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Design of experiment (DOE) for roboticmachining operation

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ABSTRACT: The aim of this article is to analyse technical boundaries of robotic machining and its utilization in mechanical machining, and also to provide basic overview of technology and technical restrictions, that need to be removed in future robotic arm development. In comparison with CNC machines, that have shape and workplace restrictions, robotic arms are flexible alternation that saves costs. Authors would like to express basic information about obstacles in robotic machining – stiffness, accuracy and repeatability, that affect usage of robotic arms in mechanical engineering the most. The main aim of this paper is to present the possibilities of usage, advantages, disadvantages of robotic machining and shown the further research activities.

KEYWORDS:machining, robot, stiffness, accuracy, repeatability, surface roughness

I. INTRODUCTION

Robotics in general are one of the main industry in automatization that are not used only in mechanical engineering, but also in medicine, armed forces, biomechanics etc. Industrial robots found their usage in wide scale of tasks, where they can replace human operators. In last 30 years, the number of applications of industrial robots was drastically increased, therefor we can say, that industrial robot has the potential and in future its applications in industry will grow. In comparison with specialized machines, industrial robots have big workspaces, which can be extended with mobile platforms. Another advantage is their number of degrees of freedom, with help of which can robotic arms produce and machine more difficult part shapes. With help of other robotic arms or specialized machines can robots be part of work groups. The biggest advantage of robotic arms in mechanical engineering is its total acquisition expenses, which are significantly lower than in specialized machining tools (e.g. CNC). Although nowadays are robotic arms used in basic processes as welding, manipulation or surface polishing of mechanical parts, there are still many operations, where robotic arm can find utilization (turning, milling) [1].

Robotic arm is manipulator with six degrees of freedom, which is programmable and have similar properties to human arm [2]. Robotic arms are usually used in research, development and teaching. Geometrically robotic arm consists of waist, elbow, shoulder and wrist such as human upper limb (Fig. 1). Those parts are connected with joints that allow rotation and sliding motion [3]. Functional end of robotic arm is called effector, and is analogous to human arm. There end effectors have two degrees of freedom and are designed to carry any tool. These tools are used for material machining, welding or manipulation. Robotic arms can be autonomous or they can be controlled by human operator and can be used in many different actions with significant accuracy. Robotic arms operated in big spaces, where base of robotic arm can be static (firmly attached to underlay) or mobile that means, base of robotic arm is equipped with a power unit and wheels that increase the overall mass [3].

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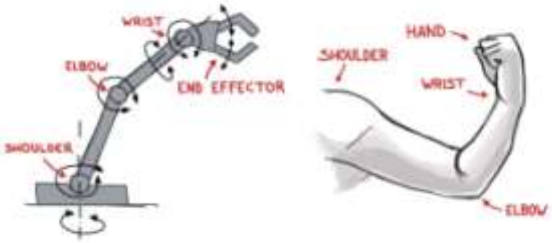

Figure 1 Geometry of robotic arm and human arm

Research of robotics machining started in year 1987 with Appleton and Williams [4], who tried to replace human operators performing simple work operations. In this research they presented serial applications of robotic arm, as drilling and grinding [5]. What an International Federation of Robotics (IFR) states, up to 74% of industrial robots are used for manipulation and welding [6]. Another statistics states, that number of robots used in industry increased between 2011 and 2016 by 212 000 pieces. In comparison, between year 2005 and 2008, number of industrial robots increased by 115 000 pieces. That is increase by 204% [5]. Even though sell of industrial robots significantly decreased due to the economic crisis in 2009, this situation started to change in 2010 and selling of industrial robots increased again. In 2011 selling of robots increased by almost 40%, especially in automotive industry [7]. Records in industrial robots selling was recorded in 2018, when was 422 271 industrial robots sold. This is the highest number of sold robots in last 6 years [4]. In 2016 there was only 1.4% of industrial robots used for grinding and milling. In comparison to operation such as manipulation and assembly, is this number very low [8]. Nevertheless, robotics machining has applications in many different industrial sectors and can solve many difficulties in manufacturing process in many industrial products. In table 1 we can see implementation of industrial robots in many industrial sectors [7].

