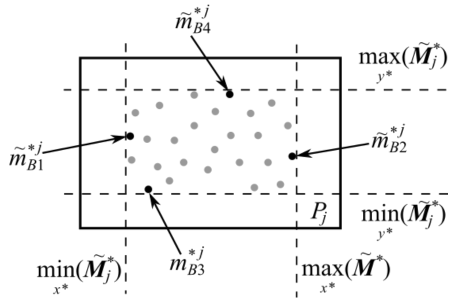


Figure 4. The estimation of coordinates of points lying on visibility boundary of projection of points cloud **M** to the plane P_j

As one can see from Fig. 4, these points define a rectangle in which the projection of the cloud **M** to the plane P_j is inscribed.

Through points $\tilde{m}_{Bk}^{*j}=(\tilde{x}_{Bk}^{*j},\tilde{y}_{Bk}^{*j},\tilde{z}_{Bk}^{*j}), k=\overline{1,4}$, one can pass two planes S_1^j and S_2^j, which divides the cloud **M** into two parts: the first corresponds to the visible part of the workpiece when it is projected to the plane P_j, and the second corresponds to the invisible part. These two planes are shown in Fig. 5 and are defined as follows.

1) If the maximum value of the coordinate $\tilde{z}_{Bk}^{*j}$ corresponds to points $\tilde{m}_{B1}^{*j}$ or $\tilde{m}_{B2}^{*j}$, then the planes S_1^j and S_2^j are determined according to [9]:

$$\begin{aligned}S_1^j(\tilde{x}^{*j},\tilde{y}^{*j},\tilde{z}^{*j})&=\begin{vmatrix}\tilde{y}_{B1}^{*j}&\tilde{z}_{B1}^{*j}&1\\\tilde{y}_{B3}^{*j}&\tilde{z}_{B3}^{*j}&1\\\tilde{y}_{B4}^{*j}&\tilde{z}_{B4}^{*j}&1\end{vmatrix}\tilde{x}^{*j}+\begin{vmatrix}\tilde{z}_{B1}^{*j}&\tilde{x}_{B1}^{*j}&1\\\tilde{z}_{B3}^{*j}&\tilde{x}_{B3}^{*j}&1\\\tilde{z}_{B4}^{*j}&\tilde{x}_{B4}^{*j}&1\end{vmatrix}\tilde{y}^{*j}+\\&+\begin{vmatrix}\tilde{x}_{B1}^{*j}&\tilde{y}_{B1}^{*j}&1\\\tilde{x}_{B3}^{*j}&\tilde{y}_{B3}^{*j}&1\\\tilde{x}_{B4}^{*j}&\tilde{y}_{B4}^{*j}&1\end{vmatrix}\tilde{z}^{*j}-\begin{vmatrix}\tilde{x}_{B1}^{*j}&\tilde{y}_{B1}^{*j}&\tilde{z}_{B1}^{*j}\\\tilde{x}_{B3}^{*j}&\tilde{y}_{B3}^{*j}&\tilde{z}_{B3}^{*j}\\\tilde{x}_{B4}^{*j}&\tilde{y}_{B4}^{*j}&\tilde{z}_{B4}^{*j}\end{vmatrix}=0,\end{aligned} \tag{4}$$

$$\begin{aligned}S_2^j(\tilde{x}^{*j},\tilde{y}^{*j},\tilde{z}^{*j})&=\begin{vmatrix}\tilde{y}_{B2}^{*j}&\tilde{z}_{B2}^{*j}&1\\\tilde{y}_{B3}^{*j}&\tilde{z}_{B3}^{*j}&1\\\tilde{y}_{B4}^{*j}&\tilde{z}_{B4}^{*j}&1\end{vmatrix}\tilde{x}^{*j}+\begin{vmatrix}\tilde{z}_{B2}^{*j}&\tilde{x}_{B2}^{*j}&1\\\tilde{z}_{B3}^{*j}&\tilde{x}_{B3}^{*j}&1\\\tilde{z}_{B4}^{*j}&\tilde{x}_{B4}^{*j}&1\end{vmatrix}\tilde{y}^{*j}+\\&+\begin{vmatrix}\tilde{x}_{B2}^{*j}&\tilde{y}_{B2}^{*j}&1\\\tilde{x}_{B3}^{*j}&\tilde{y}_{B3}^{*j}&1\\\tilde{x}_{B4}^{*j}&\tilde{y}_{B4}^{*j}&1\end{vmatrix}\tilde{z}^{*j}-\begin{vmatrix}\tilde{x}_{B2}^{*j}&\tilde{y}_{B2}^{*j}&\tilde{z}_{B2}^{*j}\\\tilde{x}_{B3}^{*j}&\tilde{y}_{B3}^{*j}&\tilde{z}_{B3}^{*j}\\\tilde{x}_{B4}^{*j}&\tilde{y}_{B4}^{*j}&\tilde{z}_{B4}^{*j}\end{vmatrix}=0.\end{aligned}$$

