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Assurance of Quality Capability of the Preparation Process of Casting Moulds

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Abstract

The article investigates the problem of assurance of the required capability of robotized process of placing of steel inserts in a casting die. Dependence enabling the determination of the repeatability positioning of the robot, which has been verified in experimental tests is presented. A method to determine the most beneficial location in a workspace of the assembly stand ensuring the highest value of multivariate quality capability index MCp is also proposed. In the final part, the results are discussed and conclusions are formulated.

Keywords: Automation of casting process, Robotization of casting process, Robot selection

1. Introduction

Modern industrial robots are very universal. They were applied with success in so different areas, such as welding, painting, assembling and casting. The effect of using robots in casting processes increases the production capability and decreases the numbers of defective casts and the product costs through the increase of capability [1].

The robots are used both in the casting process under pressure and also in gravity casting. The use of robots in most cases is applied to [2-5]:

- plotting on the surface of section phase of separate medium,
- pouring the pressure casting die,
- taking out of the caked casts from the pressure casting die,
- cooling of the casts through their submersion in the cooling reservoir,
- moving of the casts from cooling reservoir to the automatic position of trimming,
- placing steel piece inside the pressure casting die,
- the dimensional control of the casts.

Generally, the high precision of robots used in foundry engineering is not required. However, an exception is the process of placing of steel inserts poured in moulds. In that case a robot has to be precise enough to orient properly and locate the steel insert. It is especially important in case of programming of robot's working cycle using *in tech* method. The industrial robots are delivered to a user with insufficient information about their accuracy [6, 7]. An example can be the Mitsubishi RV-M2 robot. In its documentation, there exists only a small amount of information that the robot is loaded with a repeatability positioning error equaling ±0.1mm for all axes in its global coordinate system during operation under conditions not exceeding the given values concerning the surrounding environment and the load of the robot. Taking into consideration the fact that the robot rarely operates under full load and that repeatability positioning is not identical at all points of the performed task, the user (assuming the possibility of the maximum value of the error occurring) does not utilize the full potential of the assembly stand.

2. Quality capability indices

The significant problem in the scope of work of robotized casting stands is assurance of required reliability level, which can be obtained by assurance of suitable values of quality capability index. Investigation of quality capability of the machine or process depends on the reference of process spread to the width of assumed tolerance range. In case of placing of steel inserts inside the form (which is an example of assembly of typical machine parts) this test consists in reference to errors generated by a robot (linear or/and angular) to tolerance range on relative displacement or torsion of steel insert axes. Because the errors generated in the casting stand are multidimensional random variables, so for analysis of quality capability of stand should be used a multidimensional index MCp (Multivariate Capability Process Index). In the literature [8-12] a lot of methods of determination this index are known. These may be expressed using following equation:

$$MC_p = \frac{T}{RP} \qquad (1)$$

where:
RP – reputability positioning error of robot,
$T_{\Delta l}$ - tolerance of relative linear displacement of axes of joined elements.

3. Repeatability positioning of the robot

During assembly processes, the robot's gripper at any moment should occupy a precise position in space set by programmed joint coordinate values q_i. Any characteristic position of the M point of the gripper can be determined, in an accepted stationary coordinate arrangement, by a certain function of the joint coordinates [6]:

$$\begin{aligned} X &= X(q_1, q_2, \ldots, q_n), \\ Y &= Y(q_1, q_2, \ldots, q_n), \\ Z &= Z(q_1, q_2, \ldots, q_n) \end{aligned} \qquad (1)$$

In reality, the values of the joint coordinates are with certain errors Δq_i ($i = 1, 2, \ldots, n$), which result in deviation of positioning of the piece from the programmed. The measure of the position dispersion or of the real orientation, obtained by the n-fold repetition of motion in the same direction as the position of the set task, is referred to as repeatability positioning [7]. If we assume the errors Δq_i of variable stochastic independence q_i relative to their nominal values, have certain given normal distribution and that they are statistically independent. Then the reputability positioning will be a two-dimensional variable norm, which is an deviation vector of actual position from the nominal position of the determined parameters in the following manner [6, 13]:

$$\sigma_x = \left[\left(\frac{\partial X}{\partial q_1}\right)^2 \sigma_{q1}^2 + \left(\frac{\partial X}{\partial q_2}\right)^2 \sigma_{q2}^2 + \ldots + \left(\frac{\partial X}{\partial q_n}\right)^2 \sigma_{qn}^2\right]^{0.5} \qquad (2)$$

$$\sigma_y = \left[\left(\frac{\partial Y}{\partial q_1}\right)^2 \sigma_{q1}^2 + \left(\frac{\partial Y}{\partial q_2}\right)^2 \sigma_{q2}^2 + \ldots + \left(\frac{\partial Y}{\partial q_n}\right)^2 \sigma_{qn}^2\right]^{0.5} \qquad (3)$$

