Використання атомної енергетики в Росії активно розвивається, і її частка в загальному обсязі енергогенерації незмінно зростає. Разом з тим, з огляду на масштаб потенційної небезпеки в разі виникнення будь-яких порушень, дана галузь вимагає постійного контролю і забезпечення безпеки. Це також стосується забезпечення технічної безпеки використовуваного обладнання. У зв'язку з цим, в атомній галузі діють нормативні документи, що регулюють не тільки рівень якості кожної категорії компонентів, але також і застосовувані методи контролю їх якості. В рамках даної статті компоненти зі стиковими зварними з'єднаннями, які є невід'ємною частиною трубопроводів першого і другого контурів, розглянуті в якості об'єкта контролю. Показано, що застосований на сьогоднішній день традиційний метод візуального контролю, для оцінки їх якості, не володіє достатньою достовірністю, що обумовлює необхідність його удосконалення. В результаті дослідження запропоновано метод автоматизованого оптичного сканування для контролю зсуву кромок зварних з'єднань на основі структурного світла. Для підвищення точності і повторюваності результатів контролю запропоновано використання роботизованого маніпулятора, що зажадало створення спеціального методу калібрування системи. Відсутність регламентованих методик щодо застосування даної технології для досліджуваного типу обладнання вимагає проведення апробації та оцінки можливості виявлення мінімальних відхилень, прийнятих в якості критерію дефектності об'єкта. Проведена експериментальна апробація виявила відхилення геометричних параметрів з точністю до 0.47 мм, що підтверджує можливість використання методу з метою визначення зміщення кромок зварних з'єднань компонентів атомної енергетики

Ключові слова: 3D-реконструкція, візуальний контроль, структурне світло, калібрування промислового робота, зміщення кромок зварних з'єднань

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WELDED JOINTS GEOMETRY TESTING BY MEANS OF AUTOMATED STRUCTURED LIGHT SCANNING

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1. Introduction

Nowadays the nuclear industry is one of the most promising sources of carbon-free energy [1]. However, sometimes nuclear power plants are considered to be dangerous due to the potential risk of environmental contamination in case of a failure. This risk is formed by both nuclear criticality and release of radioactive materials. Therefore, safety standards of the nuclear industry are to be significantly higher in comparison with others. Design of nuclear power plants exploiting high-quality materials and components in compliance with strict regulation documents is aimed at the integral safety assurance. And the reliability of the suggested solutions is one of the relevant issues in order to provide a safe source of energy for the future.

The critical components that require constant maintenance are mostly placed in primary or secondary circuits. They are generators, reactor vessels and reactor internal components, reactor coolant piping and recirculation piping as well as steam generators and feeder pipes. Piping system has a crucial role as a component which provides interaction of the heating medium with other parts of a plant. The total length of the piping can reach several kilometers or even dozens of kilometers. They can be manufactured mechanically such as cold drawn and hot rolled steel pipes. At the same time, if there are several components and assembly units, they are to be connected by welding or flanged joints [2].

In Russia, piping systems of primary and secondary circuits are mostly welded. Sealed areas of pipeline sections or between pipeline and separate unites of reactor circuits are considered to be the most critical. It is evident that due to temperature and chemical treatment of the material appearance of defects or non-conformances is most likely in welded joints [3, 4]. For that reason, the performance of effective welding quality assurance is vital.

Aforesaid, one of the major aspects of safety control in the nuclear industry is compliance of all the procedures with the requirements provided in regulatory documents. Each country has its own regulatory system based on national nuclear capacity and containing corresponding approaches and standards [5].

The legal regulation system of the Russian Federation includes different levels of documents. The level depends on the competence of the institution that has developed it. The main regulatory document for welding quality assurance in the nuclear industry is "Equipment and Piping of Nuclear Power Installations. Weld Joints and Weld Overlays. Rules of Inspection" PNAE G-7-010-89 [6]. It determines that piping systems can contain different types of welded structures that are categorized depending on potential operating conditions. Furthermore, applied welding mode, geometry or materials that were used during the manufacturing process can vary and influence the quality of a pipe as well.

