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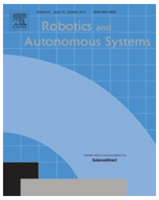

Analysis of the optimal orientation of robot gripper for an improved capability assembly process

Rafał Kluz[a,1], Tomasz Trzepieciński[b,*]

[a] Rzeszow University of Technology, Faculty of Mechanical Engineering and Aeronautics, Department of Manufacturing and Production Engineering,
12 Powstańców Warszawy Avenue, 35-959 Rzeszów, Poland

[b] Rzeszow University of Technology, Faculty of Mechanical Engineering and Aeronautics, Department of Materials Forming and Processing,
12 Powstańców Warszawy Avenue, 35-959 Rzeszów, Poland

HIGHLIGHTS

- We presents the method of determining the optimal angle of rotation of the robot gripper.
- By the suitable rotation of the robot gripper, the probability of joint is increased.
- The proposed method allows to increasing the value of process capability index C_p.
- Optimum setting of the gripper enables the reduction of clearance fit between mating parts.

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ABSTRACT

The objective of the article is to increase the probability of achieving a joint of cylindrical machine parts, through appropriate orientation of the robot gripper of the assembly robot, while ensuring the best parameters of the assembly process and the required process capability, without unnecessarily increasing the accuracy of the assembly workstation equipment. The presented methodology for the summation of errors, besides its simplicity, has an additional advantage compared with the method of the summation of variance or error vectors separately in regard to each axis of the adopted coordinate system, because it takes into account the nature of the relationships between variables (covariance). The analysis showed that by rotation of the gripper around an oriented axis of the machine cylindrical part, the probability of the joint and process capability index C_p value can be increased from $C_p = 1.17$ to $C_p = 1.33$. The optimal orientation of the robot gripper enables the clearance fit between mating parts to be reduced by 8% and 19% with respect to its extreme unfavourable setting. However, this setting of the robot gripper reduces the sensitivity of the system to the effects of systematic errors.

1. Introduction

In industry, robots are used to increase levels of production. This fact has been proven as productivity levels have risen by 67% compared to before the implementation of robots [1]. The performance of an industrial robot can be defined by a few vital factors such as [2]: accuracy, resolution, repeatability, operational speed, positional error and payload ability. The positional accuracy depends on many factors, among the most important of which are the position of the working zone in the workspace and the transported load. The positional accuracy can be absolute, when we have a fixed reference, and repeatable, when it represents the reproducibility accuracy of the same zone [3]. Taking into consideration the fact that the robot rarely operates under full load and that the positioning repeatability 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 use the full potential of the assembly workstation.

A lot of specialized devices are being developed for specific assembly processes and/or for specific parts. However, they still have faults that cannot be easily and cheaply eliminated, and which must be taken into consideration when designing the assembly workstations. These faults include additional positioning and

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* Corresponding author. Tel.: +48 17 86 51 714; fax: +48 17 85 43 116.
E-mail addresses: rkktmiop@prz.edu.pl (R. Kluz), tomtrz@prz.edu.pl (T. Trzepieciński).

[1] Tel.: +48 17 86 51 725; fax: +48 17 85 43 116.

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Nomenclature

α	Deviation angle of the principal axes
β	Angle of rotation of the gripper
φ, ω	Angle of gripper rotation around axes x_1 and x_2, respectively
η_1	Positioning repeatability error of the robot
η_2	Positioning repeatability error of the gripper
η	Random vector describing the location error of a joined part
ξ	Positioning repeatability error of the base part
ς	Vector, difference between the vectors ξ and η
δ	Clearance fit of the joint
σ	The standard deviation for a population
μ	Process mean
λ_{gr}	Permissible axis torsion of mating parts
q_i	Joint coordinates
$r(\varsigma_1, \varsigma_2)$	Radius of a hypothetical cylinder
$P_e^{(i)}, P_t^{(i)}$	Probability evaluated experimentally and analytically, respectively
$\sigma_{\Delta\varphi}, \sigma_{\Delta\omega}$	Standard deviation of a random variable of the gripper orientation error with respect to axes x_1 and x_2, respectively
$\Delta\varphi, \Delta\omega$	Orientation error of the gripper with respect to axes x_1 and x_2, respectively
$C_{\mathrm{p}}, C_{\mathrm{pk}}$	Capability indices
(x_1, x_2)	Coordinates point of two-dimensional Euclidean space
$\sigma_{\xi x_1}, \sigma_{\xi x_2}$	Standard deviation of x_1 and x_2 of components of the error vector of positioning repeatability of the base part
$\sigma_{\varsigma_1}, \sigma_{\varsigma_2}$	Standard deviation of the error vector of x_1 and x_2 components of the relative displacement of parts axes
$N(\mu_\xi, \Sigma_\xi)$	Two-dimensional normal probability distribution of the location error of the base part
$N(\mu_\eta, \Sigma_\eta)$	Two-dimensional normal probability distribution of the location error of the joined part
$\Sigma_\varsigma, \Sigma_\xi, \Sigma_\eta$	Covariance matrices of vectors ς, ξ and η, respectively
$\Sigma_{\eta 1}, \Sigma_{\eta 2}$	Covariance matrices of random variables of the error of the robot and gripper, respectively
Σ_ς	Covariance matrix of the error vector of relative displacement of the axes of joining elements
Σ_c	Covariance matrix of vector of positioning repeatability error of the robot gripper
$\mu_{\eta 1}, \mu_{\eta 2}$	Matrices of expected values of random variables of the error of the robot and gripper, respectively
μ_ξ	Matrix of expected values of the random variables of the error of the base part
μ_ς	Matrix of expected values of relative displacement of the axes of joining elements