$$\rho = \left[\frac{\partial X}{\partial q_1}\frac{\partial Y}{\partial q_1}\sigma_{q_1}^2 + \frac{\partial X}{\partial q_2}\frac{\partial Y}{\partial q_2}\sigma_{q_2}^2 + \cdots + \frac{\partial X}{\partial q_n}\frac{\partial Y}{\partial q_n}\sigma_{Q_n}^2\right] \cdot \left(\sigma_x \cdot \sigma_y\right)^{-1} \qquad (4)$$

where: σ_x – standard deviation component of Δx error vector,
σ_y – standard deviation component of Δy error vector,
ρ – correlation coefficient components of Δx and Δy error vector.

4. The identification repeatability positioning error of the robot

Due to the fact that the purpose of the study was not to define the exact map of parameter values of random variables, defining the errors of repeatability positioning in all the typical places of the robot's working environment, but to verify the method for determining the errors, measurements of the variables were taken only in a few points of the robot's task, found in its recommended working space. The results of the measurements were verified by statistical studies. In statistical populations, the studied characteristics (error on the direction of axis X and Y – Δx, Δy) are two-dimensional normal distributions with a linear coefficient factor, determined with the help of a mathematical model, with a value of ρ (4) and marginal distributions respectively equaling $N(0, \sigma_x)$ and $N(0, \sigma_y)$, the analysis of the results of experimental data was conducted in two stages. The first phase verified the hypothesis of compliance of the boundaries of probable distributions with the distributions obtained theoretically. To verify the hypothesis of the compatibility of the empirical distribution with the hypothetical distribution, the Kolmogorov test was used. Then on the second phase, the hypothesis $H: \rho_o = \rho$ was verified, meaning that the correlation coefficient ρ_o, in the studied population, is equal to the theoretically calculated value ρ (4). Each of the analyzed points, in the work area, of statistical value did not belong to a crucial set, so there was no reason to reject the hypothesis on the basis of the significance that $\alpha = 0.05$, and that the parameters of the random variable error take the value obtained by means of mathematical modelling. The results of the calculations and measurements of the errors, for two sample points in the workspace of the robot, are presented in Figure 1 and 2.

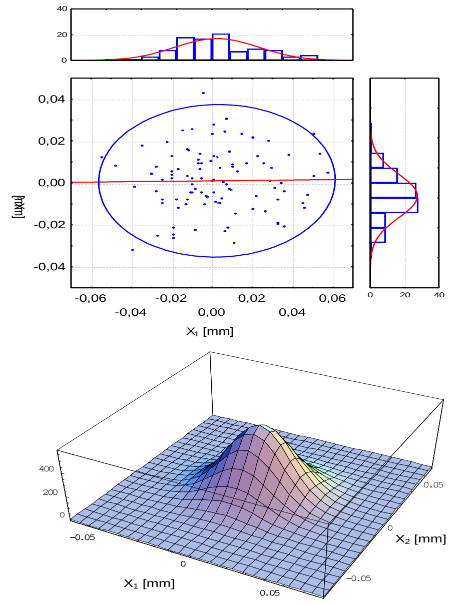

Fig. 1. Results of measurement errors of robot's repeatability positioning ($\sigma_1 = 0.017$ mm, $\sigma_2 = 0.016$ mm, $\rho = 0.045$) and density function diagram comply with determined parameters

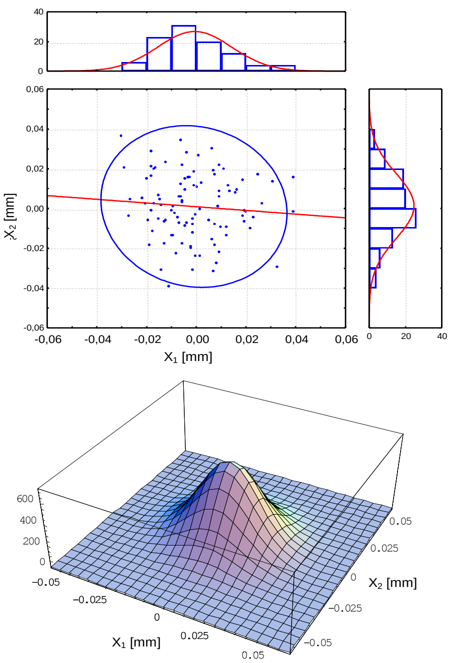

Fig. 2. Results of measurement errors of robot's repeatability positioning ($\sigma_1 = 0.015$ mm, $\sigma_2 = 0.014$ mm, $\rho = -0.086$) and density function diagram comply with determined parameters