However, there are strict specifications that are to be fulfilled for any type or category of a welded structure. These characteristics are considered to be vital in order to provide safe nuclear power plant operation, so its inspection is essential. Among the most important factors considered are geometrical parameters.

In accordance with the aforementioned regulatory documents in order to examine these geometrical parameters visual inspection is to be performed. Visual testing is the most common and oldest approach which is necessary for all of the welded components of nuclear facility. It is the first step of any inspection that enables prompt evaluation of the technical condition of a component. Also, it is the least expensive method for quality assurance of a weld component.

Unfortunately, the existing visual testing methodologies that are regulated by PNAE G-7-010-89 are based on the conventional approach that includes only the use of the eye. This makes the results of the inspection highly dependent on the skills of the inspector and even with the use of the special devices, such as magnifying glasses and mirrors it still provides low accuracy when measuring geometrical parameters.

In this paper, the novel inspection approach of the geometry of butt welded piping systems components is suggested. It is based on application of optical scanning methods and includes implementation of a robotic manipulator. For that reason, state-of-the art optical scanning techniques were investigated and necessary accuracy levels for the controlled object were estimated further.

2. Literature review and problem statement

During manufacturing or assembling of equipment the welded joint is to be inspected by the different testing methods. The primary goal of any inspection is to identify the location, type, and dimensions of any flaws or structural defects that can occur in a component. In-process quality assurance allows by evaluation of the inspection results and given requirements to determine whether an object is serviceable for the operation. As defects there can be identified particular types of imperfections or unintentional discontinuities stated in corresponding regulatory documents. Selection of the appropriate method for the inspection depends on the type of a controlled object, its geometry and material characteristics, as well as on the operational and technological conditions and cost and availability of the inspection [7].

In accordance with PNAE G-7-010-89 for welded parts of piping system of a nuclear power plants misalignment is one of the parameters that influences the quality of a component.

In butt welded joints the parts with identical rated thickness assembled for the welding and not subjected to machining after welding in the zone of the weld seams, the displacement of edges (misalignment of surfaces of joined parts) at the side of the welding is not to exceed the norms given in Table 1, where S corresponds to the thickness of an object [6].

Table 1

Norms of permissible displacements of edge in butt joints

Thickness of welded parts, mm	Maximum permissible displacement of edges in butt joints, mm		
	Longitudinal, meridianal, chord and circular during welding of any parts and crucial for welding end plates	Transverse	Circular
		welding pipes and tapered parts	when welding cylindrical casing parts from plates or forgings
Up to 5	0.20S	0.20S	0.20S
Over 5 to 10	0.10S+0.5	0.10S+0.5	0.25S
Over 10 to 25	0.10S+0.5	0.10S+0.5	0.10S+1.5
Over 25 to 50	0.04S+2.0	0.06S+1.5	0.06S+2.5
Over 50 to 100	0.02S+3.0	0.03S+3.0	0.045S+3.5
Over 100	0.01S+4.0, but not over 6.0	0.015S+4.5, but not over 7.5	0.025S+5.0, but not over 10

Most recently due to the rapid advances visual testing equipment and techniques have been improved and became automated. For these purposes cameras and robotic manipulator equipment are applied. Such systems enable obtaining reliable and reproducible results from visual inspections. This has contributed significantly to visual techniques as nondestructive testing methods for application in nuclear power plants for high-quality inspections that are quicker and less consuming than other nondestructive methods and even allow to perform remote quality control.

For instance, in [8] a method for visual inspection of fuel channels was proposed. It is shown that manual visual estimation has lower efficiency and new techniques based on automated processing are promising for nuclear industry application. The research also suggests that creating of 3D models based on the obtained point clouds could be the next step in terms of automated visual testing. Therefore, development of an algorithm that allows such modelling was stated as one of the tasks under the scope of this paper.

The similar solution based on the development of image processing techniques was described in [9]. The main characteristic is the implementation of the robotic system that will allow to perform a remote inspection based on the machine vision. However, it was also revealed that the application of robotic manipulators leads to a necessity to develop a specified calibration technique.

