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doi:10.15199/48.2019.11.22

Testing the extended capabilities of an industrial robot equipped with an adapted working tool

Abstract. *This paper presents the course of work related to the modification of an industrial robot. The functionality of the industrial robot has been extended by including an adapted tool in its kinematic chain instead of the original tool. The article shows the way of modernizing the robot, the method used to test and calibrate the robot. The diagram of the robot's operation during tests is shown and the test results are discussed.*

Streszczenie. *W artykule przedstawiono przebieg prac związanych z modyfikacją robota przemysłowego. Funkcjonalność robota przemysłowego została rozszerzona przez zastosowanie zaadaptowanego narzędzia w jego łańcuchu kinematycznym zamiast oryginalnego narzędzia. W pracy przedstawiono sposób modernizacji robota, zastosowaną metodę testowania i kalibracji robota. Pokazano schemat działania robota podczas testów i omówiono wyniki testów. (**Badanie rozszerzonych możliwości robota przemysłowego wyposażonego w zaadaptowane narzędzie robocze**).*

Keywords: industrial robot, calibration, accuracy, repeatability.
Słowa kluczowe: robot przemysłowy, kalibracja, dokładność, powtarzalność.

Introduction

Industrial robots carry out various tasks depending on their design and functional properties. The tasks they can perform depend on their working space and the working tool (called the end-effector), usually located at the end of the kinematic chain of the robot [1]. The characteristics and properties of industrial robots are related to the specificity of their applications. The most important feature of industrial robots is their programmability. This enables the robot to be used for various industrial purposes without interfering with the mechanical construction of the robot and its control. Only two robot axes are required to reach any point on the surface. The robot must be provided with an additional axis to reach any point in space. Six-axis robots allow for any manipulation of the tip at any point in space thanks to their anthropomorphic (human-like limbs) construction.

The number of robot axes is related to the number of degrees of freedom, as a rule it connects with the number of drives that set the joint in motion. The joint is a movable connection of two links (arms). The following types of joints are used: rotary, sliding, spherical, cylindrical and helical. The number of degrees of freedom is defined as the number of items moving independently in the robot, thus creating the scope of the robot's working space [2]. The working space is increased using the end-effector (working tip) depending on the needs. The space in which the tip of the robot can move can be limited by software to prevent mechanical damage to robots or neighbouring devices.

An important feature of the robot is its lifting capacity. It defines the maximum permissible mass of transferred elements. At the design stage of the robot, this property cannot be determined without taking into account other factors, such as the allowable moments loading the robot's arm, namely the moment of inertia and the moment of force generated by the load. The speed of the robot's work is related to the speed of movement of its tip. It results from linear and angular velocities of individual axes. The accuracy of the robot determines the measure of the error (proximity) with which the end-effector can reach the set point in the working area. The concept of accuracy involves repeatability, that is, proximity to a previously obtained position. Both of these features can be increased as a result of robot calibration.

The purpose of this work is to analyze, develop assumptions, design, simulation tests and study an industrial robot with a replaced working tool [3]. This tool is not a standard accessory of considered robot but it was adapted as the robot end-effector.

The considered robot is used in the Laboratory of Measurement and Control Systems in the Marine Electrical Power Engineering Department of Gdynia Maritime University.

The robot

The industrial robot Epson LS3-401S (see Fig.1) is a 4-axis SCARA (Selective Compliance Assembly Robot Arm) robot [4]. From the standard 3-axis robots of this class, it is distinguished by an additional rotary axis that allows the end-effector to rotate. The whole robot arm has 4 degrees of freedom. It is based on two parts (see Fig.2): Arm 1 and Arm 2 as well as four joints. Joint 1 performs a rotational movement of Arm 1, Joint 2 works similarly, but the range of movements of Arm 2 is greater than Arm 1. Joint 4 is responsible for the angular position of the end-effector, while Joint 3 performs an upward or downward movement of the end-effector, adjusting the height of the robot working tool. The robot is powered by an electric drive, each joint is equipped with a servomotor that drives them. The robot can raise loads up to a maximum weight of 3 kg, but the recommended weight during normal work is up to 1 kg.

Such robots are used when moving elements from one production line to another or from a line to another place, e.g. on the packaging. They are also used to level the route of elements on the production line. Their design allows for quick loading or unloading of goods. They also participate in the assembly of precise mechanisms. In short, they are used for palletizing, de-palletizing, loading, unloading and assembly.

