1. Introduction

The basic idea behind the delta robot ABB design is the use of parallelograms. A parallelogram allows an output link to remain at fixed orientation with respect to an input link. The use of three such parallelograms restrain completely the orientation of the mobile platform which remains only with three purely translational degrees of freedom. The input links of the three parallelograms are mounted on rotating levers via revolute joints. The revolute joints of the rotating levers are actuated in two different ways: with rotational (DC or AC servo) motors or with linear actuators. Finally, a fourth leg is used to transmit rotary motion from the base to an end-effector mounted on the mobile platform. The use of base-mounted actuators and low-mass links allows the mobile platform to achieve accelerations of up to 50 G in experimental environments and 12 G in industrial applications. This makes the delta robot ABB a perfect candidate for pick and place operations of light objects (from 10 g to 1 kg). The delta robots ABB available on the market operate typically in a cylindrical workspace which is 1 m in diameter and 0.2 m high [1, 2].

2. Basic properties of robotized workplace

The delta robot ABB is a part of a training workplace equipped with a pair of conveyors. The material flow configuration depends on the type of training that is being realized. At the workplace, it is possible to set two bases of the flow of the material to be handled. In basic training a configuration is used where the delta robot ABB picks up the manipulated objects from the pallet, which is transported on the Bosch pallet conveyor [3]. During the manipulation, the pallet is placed in a precisely defined position using programmable stops. After removing the object and moving it over the conveyor belt, the manipulated object is released and carried by the conveyor to the respective exit position. In advanced training, conveyor functions are opposite. The delta robot ABB picks up manipulated objects randomly placed on the conveyor belt. It then stores them on selected positions in the technological pallet conveyor Bosch. For manipulation used a vacuum gripper with a suction cup with diameter of 5 to 20 mm. The weight of manipulating objects ranges from 50 g to 2 kg. A view on robotized workplace equipped with delta robot ABB is shown in Figure 1.

The delta robot ABB is intended primarily for material handling, part removal, packaging operations or assembly. It is characterized by a high speed of movement, with an integrated
3. Selection of measurement tests and their description

After the measurement it was possible to use the measured data to create compensatory deviations. After the implementation of the compensatory deviations in the robot program, control measurements were carried out to compare the identified inaccuracy towards the manufacturer’s inaccuracies. To measure the relevance of the measurement carried out, it was based on the data and measurement methodology provided by the delta robot ABB manufacturer. In this material the manufacturer surveyed robot parameters using ISO 9283 [5, 6], where focused overall on four types of tests (Pose accuracy \( \text{AP} \), Pose repeatability \( \text{RP} \)). The robot manufacturer reports the measured values in Table 1, with speed 0.8 m.s\(^{-1}\) and a load of 0.1 kg.

In order to compensate for the inaccuracy caused by the damaged arms, we decided to carry out a control measurement using two tests (Pose accuracy \( \text{AP} \), Pose repeatability \( \text{RP} \)). Before the test, the movements of the delta robot ABB must be limited as necessary to set up the measuring instruments. The test must be preceded by a specified heating operation if specified by the manufacturer. The ambient temperature in the tests should be kept within “20±2 °C”. Measured location data (coordinates \( x_j, y_j, z_j \)) must be expressed in a coordinate system whose axes are parallel to the coordinate system axis coordinates of the base of the delta robot ABB being measured. All tests must be carried out under the 100% (10, 50% optional) of rated load (mass, centre of gravity, moment of inertia) in accordance with the manufacturer’s specification (technical specifications). All position characteristics must be tested at the speed of 100 % (optionally 50 %, 10 %) achievable between the prescribed positions. The following requirements must be met: placing the measuring cube in the robot workspace: five points (P1 to P5) are located on the diagonals of the selected plane. These five points together with manufacturer’s guideline, form the test positions must reach the centre of the mechanical test interface. The test positions must be defined by the coordinates of the base. P1 is the
diagonal intersection and is the centre of the cube. Points P2 to P5 are spaced from the diagonal ends “10±2 %” of the diagonal length. If this is not possible, the nearest diagonal point must be selected. All robots joints must be applied while moving between all test positions. Based on the experiments performed on 100 cycles it was decided that the measurement would not be carried out exactly according to ISO 9283. The robot’s workspace has a value “±X,Y= 342.5 mm” and “±Z=125 mm”. The dimension of the cube according to the standard is given by the robot’s workspace, where it was limited in this case by “Z = 250 mm”. For this reason, the cube would have a size of 250x250x250mm, which would not allow a meaningful measurement to be made. The result was a design in which the measurement plane would be parallel to the plane X, Y of the delta robot ABB base, Figure 2. The distance between the extreme points of the plane (P2-P3, P3-P4, P4-P5 and P5-P2) is 685 mm. Measuring points P2, P3, P4 and P5, were selected for measurement where measurements between placements and orientation of the positions achieved were made to provide similar environmental conditions for all points [7].

Selected test parameters with load definitions, output speed of rotation and cycle counts are listed in Table 2.