The advantages of the remote inspection were also discussed in [10], suggesting that it can reduce the overall radiation exposure of the personnel and increase efficiency of nuclear power plant maintenance. For that reason, this paper proposed implementation of a robotic visual testing system for evaluation of the geometrical parameters of the fuel channels.

Aforementioned solutions are based on implementation of visual systems that allow to receive 3D-reconstructed images of the surfaces. These methods also imply application of computational intelligence systems for further image processing. Thus, the right choice of such system becomes the most relevant problem. Among three-dimensional vision systems there are two major types based on passive or active principles.

Passive systems such as photogrammetry equipment require several measurements of the object usually with several cameras within high quality lighting conditions, that can be difficult to perform without interruption of manufacturing processes. At the same time, active visual testing methods such as laser and structured light scanning are becoming more relevant for application in various fields. They allow quickly and directly obtain 3D-coordinates and calculate corresponding dimensions of the measured surface.

The previous research work investigated the possibility of implementation of laser scanning systems via industrial robotic arm for non-contact measurements. The laser scanner [11] was fixed on the robot, which allowed to follow the shape of the object during inspection. In [12] it was demonstrated that the application of such systems improves the precision and speed of the weld recognition. The geometrical extraction methods were applied for the system. However, the described improvement was achieved due to obtaining data only from the featured points. Even though it can be used for gaining information about the weld groove images it is not enough for modelling of the 3D models of the entire object. Moreover, laser-based systems are expensive and not available as a common used equipment for most of Russian manufacturing industries.

On the other hand, structured light approach obtains data from the whole measured surface, which can be used for misalignment estimation.

The benefits of structured light scanning for weld seam detection are discussed in [13], such as high accuracy, low cost and broad range of estimated characteristics. However, this research does not provide a methodology for calculation of the geometrical parameters of the component. The feasibility study of the structured light testing for welded structures was demonstrated in [14]. It can be considered as a proof of concept for a quantitative estimation of the geometrical parameters of the welded structures with implementation of full 3D models. Although, the misalignment estimation in this study was represented in a degree equivalent and was not compared with the quality requirements established for the given controlled object.

In accordance with the literature review it is evident that further investigation of structured light visual scanning systems application can be considered as the most promising approach for welded joints geometry testing.

3. The aim and objectives of the study

The aim of this study is development of low-cost visual testing method based on structured light technique for robotic quality assessment of misalignment of the welding of nuclear power plants components.

To achieve the set aim, the following tasks were determined:

– development of the calibration procedure of the robotic manipulator and the scanning system;

– development of the algorithm for 3D modelling of the entire component;

– experimental validation of the proposed solution in accordance with the minimal displacement value.

4. Methods applied for automated visual testing of butt joints

Structured light scanning is one of the active scanning methods that are based on triangulation principles. In general, it is performed as a projection of the given pattern such as a light grid onto the surface of an object. At the same time a camera captures the pattern that is formed on this surface and the model of the object is built in accordance with the deformation of the projected light by knowing the distance between the projector, camera and the object.

One of the advantages of application of structured lighting technique is an ability to program the projected lighting pattern. This method also allows to project the lighting patterns and to perform scanning of the surface from several positions. Due to the fact that the patterns are programmed the correspondence betwe8en the obtained images and the initial pattern can be established with high accuracy.

In some cases, the plane of the object surface can be misaligned comparing with the scanning plane and the obtained coordinates information is not reliable. In order to receive coordinates of the real plane a subtraction algorithm is to be applied. The scanning procedure is demonstrated in Fig. 1.

Points P and I in Fig. 1 represent optical centres of the projector and the camera correspondingly. Point O is a cross-point for optical axes of the projector and the camera. Prior to the scanning of the object surface the measurement of the reference plane is performed, which can be further used as a standard. The surface profile is to be compared to the reference plane measurement. Point D on the surface of the object is equivalent to the point C on the reference plane with respect to the position of the projector matrix plane. Point D on the scanned surface and point A on the reference plane are projected as one pixel at the camera matrix.