Table 1 Implementation of industrial robots in different industrial sectors [4]

INDUSTRIAL SECTORS	PROCESS	PRODUCT
manufacturing	milling	rapid prototyping
automobiles	grinding, drilling, milling, cutting	engines, truck frames, body panels, bumpers,
aviation	drilling, cutting, grinding, polishing	turbine blades, dividing, isolation, wing parts
foundries	milling, drilling, finishing	mold, castings
fashion	milling, grinding	
navy	milling	ship spaces
medicine	grinding, polishing	prosthetics
woodworking	milling, manipulation	solid forms, furniture, upholstery, railing, modelling board

II. COMPARISON OF CNC MACHINE AND ROBOTIC ARM

CNC machines are metalworking machines that can produce complicated parts with help of industrial processes as drilling, turning, milling and grinding. These machines provide great accuracy of machining with great stability. In addition to performing these processes uniformly, no additional CNC machine is required for further operations.The main disadvantage of CNC machines is their purchase price and therefore the cost of procuring CNC machines will still be out of reach for some companies. Another disadvantage of CNC machines is their limited workspace and thanks to this, CNC machines are unable to produce components of large dimensions and complicated shapes.Although the CNC machine market is constantly evolving by adding axes, bringing new models and new ways to make work easier, industrial robots are great alternative, especially in places where more complex geometry and a lot of work are required. The constant increase in the use of industrial robots is justified by their reliability, functionality, protection of the operator in difficult working conditions, it is time-saving, increases productivity and, last but not least, has low acquisition costs compared to CNC machines.As shown in Fig. 2, industrial robots, compared to a CNC machine, can

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achieve more complex 3D shapes due to their own large workspaces (Fig. 3), have good programmability and are flexible enough [4].

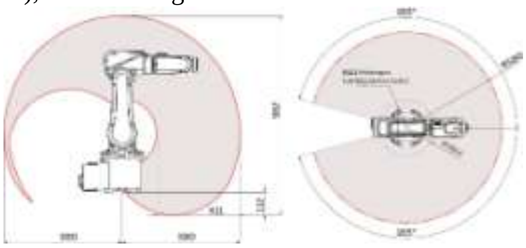

Figure 2 Workspace of robotic arm

Originally, industrial robots were used for tasks that required millimeter accuracy. These were mainly manipulating operations such as moving objects from point A to point B. In the last two decades, the applications of industrial robots have increased drastically and began to be used for operations such as grinding, welding and polishing, especially in the automotive industry [4].

Advantages: purchase price, accuracy

Disadvantages: workspace that cannot by expanded

Advantages: workspace, flexibility, reprogramming
Disadvantages: low stiffness of the arm, purchase price, accuracy

Figure 3 Comparison of CNC machine and robotic arm

Table 2 Detailed comparison of CNC machines and robotic arms [9]

INDICATOR	CNC	ROBOTIC ARM
accuracy	-0,005 mm	-0,1 – 1,0 mm
repeatability	-0,002 mm	-0,03 – 0,3 mm
workspace	limited	great
workspace extension	impossible	by adding an additionally activated axis
number of axes	3 or 5	6+
trajectory complexity	suitable for 3 – 5 axes	any complicated trajectory
relationship between activation and operating space	linear	nonlinear
feedback	sensor	one or more sensors
mechanical compliance	relatively low	relatively high
flexibility of production	one or few similar operations	any operation type
cost	competitive for three-axis tools, expensive for five-axis tools	competitive for six-axis tools

The main disadvantage of industrial robots is their lower machining accuracy. This is due to the low stiffness compared to CNC machines. The stiffness of the industrial articulated robot is at the level of 1N/µm, which is several times lower than the stiffness of a standard CNC machine, which has a stiffness of 50 N/µm. This factor, in combination with the cutting forces, creates deformations in the end effector, which causes vibrations, poor quality and low geometric machining accuracy. In some cases, the end effectors achieved a deflection of 10 mm while machining parts. In Table 2 we can see a detailed comparison of CNC machines and industrial robots in the machining application [9].