**Pose accuracy (AP)** - represents a deviation between the programmed position and the average of the positions achieved when moving to the programmed position from the same direction. One way position accuracy is calculated according to:

\[
AP_{1} = (x - x_{c}), \ AP_{2} = (y - y_{c}), \ AP_{3} = (z - z_{c})
\]

Where, \((x_{c}, \ y_{c}, \ z_{c})\) are the programmed values and \((x, \ y, \ z)\) are the actual (measured) values. While:

\[
x = \frac{1}{n} \sum_{j=1}^{n} x_{j} \quad y = \frac{1}{n} \sum_{j=1}^{n} y_{j} \quad z = \frac{1}{n} \sum_{j=1}^{n} z_{j}
\]

The resulting value of one-way wrist precision is based on the relationship:

\[
AP = \sqrt{(x - x_{c})^2 + (y - y_{c})^2 + (z - z_{c})^2}
\]

**Pose repeatability (RP)** - indicates the degree of match between placements and orientation of the positions achieved after n-repetitions to the same programmed position on the same direction. For a given position, it expresses the RP value that is the radius of the sphere whose centre is the barycentre and which is calculated:

\[
RP = l + 3S_{r}
\]

where,

\[
S_{r} = \sqrt{\frac{\sum_{j=1}^{n} (l_{j} - l)^{2}}{n - 1}} \quad l = \frac{1}{n} \sum_{j=1}^{n} l_{j}
\]

The coordinates of the barycentre of the achieved points at n-repetitions of the same position are calculated according to Equations (2).

A set of three Heidenhain MT 25 sensors was used to make the measurement (system accuracy “±2 μm”). The sensors were placed in the measuring base, which ensured their exact fitting in three perpendicular planes. Since the sensors are touching, it is necessary to carry out their admission and removal to the measuring object. This was accomplished by means of a system of three automatic triggers, the control of which was realized by means of control system delta robot ABB. The measured object was a measuring sphere with an outer diameter of 25 mm, with the center located in the axis of the outlet flange. The view of the location of the sensors and the robot is shown in Figure 3.

### 4. Results and discussion

To determine the degree of the accuracy of a robot caused by robot damage, a control measurement was carried out at the four P2 to P5 measurement points. At each point, 30 measurements were made. The average values of the deviation at point P1 were mathematically calculated and graphically verified in CA environments of CREO, Table 3.

The deviations in the direction of the plane XY axis are shown in Figure 4. Z-axis deviations have been neglected when creating compensation in the respective program. This is due to the use of a spring suction as the end effector that allows the delta robot ABB in the Z-axis to compensate [8].

The measured deviations were subsequently used in the robot program. On the basis of the tests carried out a method was chosen where, every 5 cycles a half value of the mean deviation was entered in the appropriate direction. After repeating 100 cycles, it was found that the resulting robot inaccuracy was within the prescribed limits.

<table>
<thead>
<tr>
<th>Characteristic (ISO 9283)</th>
<th>Load (kg)</th>
<th>Speed (m.s⁻¹)</th>
<th>Number (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pose accuracy (AP)</td>
<td>0.1</td>
<td>0.8</td>
<td>30</td>
</tr>
<tr>
<td>Pose repeatability (RP)</td>
<td>0.1</td>
<td>0.8</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 3 Average inaccuracy values on the delta robot ABB, point P1A

<table>
<thead>
<tr>
<th>AP</th>
<th>Axis X</th>
<th>Axis Y</th>
<th>Axis Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00183</td>
<td>-0.00171</td>
<td>0.00156</td>
<td></td>
</tr>
</tbody>
</table>

### Table 1 Manufacturer’s measured values according to ISO 9283

<table>
<thead>
<tr>
<th>Characteristic (ISO 9283)</th>
<th>(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pose accuracy (AP)</td>
<td>0.01</td>
</tr>
<tr>
<td>Pose repeatability (RP)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### Table 2 Selected test parameters

<table>
<thead>
<tr>
<th>Characteristic (ISO 9283)</th>
<th>Load (kg)</th>
<th>Speed (m.s⁻¹)</th>
<th>Number (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pose accuracy (AP)</td>
<td>0.1</td>
<td>0.8</td>
<td>30</td>
</tr>
<tr>
<td>Pose repeatability (RP)</td>
<td>0.1</td>
<td>0.8</td>
<td>30</td>
</tr>
</tbody>
</table>
necessary time. In a controlled environment where the speed was limited to 1 m.s\(^{-1}\) and the load per 0.1 kg it was confirmed for about 500 cycles. Using a damaged robot in a normal running would not be possible in terms of security.

5. Conclusions

On the basis of the measured parameter measurements of the wrist-assembled modules with three degrees of freedom, we came to the following conclusions: The partial result of the measurement was the formation of the measured plane whose peaks P2A, P3A, P4A and P5A were obtained by determining the mean values of deviations to points P2, P3, P4 and P5. By overlapping the measured plane with the programmed plane it was possible to determine the resulting inaccuracy of the delta robot ABB at these points. Deviations could be used to create compensation values embedded in the robot’s program, so that
Damaged delta robot ABB from a safety point of view can only be used at lower speeds. For this reason, it is only suitable for use in training or during exhibitions.

Acknowledgements

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References