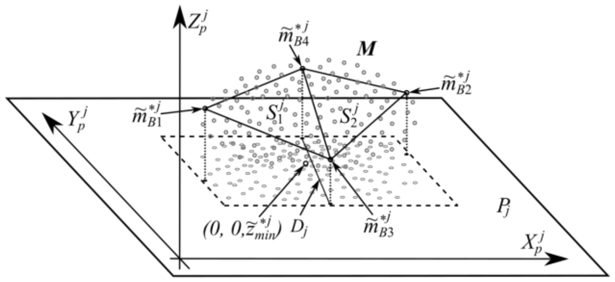


Figure 5. Splitting of point cloud **M** on visible and hidden parts

2) If the maximum value of the coordinate $\tilde{z}^{*j}_{Bk}$ corresponds to points $\tilde{m}^{*j}_{B3}$ or $\tilde{m}^{*j}_{B4}$, then the planes S_1^j and S_2^j are determined by the equations:

$$S_1^j(\tilde{x}^{*j},\tilde{y}^{*j},\tilde{z}^{*j}) = \begin{vmatrix} \tilde{y}^{*j}_{B1} & \tilde{z}^{*j}_{B1} & 1 \\ \tilde{y}^{*j}_{B2} & \tilde{z}^{*j}_{B2} & 1 \\ \tilde{y}^{*j}_{B4} & \tilde{z}^{*j}_{B4} & 1 \end{vmatrix} \tilde{x}^{*j} + \begin{vmatrix} \tilde{z}^{*j}_{B1} & \tilde{x}^{*j}_{B1} & 1 \\ \tilde{z}^{*j}_{B2} & \tilde{x}^{*j}_{B2} & 1 \\ \tilde{z}^{*j}_{B4} & \tilde{x}^{*j}_{B4} & 1 \end{vmatrix} \tilde{y}^{*j} + $$
$$+ \begin{vmatrix} \tilde{x}^{*j}_{B1} & \tilde{y}^{*j}_{B1} & 1 \\ \tilde{x}^{*j}_{B2} & \tilde{y}^{*j}_{B2} & 1 \\ \tilde{x}^{*j}_{B4} & \tilde{y}^{*j}_{B4} & 1 \end{vmatrix} \tilde{z}^{*j} - \begin{vmatrix} \tilde{x}^{*j}_{B1} & \tilde{y}^{*j}_{B1} & \tilde{z}^{*j}_{B1} \\ \tilde{x}^{*j}_{B2} & \tilde{y}^{*j}_{B2} & \tilde{z}^{*j}_{B2} \\ \tilde{x}^{*j}_{B4} & \tilde{y}^{*j}_{B4} & \tilde{z}^{*j}_{B4} \end{vmatrix} = 0, \qquad (5)$$
$$S_2^j(\tilde{x}^{*j},\tilde{y}^{*j},\tilde{z}^{*j}) = \begin{vmatrix} \tilde{y}^{*j}_{B2} & \tilde{z}^{*j}_{B2} & 1 \\ \tilde{y}^{*j}_{B1} & \tilde{z}^{*j}_{B1} & 1 \\ \tilde{y}^{*j}_{B4} & \tilde{z}^{*j}_{B4} & 1 \end{vmatrix} \tilde{x}^{*j} + \begin{vmatrix} \tilde{z}^{*j}_{B2} & \tilde{x}^{*j}_{B2} & 1 \\ \tilde{z}^{*j}_{B1} & \tilde{x}^{*j}_{B1} & 1 \\ \tilde{z}^{*j}_{B4} & \tilde{x}^{*j}_{B4} & 1 \end{vmatrix} \tilde{y}^{*j} + $$
$$+ \begin{vmatrix} \tilde{x}^{*j}_{B2} & \tilde{y}^{*j}_{B2} & 1 \\ \tilde{x}^{*j}_{B1} & \tilde{y}^{*j}_{B1} & 1 \\ \tilde{x}^{*j}_{B4} & \tilde{y}^{*j}_{B4} & 1 \end{vmatrix} \tilde{z}^{*j} - \begin{vmatrix} \tilde{x}^{*j}_{B2} & \tilde{y}^{*j}_{B2} & \tilde{z}^{*j}_{B2} \\ \tilde{x}^{*j}_{B1} & \tilde{y}^{*j}_{B1} & \tilde{z}^{*j}_{B1} \\ \tilde{x}^{*j}_{B4} & \tilde{y}^{*j}_{B4} & \tilde{z}^{*j}_{B4} \end{vmatrix} = 0.$$