By subtracting the obtained phase map of the reference plane from the phase distribution on the surface, the phase difference for the same pixel can be calculated:

$$\varphi_{AD}=\varphi_A-\varphi_C. \quad (1)$$

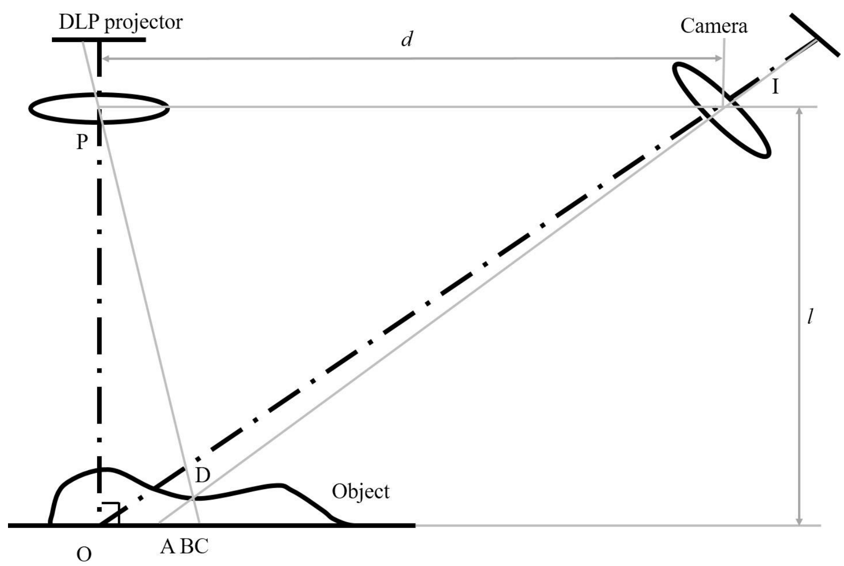


Fig. 1. Structured light scanning principle

To apply triangulation principles approach it is suggested that points P and I are located on the same plane with vector *l*, that corresponds to the distance to the reference plane, with a given distance between these points, and the reference plane is parallel to the line between the projector and the camera. Therefore, triangles ΔPID and ΔCAD are similar. The distance from the point D, that belongs to the surface of the object, to the reference plane DB is to be calculated with respect to the distance between A and C points. Further, the location of each point of the surface of the object is determined this way. By performing these calculations for all of the surface points within the scanning area the corresponding point cloud is formed. It contains data about geometrical parameters of the object which are to be determined for reliable quality assurance.

Advanced structured light scanning equipment allows to create different types of lighting patterns such as a given number of points, lines or grids. In this paper an application of a projector that creates lines on the controlled object surface is suggested.

For the research 3-DLP projector ACER K132 was chosen as a source of the light as a part of DAVID-SLS-2 3D-scanner (David Vision Systems GmbH, Germany). A single shot of DAVID-SLS-2 structured-light scanner generates up to 1.2 million data points. As a sensor to record a projected pattern David-Cam-3.1-M camera with the framerate of 25 FPS and resolution of 1280×960 pixels was chosen. Technical characteristics are given in Table 2. Fig. 2 represents the experimental setup.

Fig. 2. DAVID-SLS-2 structured-light scanner

Table 2

Technical parameters of 3D-scanner DAVID SLS-2

Size of the possible controlled objects	60–600 mm
Minimal scanning area	60 mm
Maximum scanning area	500 m
Accuracy	Up to 0,1 % of the scanning area (or up to 60 μm)
Scanning grid parameters	Up to 1 200 000 points via one scanning
Scanning speed	2–4 seconds for one scanning

In order to reconstruct a controlled object several measurements from different angles are required. The aim of this research work is to develop the method for transformation of measured coordinates to a combined coordinate system. In general, the transformation algorithm proposed in this paper allows to convert any point cloud data obtained by the scanner into the coordinate system of a robotic manipulator.

The main task for an effective robotic control is to establish strong correlation between the coordinate system of a scanner and a robotic manipulator. Then each scan of an object will be determined at a certain position that will change correspondingly to the movement of a robot. In the case when there is no transformation algorithm, scanned shots do not match, and it is not possible to reconstruct an accurate 3D-model of an object. Reconstruction will be possible only by manual fusion of the obtained data, which is a time-consuming and imprecise process. The suggested automatization method is aimed to solve this problem.

