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Basics of preparing a digital twin for a cooperative robot (cobot) with an attached rigid-contact head

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Abstract
The article describes the preparation of a collaborative robot for a contact measurement task. Technical and software solutions enabling the performance of such a task were proposed, and then a preliminary, simplified, and initial digital twin model was developed. An analysis of the impact of the robot's operating speed during the collection of measurement points was carried out, and it was shown that the speed of the cobot calibration robot does not affect the accuracy of the read data. Further steps were discussed that would allow for the introduction of corrections to the operation of such a system.

Type the keywords here: digital twin, cobot, metrology, kinematics, measurement systems

1. Introduction

The digital twin (DT) is currently one of the key tools supporting intelligent manufacturing, maintenance, and quality assurance in the Industry 4.0 paradigm. In terms of the ISO 23247 standard, a digital twin is defined as "a purpose-built digital representation of an observable manufacturing element with guaranteed synchronization" between the physical object and its digital representation, whereby data exchange can be unidirectional or bidirectional [1]. The literature review emphasizes that the essence of DT is not the model itself (e.g., CAD), but the continuous coupling of data, the ability to perform what-if analyses, and integration with technologies such as IoT, simulation, and AI [2,3].

In manufacturing applications, DT is being developed, among other things, towards managing geometric and quality variability in near real time. The work of Söderberg and co-authors indicates that "geometric assurance" may become an area where the digital twin combines production and inspection data with tolerance/variability models, enabling a shift from a reactive to a predictive approach.[4] Wärmefjord's research, on the other hand, emphasizes the role of DT in "variation management" – from variability simulation, through setting and tolerance planning, to the use of measurement data for process control [4].

A special case of DT in the area of quality is the digital metrological twin, in which the metrological model of the measuring device and uncertainty simulation play a key role. In coordinate metrology, concepts of virtual measuring machines (VMM) are being developed which, thanks to the kinematic description of the device and error models, enable the generation of measurement results together with uncertainty assessment by simulating multiple measurements (e.g., using the Monte Carlo method).[5] In this approach, DT becomes not only a visualization tool, but also an element of the quality data infrastructure: results (actual and simulated) can be stored in a database and used by metrology, quality, and maintenance, as well as feedback for manufacturing processes [5].

Parallel to the development of digital metrological twins, the importance of collaborative robots (cobots) as carriers of measurement tasks is growing. Cobots are attractive due to their easy system integration, safety when working near the operator and relatively low implementation threshold. At the same time, the limited rigidity of the system, susceptibility to contact loads, and control characteristics (including safety mechanisms/torque limits) mean that the implementation of contact measurements requires a conscious analysis of repeatability and identification of factors affecting the accuracy of TCP determination. From the point of view of a digital twin, this means that it is necessary to adopt a formal description of kinematics (e.g., Denavit–Hartenberg) and prepare the basis for subsequent geometric and functional error models [5].

This article is the first stage of a series of publications aimed at developing a digital twin of the UR3 cobot for measurement applications, as well as developing robot corrections. This stage focused on a preliminary analysis of the repeatability of movement and stability of the robot's position, adapting it to contact measurements, and developing the mathematical basis for the digital twin, without yet taking corrections into account.

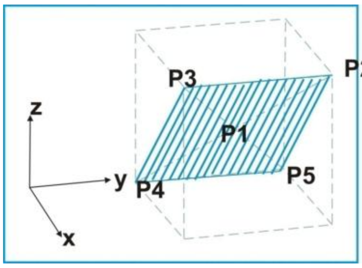
The main objectives of the research were: to determine the repeatability of the UR3 cobot's positioning at different speeds, to analyze the effect of speed on the behavior of the robot's axes and the TCP point, and to collect reference data to serve as a basis for further stages of digital twin development.

2. Hardware basics

Before starting the work, the accuracy of the robot (cobot) was checked in accordance with the PN-EN ISO 9283:2003 Industrial robots – Methods for testing functional characteristics [8] standard. Instead of a gripper, a Leica LTD 840 Laser Tracker retroreflector was mounted on the last link (Fig. 1a). The tests were performed in the "oblique" plane (Fig. 1b) recommended in the standard for a six-axis robot with an open kinematic chain. The test of a linear track should be performed along the diagonal of a cube, with a path length equal to 80% of the distance between opposite corners of the selected plane.