After defining the equations of the planes S_1^j and S_2^j, that separate the visible for projection part of the point cloud **M** from the invisible, one should define the straight line D_j of the plane P_j. This line will divide the projection into two parts, lying under the planes S_1^j and S_2^j, respectively. For the first case, the equation of the line D_j will be as follows:

$$D_j(\tilde{x}^{*j},\tilde{y}^{*j}) = (\tilde{y}^{*j} - \tilde{y}^{*j}_{B3})(\tilde{x}^{*j}_{B3} - \tilde{x}^{*j}_{B4}) + \\ + (\tilde{x}^{*j} - \tilde{x}^{*j}_{B3})(\tilde{y}^{*j}_{B4} - \tilde{y}^{*j}_{B3}) = 0 \qquad (6)$$

for the second case:

$$D_j(\tilde{x}^{*j},\tilde{y}^{*j}) = (\tilde{y}^{*j} - \tilde{y}^{*j}_{B1})(\tilde{x}^{*j}_{B1} - \tilde{x}^{*j}_{B2}) + \\ + (\tilde{x}^{*j} - \tilde{x}^{*j}_{B1})(\tilde{y}^{*j}_{B2} - \tilde{y}^{*j}_{B1}) = 0 \qquad (7)$$

Then, from the set of points $\tilde{m}^{*j}_i$, a cloud $\tilde{\mathbf{M}}^j_P$ is separated. It contains only those points that form the projection to the plane Pj only visible part of the workpiece surface. A point $\tilde{m}^{*j}_i$ membership to cloud $\tilde{\mathbf{M}}^j_P$ is determined by the following expression:

$$\tilde{m}^{*j}_i \in \tilde{\mathbf{M}}^j_p,\ if\ \left(D_j(\tilde{m}^{*j}_i) > 0\ and\ S_1^j(\tilde{m}^{*j}_i) < 0\right) or \\ \left(D_j(\tilde{m}^{*j}_i) \le 0\ and\ S_2^j(\tilde{m}^{*j}_i) < 0\right) \qquad (8)$$

The expression (8) shows that the cloud $\tilde{\mathbf{M}}^j_P$ will include only those points from the **M** cloud that lie to the left of the D_j line and below the plane S_1^j or to the right of the D_j line and below the plane S_2^j. As a result, a cloud $\tilde{\mathbf{M}}^j_P$ containing N^j_p points is formed.

At the third step of the algorithm, the distribution of the density of points in the resulting projection and the quality evaluation of the obtained model are calculated. To do this, the projection of the cloud $\tilde{\mathbf{M}}^j_P$ to the plane P_j is divided into rectangular areas with a given step Δx and Δy along the axes X^j_p and Y^j_p, accordingly, starting from the point $(\tilde{x}^{*j}_{B1}, \tilde{y}^{*j}_{B3})$. For each area the density of points is calculated as follows:

$$\rho^j_i = N^j_{p,i} \big/ (\Delta x \Delta y) \ , \qquad (9)$$

where $N^j_{p,i}$ is number of points belonging *i*-th segment.

If $\rho^j_i \ge \rho^*$, then the considered part of the model has sufficient point density to use it for further work. The poor quality of the model is indicated by regions with low density of points with area larger than the permissible. After finding such area, it is necessary to repeat the scanning, but with the changed parameters (the orientation of the VS, lighting settings, etc.).

IV. Study of the Method of Determining the Quality of Obtained Three-dimensional Models

To determine the efficiency of proposed method, its study was conducted on a test example. The test point cloud (Fig. 6a) is generated from the CAD model of the workpiece (Fig. 6b) and contains areas where the density of the points is low.

The coordinates m_i of the initial point cloud according to (1)-(3) were transformed into the coordinates $\tilde{m}^{*j}_i$ specified in the CS $X^j_p Y^j_p Z^j_p$. Therewith the matrix $\mathbf{R}^{*j}_p$ in (1) set the rotation relative to the *Y* axis of the original

CS (see Fig. 7a), the angle varied from 90° to -90° with step 60 (two steps are shown in Fig. 7b-8b). After that, according to (4)-(8), the part of the points that corresponded to the invisible part of the model was removed. The resulting projection on the plane was divided into 3x3 mm sections for which the density of points was calculated according to (9).

The calculation results are shown in Fig. 7-8. In these figures a) indicates the location of the projection plane P_j relative to the original model; b) the projection of the cloud of points **M** on the plane P_j; c) the projection of the point cloud $\tilde{\mathbf{M}}^j_P$ on the plane P_j; d) points density map (the closer color to red the higher the density of points); d) gaps map (blue color indicates the area where the density of points below the permissible 1 point/mm^2).