Nowadays, industrial robots are generally applied to machining processes with low machining loads such as polishing, grinding, and drilling. These processes remove a small amount of material from parts where small abrasive forces are generated. Since the main goal of polishing or grinding is not to change the shape of the part geometrically, but only to soften the surface, it is not necessary to use the precise movements of an industrial robot for these processes. Industrial robots are used for such processes rather than for processes where precision in millimeters is required, such as turning or milling. On the other hand, polishing and grinding operations using a robot yield better surfaces than three-axis machine tools. Another process suitable for industrial robots is welding, where the welding process has a low machining load [1]. The characteristics of an industrial robot are very important for many industrial applications, such as automated robotic assembly processes. The main problem with introducing an industrial robot into machining processes is its stiffness. From a tactical point of view, low stiffness represents a great inaccuracy in the production of components due to the deflections of the end effector, but also the entire robotic arm during the machining process. From a dynamic point of view, low-frequency vibrations occur during the machining process with low stiffness of the entire system. These vibrations adversely affect the robotic arm itself, where the service life of individual components is reduced, but mainly there is poor surface treatment, which means the formation of uneven width and depth of cut [10].

III. ROBOTIC ARM STIFFNESS

The main and biggest disadvantage is the stiffness of the machining robots for high MRR (fast material removal) operations, such as robotic milling, turning and drilling. Robot stiffness refers to absolute and relative stiffness. We can improve absolute stiffness by improving robot components and optimizing parameters, while relative stiffness is derived from the location and position of the work piece [5]. While temperature-induced error is one of the largest errors in CNC machining components, the motion error caused by machining force contributes most to the overall machining error for robots. While a cutting force of 500 N in a robotic arm milling process causes an error in geometric accuracy of 1 mm, on CNC machines with the same cutting force the geometric accuracy error is 0.01 mm. In order to achieve higher dimensional accuracy, the deformation caused by the interactive force must be compensated. Force compensation is performed in the Cartesian area.

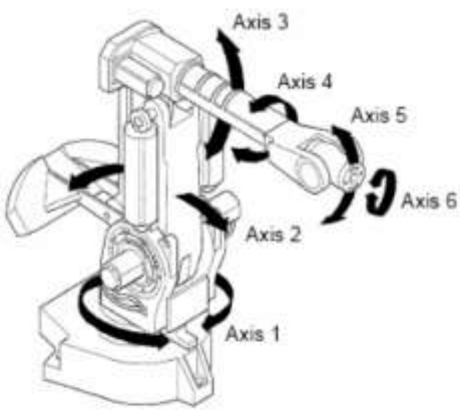

Figure 4 Structure of robotic arm with six degrees of freedom

The model must be accurate to predict the deformation of robotic structures under any load conditions, but it must also be simple to implement in real time. Industrial robots are designed to achieve high strength and accuracy. Elastic properties are insignificant. The dominant factor for the large deflection of the end effector is caused by the flexibility of the joint. This means through the elasticity of the gears. Robotic stiffness modeling is reduced to six components of rotational stiffness in the joint space [11].

To analyze the design of the robot, it is necessary to determine the stiffness value of each joint. The stiffness of the robotic arm and so important that this issue will take place in several researches in the field of robotics. Aspects such as stiffness modeling of serial and parallel robots have been much discussed in these topics. According to the analyzed literature, commonly used models corresponding to Cartesian stiffness matrices [12, 13]. To determine the Cartesian stiffness matrix the principle of virtual task is used, which makes it possible to make certain assumptions about a static case. In this principle, the task must be the same in all coordinate systems, that is, the task in Cartesian coordinates must be the same as the task in articulated coordinates. Therefore, by mathematically deriving the virtual task equation, the expression for the Cartesian stiffness matrix is given as:

$$K_x = J(Q)^{-T} \cdot K_q \cdot J(Q)^{-1} \quad (1)$$

Where K_q corresponds to the joint stiffness matrix and (Q) the Jacobian robot matrix. This formulation only applies if the robot is in a quasi-static configuration, without external loads. Through Conservative Congruence Transformation (CCT), another term known as K_g or K_F has been added, which takes into account changes in geometry in the presence of external changes F.

$$K_x = J\ (Q) - T \cdot (k_q - Kg) \cdot J(Q)^{-1} \quad (2)$$

Where K_q is defined as:

$$Kg = \frac{\partial[J(Q)]^{-T}}{\partial\theta_1}F \ldots \frac{\partial[J(Q)]^{-T}}{\partial\theta_{n-1}}F \ \frac{\partial[J(Q)]^{-T}}{\partial\theta_n}F \quad (3)$$