The accuracy of the segment mapping expresses the deviation of linear positioning between the set distance and the average value of the actual segment. The accuracy of the segment mapping, which expresses the linear positioning deviation between the specified distance and the average value of the actual segment, was ±0.078 mm for the tested robot, while the repeatability of the segment mapping, which is the value of the dispersion of the actual lengths of the n-times mapped segment, specified in the same direction, was ±0.102 mm.

Figure 1a) Testing the robot in accordance with PN-EN ISO 9283:2003, using the Lieca LTD 840 tracking system, Figure



1b) Location of the track where the robot was tested

The tests are of a verification and preparatory nature. Their purpose is not yet to calibrate the robot metrologically, but to check the stability and repeatability of movement under controlled laboratory conditions. At the preliminary stage, a dedicated measuring head was not used, which will be used in further work to perform precise measurements. This decision was based on several important considerations: the high cost of the measuring equipment, the risk of damage during testing, the trajectory and movement parameters, and the need for prior validation of the robot itself as a carrier of the measuring system.

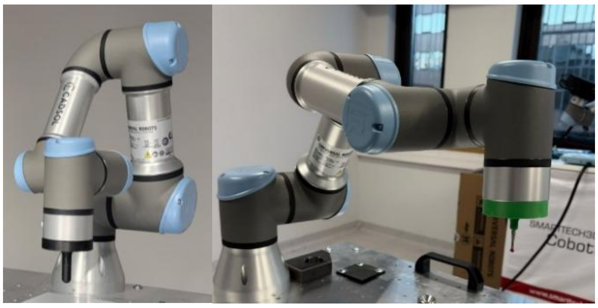


Figure 2a) Gripper equipped with a pin acting as a contact element, 2b) Modeled rigid contact head

Instead of a measuring head, a standard gripper equipped with a pin acting as a contact element was used (Fig. 2a). This solution allows for safe repeatability testing without exposing expensive equipment to overload or collision. It was then decided to use a type of rigid contact head (Fig. 2b), where a measuring pin with a 3 mm diameter ball was rigidly attached to the designed gripper.

The test object is a six-axis industrial robot used for measurement tasks. The kinematic structure of the robot includes the following axes (joints): J1 – Base, J2 – Shoulder, J3 – Arm, J4 – Wrist 1, J5 – Wrist 2, J6 – Wrist 3. The robot operates in Cartesian space, and its position and tool orientation are described by the TCP (Tool Center Point) vector in the form: $TCP=[X,Y,Z,Rx,Ry,Rz]$ (1) where X,Y,Z denote the coordinates of the tool position, while Rx,Ry,Rz denote the angles of orientation of the tool relative to the axes of the coordinate system.

The TCP in the UR 3 robot was determined using the robot's internal software by setting the tool tip four times in the internal cone at different angles.

Figure 2a) View of the tool center point determination from the TCP robot program,

Figure 2b) Photo of an example setting of the measuring tip in the internal cone

The measurements were performed according to a repeatable procedure: the robot approached the measurement point from above, then from the y-axis and then the x-axis (10 points were collected each time), moving in a straight line in Cartesian space. The movement took place at various TCP linear speeds, ranging from 1 mm/s to 10 mm/s. When the pin came into contact with the reference surface, the overload protection was activated. The overload threshold was set to 30-40 (robot system units). When an overload was detected, the robot's movement was immediately stopped. This was followed by a reading of the robot's data, including: the position of all axes (joints), the position and orientation of the TCP. This method allows the moment of contact to be determined unambiguously and ensures the repeatability of the robot's stopping conditions.

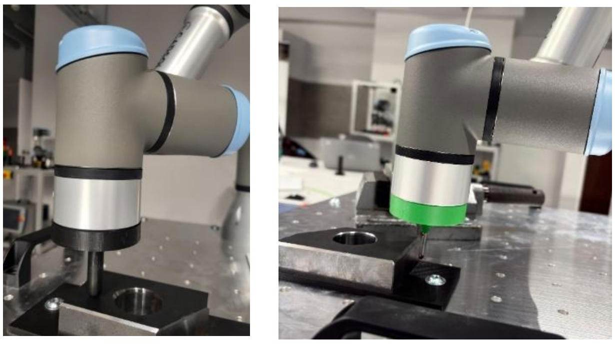


Figure 3a) Contact readings of a gripper equipped with a pin acting as a contact element, Figure 3b) Contact readings of a modeled rigid contact head

Measurements taken at different speeds did not show significant changes in the readings [Table 2], which allows us to conclude that the change in speed did not affect the readings of the contact between the measuring element and the pin. This may be due to the fact that collaborative robots do not reach speeds as high as conventional industrial robots.