5. Determination of optimal location in the robot workspace

The task of determining the optimal location in the assembly workspace, consists in seeking the point at which the robot generates the lowest error value and thereby the highest value of index of repeatability positioning is reached. The objective function depends only on the choice of site for the connection in the space of the robot, characterized by the set of joint coordinates [6, 14, 15]:

$$\max f(Q) \tag{5}$$

$$Q = [q_1, q_2, \ldots, q_n] \in Z_M = \{Q : \psi_i(Q) \le 0, \quad i = 1, \ldots, m\} \tag{6}$$

where: f – the objective function, the function n – variables, transforming the n-dimensional real space R^n into a set of real numbers R^1,
Q – n-dimensional vector of deciding variables (joint coordinates),
Z_M – set of feasible solutions (set of possible to generate joint coordinate values),
$\Psi_i(Q)$ – functions limiting the set of feasible solutions.

In realistic conditions, assembly may not take place in all points within the workspace. The most notable area in the Cartesian coordinate system, associated with the robot's base, in which it is possible to carry out the assembly process of steel insert locating in the into form and also the orientation which the manipulated element must possess in the form of:

$$Z_M = \begin{cases} x_1 \le X(q_i) \le x_2 \\ y_1 \le Y(q_i) \le y_2 \\ z_1 \le Z(q_i) \le z_2 \\ \Phi(q_i) = \varphi \end{cases} \tag{7}$$

where: x_i, y_i, z_i – given values of the Cartesian coordinates,
φ – angle defining the orientation of steel insert in terms of the XY plane.

The biggest influences on the process of steel inert locating of cylindrical surfaces are the errors in the plane perpendicular to their axis, therefore in the objective function as RP value the repeatability positioning of the robot in the XY plane was assumed:

$$f(Q) = MC_p = \frac{T}{3\left(\sigma_x^2 + \sigma_y^2\right)^{0.5}} \tag{8}$$

The expression (8), after taking into account formulas (2) and (3), takes the form:

$$f(Q) = MC_p = \frac{T}{3\left(\sum_{i=1}^{n}\left(\frac{\partial X}{\partial q_i}\right)^2 \sigma_{q_i}^2 + \sum_{i=1}^{n}\left(\frac{\partial Y}{\partial q_i}\right)^2 \sigma_{q_i}^2\right)^{0.5}} \tag{9}$$

In the case of assembly of steel inserts with flat surfaces, tolerance of the relative displacement of their axis, in the direction of the *X* and *Y* axis, of the adopted coordinate system is usually not the same. Therefore, the objective function can assume the standard deviation of the error of the random variable σ_x or σ_y. In the referred study, during analysis it was assumed that the tolerance of the relative displacement is smaller for the *X* axis. Therefore, the value of the objective function $3\sigma_x$, was adopted as:

$$f(Q) = MC_p = \frac{T}{3\left(\sum_{i=1}^{n}\left(\frac{\partial X}{\partial q_i}\right)^2 \sigma_{q_i}^2\right)^{0.5}} \tag{10}$$

For accepted limitations and parameters of the robot established in its documentation [6], the value of tolerance T equals to 0.2 mm, the maximum of objective function values are determined. They respectively amounted to 1.58 for steel inserts of cylindrical and 2.56 for steel inserts of flat surfaces. In order to determine the extent of quality capability index variations, in the examined space of the robot, the minimum values of functions (9) and (10) were also determined. They respectively amounted to 1.11 and 1.33. Therefore, the error values can vary from 50-90% of the robot's error value specified in its technical documentation (0.1mm), if we take into account the errors in the *XY* plane, and from 39-75% on the direction of *X* axis only. The selection of optimal place of the process realization allows to increase MCp index by 42% in case of steel inserts of cylindrical surfaces and 92% for steel inserts of flat surfaces.

6. Conclusions

Designing a robotized foundry stand is a difficult and laborious task, requiring above all the knowledge of the accuracy of the possessed equipment. In the case of an industrial robot, consisting of its main equipment, the technical documentation contains the factual information about its accuracy, but this is often inadequate. Obtaining the required information, concerning the repeatability of positioning, is usually associated with the need to carry out difficult and time-consuming measurements at many points in its workspace. However, this does not give full information about the error values of the robot because it is impossible to perform the measurements at all points in its workspace. An alternative solution to the stated problem can be the proposed method for determining the robot's errors, requiring a much smaller amount of measurements to be taken that would be necessary to determine the parameters of the random variable errors of the joint coordinates of the robot and for their verification by the repeatability of positioning in randomly selected points in the workspace. On this basis, the designer can, even at the design stage, designate the workspace at which the robot has the highest accuracy and ensure the required value of the required value of quality capability index MCp. The value of MCp index is responsible for assurance of requied reliability level of the casting stand.

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