Fig.1. View of the Epson LS3-401S robot

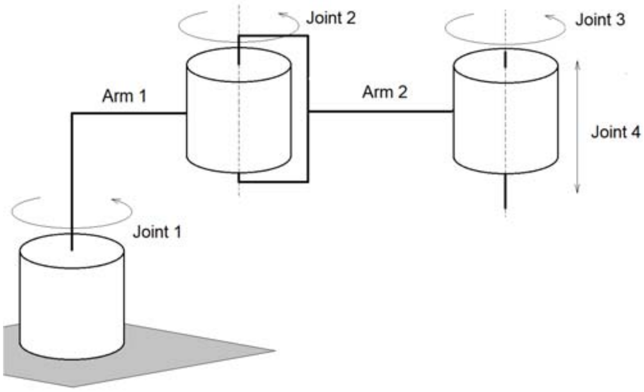

Fig.2. Kinematic model of considered robot

The robot end-effector

Originally, the robot worked with a suction cup (see Fig. 3.a) and could be used, e.g., to segregate elements on a given production line. The task of the project is to modify its working tool and controller port, as well as the robot software, so that it can work with such elements that can be picked up and moved by the gripper. As part of the study, the pneumatic gripper [5] (see Fig. 3.b) was adapted and used instead of the original working tool of the robot. An additional, specially designed mechanical adapter was needed to attach it to the robot's mounting tip on the shaft in Joint 4.

The block diagram of the LS3-401S industrial robot (see Fig.4) shows a simplified version of its mechanical, electrical and pneumatic connections in configuration with a new working tool. Supervision over the work of the robot is performed by the RC90 controller, which interprets the user program written in the RC+7.0 environment installed on a standard PC [3]. The robot supervisory program controls the movement of the working tip in all planes, including the use of all possible arms and robot joints, opening and closing the gripper and moving parts. The pneumatic hoses are connected to the compressor and the working tool. The robot base, each joint and arms are mechanically connected, which is marked in green in the diagram.

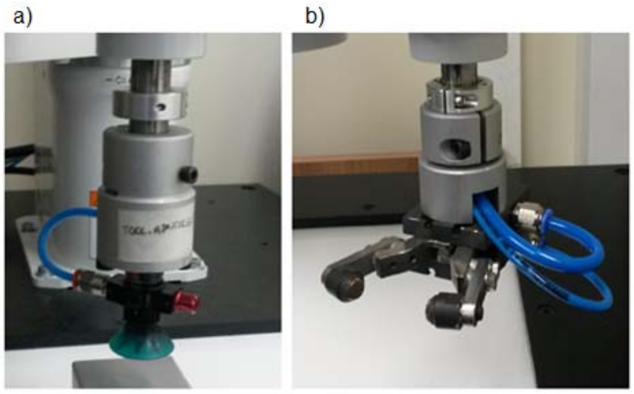

Fig.3. Working tools of the tested robot: a) original tool - suction cut, b) adapted tool – gripper

After mounting the gripper, it was necessary to ensure control of the gripper's operation. Considering that one solenoid valve has already been mounted and used previously to control the suction cup, it can be used to open the gripper arms after applying appropriate air pressure. Installation of an additional solenoid valve [6] was necessary to achieve full control over the gripper. The necessary additional electrical terminals were installed on the RC90 controller mounting rail, and the controller wiring was modified.

The coordinates of the work point for the gripper differ from the suction cup coordinates. These differences can be compensated by calibration procedures.

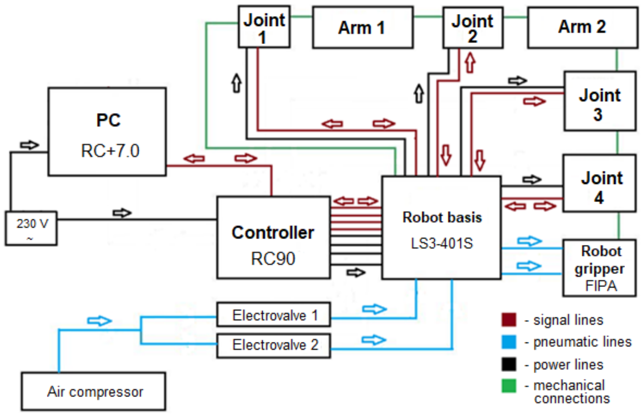

Fig.4. A simplified block diagram of a modified robot

Calibration procedures

Industrial robots, like all machines, require periodic testing. This is the basis for maintaining the efficiency of their operation and ensuring the continuity of work. One of the basic tests is to assess the accuracy and repeatability of the robot operations [7, 8, 9]. In addition to the accuracy of the robot's work, the results of such a study indicate the degree of wear of its components, which results in the lack of repeatability of performed activities.