The extended definition of the stiffness of the robotic arm takes into account the action of external forces on the end effector. This is not commonly used because many studies consider it to be a negligible value when the robot is in optimal stiffness in the workspace. For an articulated arm, the Cartesian stiffness matrix is not a diagonal matrix and depends on the robot configuration [12, 13]. This suggests that, first, the forces and deformations in Cartesian space are linked, and force applied in one direction generates a deformation in all possible directions. Second, the rigidity is a function of the robot's kinematics according to Jacobian, j(Q), which varies significantly in the robot's workspace and according to the position the robot has [9].

IV. REPEATABILITY AND ACCURACY OF ROBOTIC ARM

Another major disadvantage of robotic arm machining is the repeatability of the robotic arm movement and the position accuracy of the end effector. It is a major technological barrier in the robotic industry. Of course, nowadays we strive to increase the accuracy and reduce the error rate between the basic frame of the tool and the target frame. However, achieving high accuracy of the robotic arm is not easy. The identified parameters related to robotics calibration, as already mentioned, are accuracy and repeatability. Each of these parameters depends on the use of various components such as engines, sensors, etc. Repeatability is the ability of a robotic arm to move back to the same position and orientation [14]. In other words, repeatability is the robot's ability to move its tip of the arm to a predefined point within its workspace. This is because each time the robot returns to a predefined point after the cycle is completed, there will be a group of points whose position will be different from the original position. The main parameter influencing repeatability is the speed of the robot's movement. This means that any increase in speed will reduce the repeatability [15].

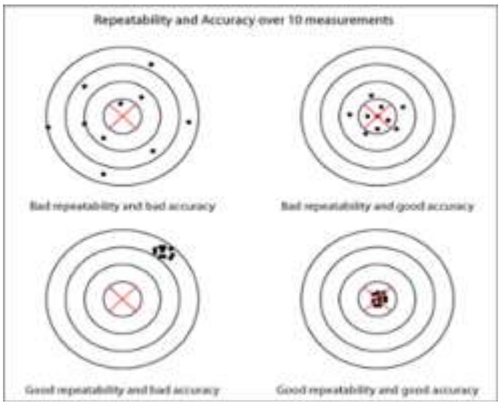

Figure 5 Accuracy and repeatability of robotic arm

Accuracy is defined as the ability of a robotic arm to move precisely to a desired position or point in 3-D space. In the robotic industry, we recognize two principles of accuracy for robotic arms, namely absolute accuracy and dynamic accuracy. Absolute accuracy and repeatability describe the ability of the robotic arm to move to the desired location without any deviation.

V. DESIGN OF EXPERIMENT

In order that the experiment can be effectively and correctly realized, various tools are required that support both the creation and the manipulation of design-space descriptions [16-20]. Design-space descriptions are therefore usually based on the design of experiments. Manufacturing process is often dependent on a relatively large number of variables. Moreover, if we consider robot machining, there are even more parameters. It is practically impossible to test every combination of variables during process development in order to determine the relevant correlations between the individual variables. DOE uses a minimal number of experiments to provide an empirical process model for the interrelationship between the control and disturbance variables in the process and the resulting product and process characteristics [18]. Figure 6 in general the methods of statistical design of experiments is displayed [19]. Fractional factorial designs (screening designs) provide the possibility of significantly reducing the number of experiments. Results from screening designs can also be transferred to a subsequent series of experiments with less investigated factors, known as response surface designs [18, 19,20]. Response surface designs are used to determine and then optimize non-linear interrelationships [20].