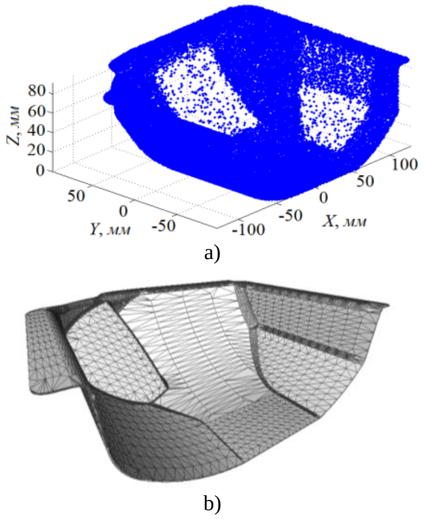


Figure 6. Test point cloud (a) and CAD-model of workpiece (b)

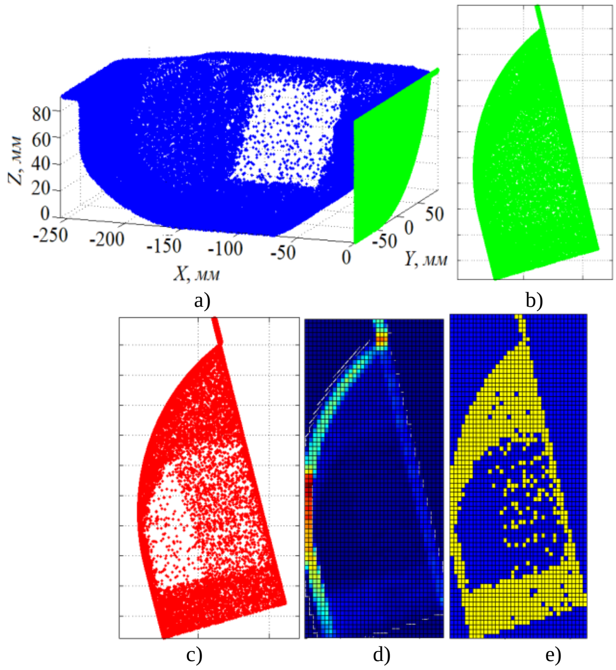


Figure 7. Results of calculation of points density under rotation of projection plane on 90° concerning an axis *Y*

From the presented figures it is seen that the use of (4) - (8) at certain angles allows to determine the presence of gaps in the original point cloud. The analysis of the obtained density maps shows that they contain areas not only with reduced, but also with increased density of points. The presence of areas with high point density indicates that the area under consideration is rotated to the projection plane at an angle close to 90°, and to estimate the quality of the model in these areas, the projection plane should be further rotated.

It should be noted that when using the proposed method, it becomes possible to move from the analysis of three-dimensional clouds of high-density points to the analysis of raster images of low resolution, which requires ten times less computing power than the use of traditional algorithms for comparing three-dimensional images.

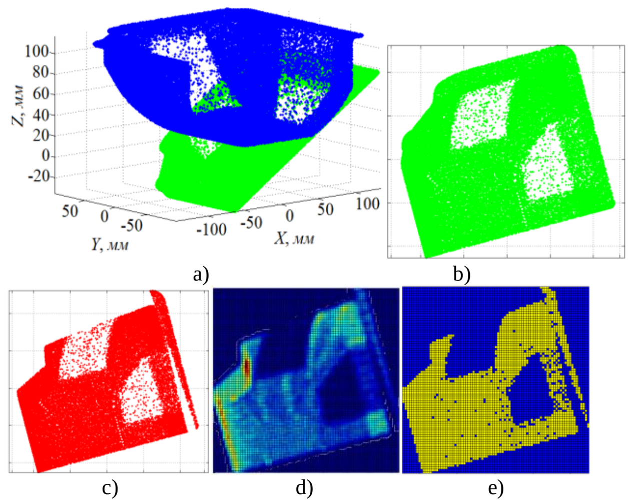


Figure 8. Results of calculation of points density under rotation of projection plane on 30° concerning an axis *Y*

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Prof. Filaretov was elected the member of Russian Engineering Academy in 1995 and the member of International Engineering Academy in 1996. Also prof. Filaretov was a recipient of the MKW Award for Professional Academics and Scientists (DAAAM International, Vienna, Austria, 2010), Honoured Professor of University of Zadar (Croatia, 2013), Medal "Engineering glory" of Russian Engineering Academy (Russia, 2014) and so on.

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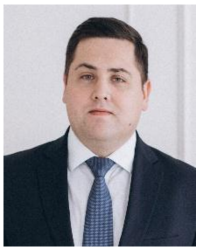

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