For estimation of the location of a scanner in accordance with the location of a robotic manipulator we suggest developing a specific reference (calibration) sample. In our case this calibration sample is a plate with three ceramic spheres Saphirwerk S4376 with a diameter of 20 mm (Fig. 3). The shaft and stem of these calibration spheres are stainless steel. The stem is 80×80 mm with the thickness of 8 mm. These dimensions were chosen due to the scan area of the 3D-scanner.

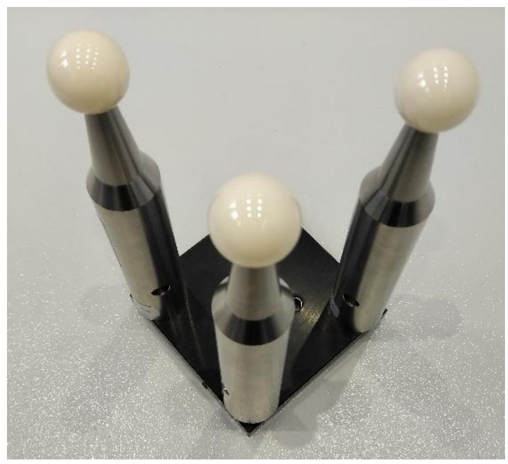


Fig. 3. Reference sample for calibration of the visual testing system

The calibration sample is placed on the scanning surface that is required by an articulated robot. It stays at the same place during the calibration. Further, it is important that the scanner is rigidly placed on the robot.

Calibration procedure.

The proposed method comprises the specific scanning method and novel mathematical algorithm for coordinates` transformation. Both of these parts can be combined into so-called calibration procedure.

The scanning consists of several steps.

First, coordinates of the reference sample are to be measured by an articulated robot in its own coordinate reference system. Thus, the coordinates of the spheres are determined in accordance with the robotic scanner. After such measurement a single shot of the scanner is performed. As a result, point cloud data of values is obtained. The coordinates of these points correspond to the reference sample spheres.

The second step of the calibration is mathematical processing. The software for 3D-scanning via DAVID scanner which is placed on the robotic manipulator KUKA KR10 (KUKA Robotics, Germany) is developed. It implements the libraries provided by the developer of DAVID scanner. Coordinates of the centers of the spheres are computed by application of special mathematical algorithms that allow to distinguish and separate particular values belonging to each particular sphere. Furthermore, considering all measured points, relative position of the scanner is estimated in accordance with the location of the robotic manipulator.

In this paper we suggest the following mathematical algorithms for point cloud processing.

The input data for evaluation of the coordinates of the spheres' centers are three point clouds obtained by the same scan.

We suppose that there is a random point with Xn, Yn, Zn coordinates. In that case calculation of the coordinates of the sphere center is possible if and only if there are known coordinates of four different points that are located at the surface of a sphere. It can be represented as a matrix (S):

$$S = \begin{vmatrix} X1 & Y1 & Z1 \\ X2 & Y2 & Z2 \\ X3 & Y3 & Z3 \\ X4 & Y4 & Z4 \end{vmatrix}. \tag{2}$$

The matrix of indexes that correspond to the sphere center can be computed by the following equitation (3), where C is a matrix that contains all of the indexes: $C = C1 \quad C2 \quad C3 \quad C4$.

$$C = S1.\backslash - \begin{vmatrix} X1^2 + Y1^2 + Z1^2 \\ X2^2 + Y2^2 + Z2^2 \\ X3^2 + Y3^2 + Z3^2 \\ X4^2 + Y4^2 + Z4^2 \end{vmatrix}. \tag{3}$$