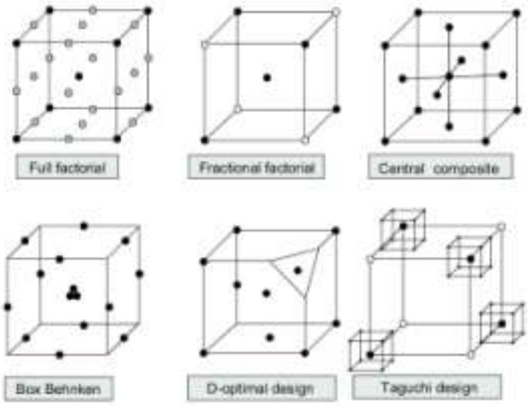

Figure 6. Methods of statistical design of experiments[19]

In our case, more than 2 levels of variables were chosen, than we have to use the Central Composite Design (CCD). A second but also very important reason for choosing of CCD in our case is volition to use surface response method, where 3 levels of variables are necessary condition for surface response modelling. The surface response method is a tool to investigate the response of a variable to changes in a set of design or explanatory variables and helps to find the optimal method for the response as a measurable output of our interest [18, 19]. The base of our CCD plan is two-level full factorial plan which is complemented by central and axial points. Value of

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number α and a number of central points on the base of other requirements (orthogonality, rotatability, number of variables, etc.), [15] related the CCD plan have to be calculated. On Figure 7can be seen the method by which can be CCD realized.

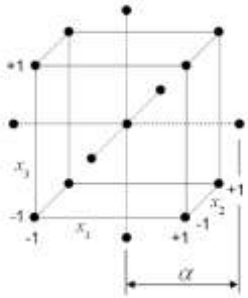


Figure 7. Scheme of CCD plan

As the base, in our case, we will use the 2-level full factorial plan and we will extend it to the shape which we need for displaying the surface response method. Extended plan will have a number of attempts (measurements) than be with 2-level full factorial plan but lower number of attempts than be with 3-level full factorial plan. Number of attempts (measurements) at such a type of plan can be calculated by

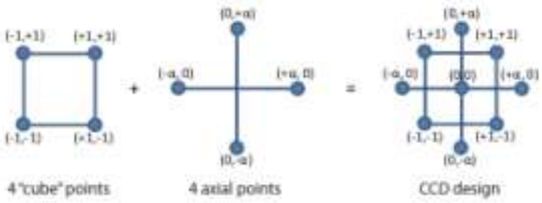
$$2^P + 2P + 1 \quad (4)$$

P – is a number of variables.

The main aim of this procedure is to reasonable decrease the number of attempts according to the fact that we want to use the surface response method. If we would have 3 variables each on 2 levels, a number of attempts would be 9. If we would have 3 variables each on 3 levels, a number of attempts would be 27. According to formula 4, we will have 15 attempts (measurements). This result (number of attempts) is optimized from a realization and also financial point of view. The input designed controllable variables for the robotic milling process can be seen on Table 3. This is basic design of our experimental investigation.Since we have 3 different types of material to be machined, the whole experiment (15 attempts) will be repeated 3 times, separately for each material.

Table 3. Input controllable variables of the robotic milling process

	VARIABLES			
	Feed rate	Depth of field	Feed per tooth	Type of material to be machined
LEVELS	(m/min)	(mm)	(mm)	(-)
1	450	0.5	0.01	Aluminium
2	600	1.0	0.03	11305
3	750	1.5	0.05	17673
4	900	-	-	-



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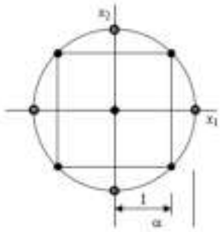

Figure 8. Generation of central composite design (above), and (beneath) Central composite circumscribed rotatable design [18]

We decided to use a central composite circumscribed (CCC) rotatable design (Figure 8), which is suitable when realizing an experiment with the aim in mathematical model form. When we use the regression analysis, the rotatable design allows the simple shape of the confidence zone for the model and also the prediction zone for the individual values [15]. The increasing of 2-level full factorial plan we will realize according the known mathematical-statistical methodology when the number of zero points and value of α depending on a number of variables. For 2 variables we have to use 8 zero points, for 3 variables we have to use 9 zero points, for 4 variables we have to use 12 zero points and for 5 variables we have to use 16 zero points. Value of α can be calculated by

$$\alpha = \sqrt[4]{2^k} \quad (5)$$

k – is a number of variables.

Result of experimental plan designing comes out from the increasing of a 2-level full factorial plan and can be seen in following Table 4, which shows number of attempts (measurements).The number of replications should be designated with using of analysis of surface roughness, repeatability and accuracy of robotic arm. When we would like to estimate the experimental errors, a number of replications should be at least 2 but is better to have more replications. In general with the increasing number of replications also increases the credibility of estimations. With randomization of tests sequences eliminate the systematic errors during the experiment [19].