orientation errors caused by such devices, as well as long duration of the work cycle, which reduces the process efficiency [4]. The designer of assembly workstations should have at his disposal a model for rapid estimation of the robot's accuracy in order to select the workstation configuration that will be the best compromise between precision and functionality [5].

Part mating is one of the basic assembly operations and has a highly nonlinear dynamic nature. During part mating, significant uncertainties are inherently present in the robot's assembly workstation. The origin can be [6]:

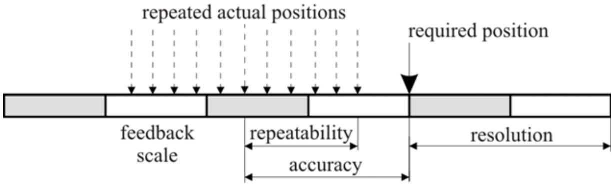

Fig. 1. Relationship among the resolution, accuracy and positioning repeatability of robot arm.

- geometrical (e.g., parts tolerances, position of environmental object, position of the robot gripper, sliding of moving object in gripper),
- dynamic (e.g., rigidity of the system, elasticity of parts in contact, uncertainties in the friction model).

The mentioned uncertainties lead to errors during robot gripper motions.

The complicated geometry of mating parts and uncertainties caused by manufacturing tolerance, as well as motion control errors, have to date been barriers to equipping the system with an adaptive capability [7]. These uncertainties generate a misalignment at the interface between mating parts, and make it difficult to achieve successful assembly.

The relationship among the resolution, accuracy and positioning repeatability of the robot arm is shown in Fig. 1. In the automatic assembly process, and particularly in the robotic one, many devices are used to ensure the correct parts mating process in the product and to increase the productivity and safety. Such equipment can be subdivided into passive [8,9] and active [10,11] devices to support the mating process.

One of the major problems of modern industry is to increase the accuracy of the robotic assembly stand. Robotic assembly stands, providing accurate positioning parts relative to each other, are the most demanding in this respect [12].

Assessing the positioning performance of an industrial robot in the assembly stand is a very complex task that requires a special metrology equipment [13,14]. Young and Pickin [15] assessed the static positioning accuracy and positioning accuracy of a six-axis industrial robot by measuring only the linear position error and the two straightness errors at five poses along a linear path parallel to the base X and Y axis. They found that the bidirectional position repeatability is within 200 μm, while the linear position errors can be as large as 1.6 mm. Summers [16] used a Krypton motion tracker to conduct a performance assessment of four six-axis industrial robots. While the volumetric accuracy errors of the robots were as large as 7 mm at one metre, repeatability was found to be 20–30 μm. Muelaner et al. [17] conducted a study of the positioning repeatability of a KUKA KR240 industrial robot. It was found that repeatability is no more than 10 μm when short periods of time are considered. Eastwood and Webb [18] used a triad of digital indicators to evaluate the impact of various sources of errors in a Tricept parallel robot, and proposed compensation strategies for some of these errors. Bréthé et al. [19] studied the positioning repeatability of a UKA IR364 industrial robot at several locations and found it to be less than 36 μm. The results of experimental investigations by Riemer and Edan [20] showed a significant statistical difference between repeatability at different work-volume locations. The height of the target point was found to be a major factor determining the repeatability of a point within the work-volume. Wang et al. [21] indicated that a robot typically has a motion error of 0.1 mm without contact. Furthermore, the majority of positioning errors come from the force of the contact causing deformation that adversely affects the robot structure. Alzarok et al. [22] investigated the positioning accuracy and path repeatability of a six-axis Mitsubishi RV-1A robot during machining movements. The results show the significant motion

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