Sources of errors concerning the robot operations can be classified into three main categories [7]: environment-dependent errors, robot-dependent errors and process-dependent errors. Environment-dependent errors concern with the way of how the robot is mounted. Robot-dependent errors deal with various deviations caused by improper robot links and joints geometry and the dynamical behaviour of the robot that is affected by structural deformations. Process-dependent errors concern mainly with working conditions such as working speed, features of details with which the robot works, etc.

The basic operation carried out to improve the accuracy, and hence repeatability of a given robot, is to calibrate the position of its joints. It consists in reducing the difference between the set point and the actual position of the robot's working tool in terms of the corresponding coordinates. The methodology of increasing the accuracy of the work path of an industrial robot using dedicated measuring instruments is described in [10, 11].

In case of considered robot, the RC+7.0 firmware is equipped with extensive calibration procedures for the end-effector position [4]. The first step is rough calibration. The same rough calibration procedure is used for each joint. For selected joint, it must first be moved to its zero pulse position, and then the coordinates of the reference point must be selected programmatically and calibration jig should be moved near this position using the jog motion command. Then, the automatic motion command has to be executed. The second step is the accurate joint calibration. It consists in precise setting of the position of the calibration jig at the reference (target) point (see Fig. 5.a) by jog motion and position confirmation.

The calibration procedure allows to take into account the zero point of the gripper, which is asymmetrical with respect to the axis of the shaft in Joint 4 (65 mm shift) (see Fig. 5.b). In this case, the coordinates of the work point do not require any additional calculations. A detailed description of the entire calibration procedure can be found in [4].

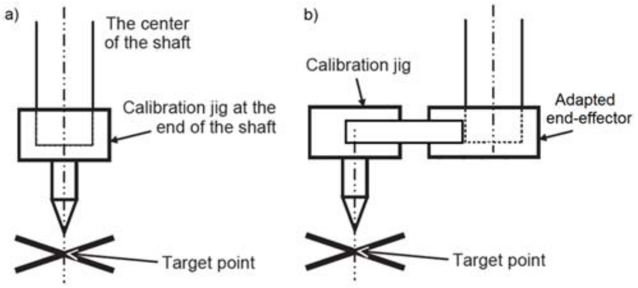

Fig.5. The calibration jig at the reference point: a) mounted on the Joint 4 shaft, b) held by the adopted end-effector

Starting from the end-effector position at any point in the working area that has a different pose, and using the automatic movement commands to move the end-effector to the reference point, the estimation of end-effector positioning accuracy can be carried out. This procedure was performed by measuring a series of positions of calibration jig and comparing them with the position of the reference point, separately for X and Y coordinates.

In accordance to [12], the accuracy of X position is defined as:

(1) $$AP_x = \bar{x} - x_r$$

where: x_r is the desired X coordinate of the reference point and $\bar{x}$ is the arithmetic mean of the n measurements; the accuracy for Y coordinate can be expressed in the same way.

The resultant distance accuracy can be expressed as:

(2) $$AP_x = \sqrt{AP_x^2 + AP_y^2}$$

The repeatability of the end-effector positioning (X coordinate) is defined as [12]:

(3) $$RP_x = \pm 3 \cdot S_x = \pm 3\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

where: n is the number of measurements; the repeatability for Y coordinate can be expressed in the same way.

The resultant repeatability RP for both coordinates have been evaluated using formula:

(4) $$RP = \sqrt{RP_x^2 + RP_y^2}$$

The measurement was applied 30 times for each of the two axes for different starting points.

The analogous measurements were carried out for the calibration jig held by the gripper.

The preliminary measurements were performed manually using the Mitutoyo Absolute Digimatic Caliper regarding the rim of the working area. The caliper´s specification is: accuracy 0.02 mm, resolution 0.01 mm and range 200 mm.

Based on the technical data of the robot under consideration, the repeatability for its joints is as follows:

- horizontal repeatability of Joint 1 and Joint 2: RPJ_1=RPJ_2=±0.01 mm,
- vertical repeatability of Joint 3: $RPJ3$=±0.01 mm,
- orientation repeatability of Joint 4: $RPJ4$=±0.01° (it corresponds to approx. 0.02 mm on the gripper catch point shifted with 65 mm from the centre of the shaft).

For the robot under consideration, Joint 1, Joint 2 and Joint 4 determine the location of the end-effector within the working area (horizontal X and Y coordinates). The resultant horizontal repeatability RPr for all three joints can be evaluated using formula:

(5) $$RP_r = \sqrt{RP_{J1}^2 + RP_{J2}^2 + RP_{J4}^2}$$

Based on technical data, the repeatability of positioning of the working tip does not exceeds RP_r=±0.02 mm.