By means of matrix C coordinates Xc, Yc, Zc can be calculated, as well as sphere radius R:

$$Xc = -\frac{C1}{2}, \tag{4}$$

$$Yc = -\frac{C2}{2}, \tag{5}$$

$$Zc = -\frac{C3}{2}, \tag{6}$$

$$R = \sqrt{C1^2 + C2^2 + C3^2 - C4} * 2. \tag{7}$$

Coordinates of the spheres centers form matrix p′. In order to convert all the values into the global coordinate system the correlation between the robotic manipulator and the robot flange is to be calculated as well as the correlation between the scanner and the same robot flange. To transform spheres center coordinates into the coordinate system of the flange of the robotic manipulator the computation (8) is required, where Mf is a transformation matrix that connects flange and the manipulator coordinate systems.

$$pf' = p' \times Mf. \tag{8}$$

Flange coordinates are the following: A B C X Y Z. For calculating Mf it is necessary to go from Eiler`s angles to direction cosines and as a result Mf matrix will be:

$$Mf = \begin{vmatrix} R11 & R12 & R13 & X*R \\ R21 & R22 & R23 & Y*R \\ R31 & R32 & R33 & Z*R \\ 0 & 0 & 0 & 1 \end{vmatrix}, \tag{9}$$

where R is direction cosines matrix.

To transform scanner coordinates into the coordinate system of the flange of the robotic manipulator matrix Ma is used:

$$p' = pf' * Ma \text{ or } Ma = pf'^{-1} \times p'. \tag{10}$$

Furthermore, the following measurement from another position of the robotic manipulator will take place in a Mn that corresponds to the coordinates of the flange in a new position.

Therefore, the resulting matrix is to be the combination of these measurements:

$$Mr = Mn \times Ma. \tag{11}$$

5. Experiment results

The experiment was conducted by inspection of a butt welded component (Fig. 4). This component is made of steel and has the shape of a pipe with the diameter of 630 mm, the wall thickness is 6 mm. The experimental data was obtained as a result of two scanning procedures. According to the mathematical algorithm described in the “Calibration Procedure” section two resulting matrixes were formed.

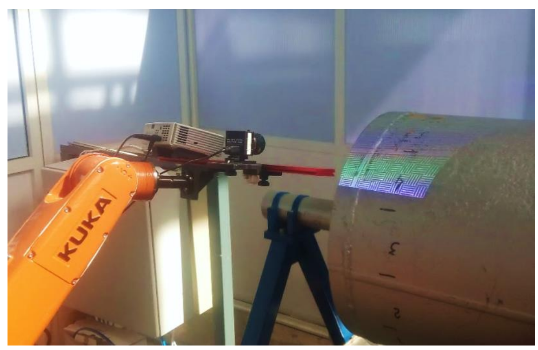
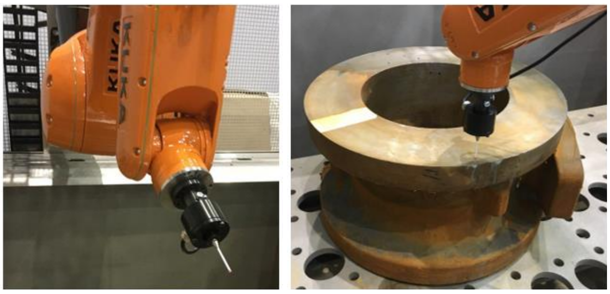


Fig. 4. Reference sample for the experimental validation of the method

The precise data for creating 3D-model of the controlled object was obtained via implementation of articulated arm coordinate measuring machine (KUKA KR10) by placing contact measuring tool on its surface (Fig. 5). The accuracy of the system is 100 μm and scanning resolution of 200 μm. Technical parameters of the measuring machine are represented in Table 3.

The advanced approach for evaluation of misalignment of welded parts is proposed in this study. It consists of several steps described below.