Table 4. Designed central composite plan for our case

TEST	X_1	X_2	X_3
1	-1	-1	-1
2	-1	-1	1
3	-1	1	-1
4	-1	1	1
5	1	-1	-1
6	1	-1	1
7	1	1	-1
8	1	1	1
9	-α	0	0
10	α	0	0
11	0	-α	0
12	0	α	0
13	0	0	-α
14	0	0	α
15	0	0	0

Results of the experiment realized according to the designed experimental plan will be in our case surface response. The surface response will represent a group of points which forms a

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continuous surface when each axe in orthogonal view represents variables which influence the process and also the output variable [18, 20]. Influence of two input variables is related to the third axes, which mainly represents the output variable. With this type of diagram can be monitored the behaviour of output variable according to the changes of influencing (input) variables. On Figure 9 can be seen as an expected result response surface with values of variables. Colour scaling is helpful and is used for better orientation when the maximum, minimum or transition is wanted.

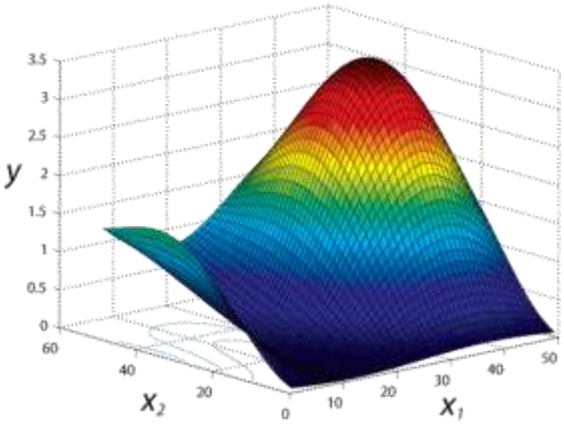

Figure 10. Experiment result displayed through the surface response

To we know to create a surface response, it is necessary to have a "prescription" under which the points in a coordinate system will be bringing out, in other words, a mathematical model that gives us a three-dimensional function displayed as surface response will create. In nowadays for creation of mathematical models are various mathematical - statistics software widely used, which enable comfortable testing of hypothesis, testing of suitability of obtained data (values) and testing of model quality itself. With mathematical - statistics software can be generated many mathematical models, which described the process with some precision and can be chosen that model which suits us from variables composition and required precision points of view. We can find the optimal mathematical model from described points of view.

In our case, multi-factorial analysis of variance (ANOVA) will be used, because we have several input variables which influence the process. ANOVA is used to compare and evaluate mean differences between two or more groups of variables on a single variable. Widely used mathematical - statistics software for all necessary analysis are e.g. JMP, Statgraphics, etc. This software will be used also in our case. Result of the mathematical - statistics software is following model with factorial design

$$y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \varepsilon_{ijkl} \quad (6)$$

μ - is level constant,
α_i - is a share of i-th level of variable x_1,
β_j - is a share of j-th level of variable x_2,
γ_i - is a share of k-th level of variable x_3,
$(\alpha\beta)_{ij}$ - is combined share of i-th level of variable x_1 and j-th level of variable x_2 (interaction),
$(\alpha\gamma)_{ik}$, $(\beta\gamma)_{jk}$, $(\alpha\beta\gamma)_{ijk}$ - represents individual combined shares of given variables (their mutual interaction),
ε_{ijkl} - is a share of l-th observation (error).

VI. CONCLUSION

This paper provides an analysis of recent research related to the application of robots in the mechanicalengineering. The potential for machining with industrial robots is huge, especially in the automotive industry, but also in the mechanical industry, where they can be included in technological operations that require high-quality machining of semi-finished products. Although this paper has shown us that the advantage of industrial robots is a high level of flexibility and larger workspaces compared to CNC machines, we must note that there is still room for improvement until robotic systems are widely used in other applications. The main aim of this paper is to present the designed experimental plan for determination of usage of robot arm for machining, accuracy and repeatability during milling operation. Authors would like to present experimental methodology and evaluation methodology which will be used for experimental evaluation in further.

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