Table 1 shows the estimated repeatability of the positioning of the calibration jig, calculated on the basis of the test results carried out during calibration operations. It also includes the estimated repeatability based on robot's declared technical data, as well as the repeatability of the positioning of the wooden block obtained during the tests described in the next sections.

Table 1. The comparison of estimated repeatability RP

	Technical data of robot	Calibration jig on shaft	Calibration jig held by gripper	Wooden block positioning
RP [mm]	±0.02	±0.15	±0.18	±0.30

Experimental setup

According to the implemented project, sequential work of the robot consists in moving three wooden blocks in the designated area (see Fig.6). Initially, the blocks are positioned in three corners and rotated by 90 degrees. The robot has the task of moving individual blocks in a loop, in steps 1 to 7. One cycle of movements of the robot's tip shows Fig. 6. The starting positions of the three blocks are marked in red, and the filled rectangles mean two blocks placed one on top of the other. One cycle from this test can be seen at https://www.youtube.com/watch?v=RDsSrSNC9YY&feature=youtu.be.

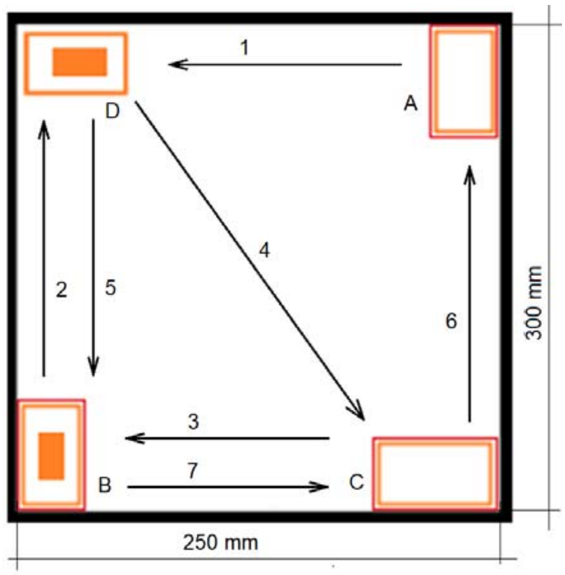

Fig.6. Robot workflow during tests – one cycle of operations within the work envelop

In the first step, the wooden block is taken from A position and moved to D position. Then, the block from B is placed on top of the block in D. In the third step, the block is transferred from C to B, than another block from D to C and so on. The cycle is completed after 7 steps and all three blocks are in the initial positions again.

Functional tests

Numerous experimental tests were carried out in terms of the correctness of the robot's movements and the repeatability of the position of the blocks. The modified robot with adapted end-effector has been subjected to continuous work related to the performing operations in many cycles. A single continuous test consisted of 50 cycles, according to the programmed sequence. The robot performed tasks at two different speeds: 50% of maximum speed and maximum working speed.

During the preliminary functional tests, the wooden blocks were moved asymmetrically relative to the individual corners of the gripper working space. It was possible to notice the lack of linearity at the block edge position when one element was set on the other. The problem has been eliminated by optimizing the Z coordinate of the gripping points on the wooden blocks to keep them stable when moving. After introducing appropriate corrections, full control over its movement was obtained. As a result, the gripper moves smoothly, realizing the successive stages of the sequence of movements.

The programmed sequence allowed to assess the correctness of the basic activities of an industrial robot equipped with a new tool: moving in various planes, correct operation of the gripper consisting of gripping and placing elements in the indicated places, correct mapping of movements of a specific trajectory. The position of the wooden blocks after 50 cycles coincides with their initial position within the margin of error ±0.3 mm (see Table 1). This difference is mainly due to the heterogeneity of wooden blocks used. It was found that the value of the gripper movement speed on a given trajectory does not affect the accuracy and repeatability of the process.

Conclusions

The conducted preliminary research allowed to state that the industrial robot, after the extension and replacement of the manipulator terminal with the adapted tip, works properly and performs the tasks programmed in the sequential work, after making the appropriate corrections and recalibration. Recalibration was associated with the optimization of points on the body of the wooden block to securely hold it.

Obtained results are proof that effective calibration of robot drives is applicable without dedicated measuring instruments, even when using an adapted robot end-effector. In the case of the robot under consideration, the calibration procedures embedded in the software allow this.

Further research will be focused on more precise and automated measurements, as well as on integration of robot control with the LabVIEW environment that cooperates with the object position detection system.

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