The scanning process is to be performed in such a way that both welded parts are in the controlled area simultaneously. At the first step two scanned images from mutually orthogonal positions are to be obtained. This way of scanning provides reliable information of any possible displacement of the flat plates. The results from two point clouds corresponding to each of the parts. These clouds are represented in accordance with the coordinate system of the robotic manipulator in Fig. 6 as finite sets of yellow dots.



a *b*

Fig. 5. Obtaining data with the contact measuring tool: *a* – articulated arm coordinate measuring machine; *b* – Placement of the contact measuring tool on the surface of the object

Table 3

Technical parameters of KUKA AGILUS KR10 R1100 WP

Working distance	1101 mm
Maximum load	10 kg
Precision	0.03 mm
Weight	54 kg
Ingress protection rating	IP67
Number of axes	6

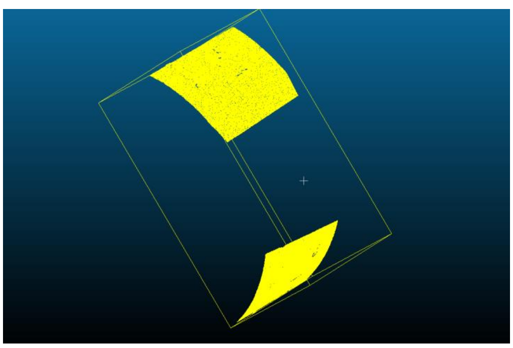


Fig. 6. The obtained values during the scanning procedure

This data contains values that correspond to the weld joint as well as to the base metal. Therefore, for reliable assessment it is important to exclude the welding values from the conducted scanned results.

For this purpose, firstly both point clouds are to be combined into one. The centroid of the system is calculated as well as the distance from each particular point in the combined cloud to this centroid. Due to the fact that the geometry of the weld joint differs significantly from the base metal the distance from the centroid to all of the joint values is to be quite long as well. So, it is possible to eliminate these points from the combined point cloud (Fig. 6). As a result, a new point cloud is created that contains values from the bottom and upper parts of each particular flat plate. This obtained data is to be divided into two point clouds in such a manner as to create separate elements that correspond to each of the flat plates separately. In Fig. 7 yellow points belong to the one of the welded components and the white dots belong to another.

The real geometry of the inspected pipe is given so it is possible to create an accurate 3D model for this object. The results of modeling of the experimental sample are shown in Fig. 8 (the point cloud of blue dots).

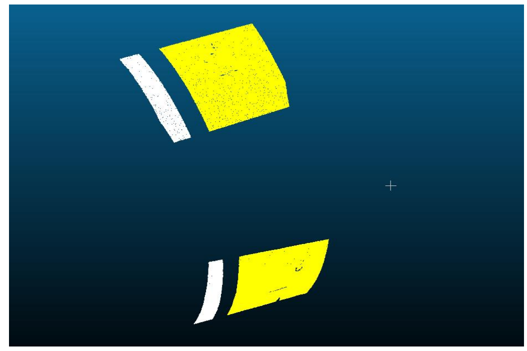


Fig. 7. The scanned results without butt joint values

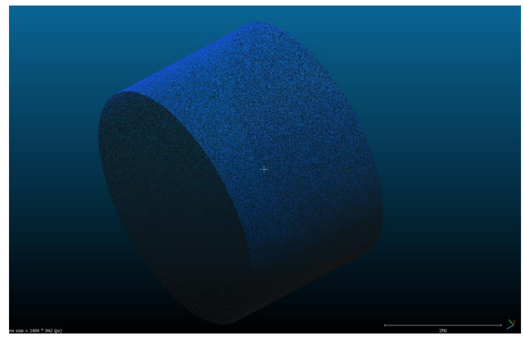


Fig. 8. 3D model of the pipe sample

Therefore, the minimum amount of values is sufficient for the solution of the set tasks in the Section 3.

6. Discussion of the received results via optical scanning of butt joints

In order to evaluate misalignment of the welded parts it is necessary to match 3D model with calculated point cloud values for one of the flat plates. For instance, the left flat plate (white point cloud) was chosen to be aligned with the 3D model by implementation of the ICP algorithm [15]. Thus, for determination of the axes deviation the distance from another flat plate (yellow point cloud) to the 3D model is to be calculated. As it is mentioned above, due to the calibration procedure the positioning of the 3D model is known in accordance to the coordinate system of the manipulator, so calculation of any distance in appliance with the model will be positioned in the given coordinate system as well. For this purpose, "Find the nearest neighbor" algorithm can be applied that allows to establish the nearest point that belongs to the 3D model and calculate the value of misalignment [16, 17].

Fig. 8 demonstrates distribution of the calculated distances from each point of the point cloud to the 3D model. The diagram demonstrates the amount of the points that are not aligned with the experimental sample distributed by value. The shape of the experimental sample is not perfect. Therefore, we considered only values with the number of counts above 20 % of the maximum counts for reliable estimation. Value distribution is shown in Fig. 9 below, points of green and blue color satisfy the given requirement.

The final analyzed area after segmentation involved 150 066 points. The histograms in Fig. 10 demonstrate deviation distribution given by a particular count number. The average distribution of the values with maximum number according to the conducted results is about 0.47 mm and it corresponds to the value of misalignment for the controlled pipe.

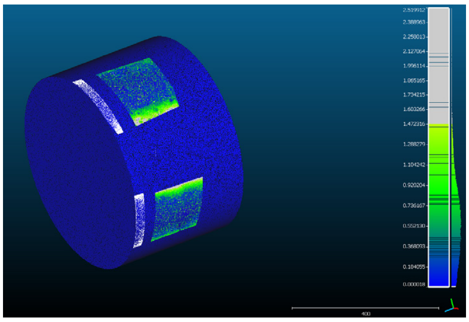


Fig. 9. Distribution of the distances from each point to the 3D model

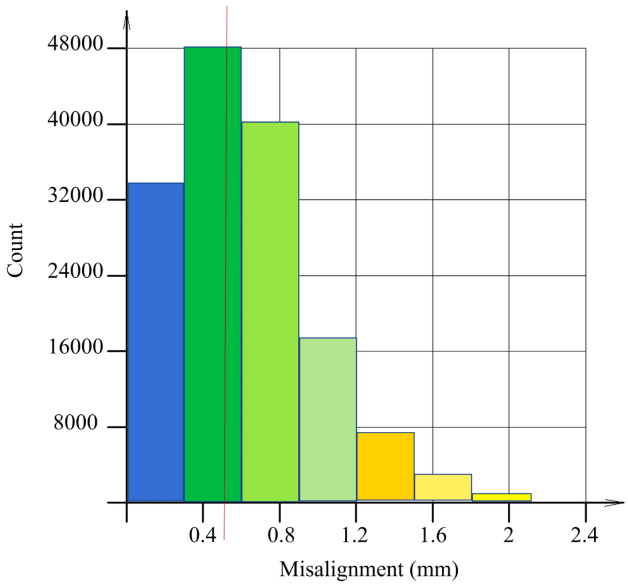


Fig. 10. Histograms in accordance with distribution of the distances from each point

These results validate the proposed method for further implementation for a practical use in the nuclear industry.

The main advantages of the method are:

1) further possibility for full automatization;
2) decreasing of the potential risk for the personnel;
3) higher accuracy.

However, there are still limitations that require further improvements of the processing algorithm such as sensitivity of the structured light technique to shiny surfaces, and the necessity for the computing power. In future work we also suggest development of the algorithm for an automatic segmentation.

7. Conclusions

1. The calibration technique that determines the correspondence between the scanning system and the robotic manipulator was developed. It provides accuracy and repeatability of the results by maintaining precise orientation of the scanning system at each point of the measurement. The technique is based on the implementation of the calibration sample with three ceramic spheres. The comparison of the results obtained by the robotic manipulator and via standard contact measuring tool demonstrated the error within the range of 115 μm, which is lower than the limiting error of the optical scanning system and the manipulator.

2. 3D modelling of the controlled object based on the obtained point clouds via structured light scanning was performed. Received modelling results were further investigated for numerical misalignment evaluation. The achieved spatial resolution was 150 μm, which allows to take measurements with a step sufficient to estimate any displacement regulated by the requirements of the nuclear industry [6].

3. The calculated distribution of the values via the suggested algorithm demonstrated that it is possible to determine a displacement with the accuracy of 0.47 mm. That corresponds to the norms of permissible displacements of edge in butt joints (Table 1), and thus validates the method for further practical application for this type of nuclear power plants components.

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