3. Mathematical and kinematic foundations of a cobot digital twin

In order to develop a digital model of a robot, it is necessary to determine the kinematic equations describing a robot with an open kinematic chain structure. Its individual links are treated as given solids in space, where only the relationships between them need to be determined. The relationship between two adjacent pairs can be represented by four variables. ai - distance from axis zi to axis zi+1 measured along axis xi , αi - angle between axes zi and zi+1 measured around axis xi , di - distance between the axes xi-1 and xi measured around zi , θi - angle between the axes xi-1 and xi measured around zi .

Every manipulator or robot with the same design can be described using the four variables presented above. The description of kinematics using this convention is referred to in the literature as Denavita-Hartenberg notation [my articles]. The first two parameters describe the link, while the next two describe the connection between them. If there is a rotational pair in the design, then the variable is the configuration angle of the moving link θi, while the rest of the parameters are constant. If there is a translational pair, then the variable is the displacement parameter of the link di, while the rest are constant [Table 1].

Table 1. UR3 Parameters

Parametry D-H dla UR 3				
i	a_{i-1} [m]	d_i [m]	α_{i-1} [rad]	θ_i
1	0	0,1519	$\pi/2$	θ1 (podstawa)
2	-0,24365	0	0	θ2 (bark)
3	-0,21325	0	0	θ3 (ramię)
4		0,11235	$\pi/2$	θ4 (nadgarstek1)
5		0,08535	$-\pi/2$	θ5 (nadgarstek2)
6		0,0819	0	θ6 (nadgarstek3)

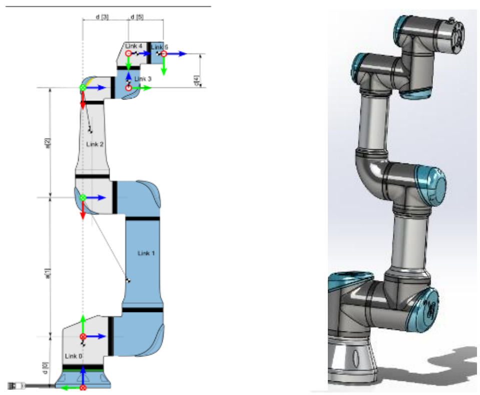


Figure 4a. Description of the UR3 collaborative robot (according to the manufacturer's data), 4b View of the model for digital twin visualization

Homogeneous coordinates were used to describe the transformations between the systems, which allow points to be represented in i-dimensional projective space (a modified geometric space by adding the points of all its directions to the set) using an i+1
coordinate system. The basic task in working with redundant devices with an open kinematic chain is the so-called simple kinematic task. It is a static-geometric task that involves calculating the position and orientation of a working member of a device, e.g., a robot gripper or a measuring head, especially when a set of configuration angles is given. The simple kinematics task maps the description of the manipulator's position in the configuration coordinate space (e.g., readings from angle measurement systems) to a description in Cartesian coordinate space (Cartesian coordinate space is understood here as a space in which the position of a point is determined by three numbers x,y, z, and the orientation of the member is determined by three other numbers). To calculate a simple task, you can use the transformation matrix from the "i" system to the base system. It is obtained by multiplying the homogeneous transformation matrices Ai, corresponding to the parameters describing the relationships between two adjacent pairs [5, 9, 10, 11].

Table 2. Results of averages from 10 readings of a given point at different speeds

1 mm/s			
Średnie z 10 pomiarów:	**Średnia po przeliczeniu przez cyfrowego bliźniaka, mm:**	**Średnie z odczytów z UR, mm:**	**Różnica średnich, mm**
x	7,595	7,494	0,101
y	-349,94	-350,212	0,272
z	82,212	81,956	0,256
2 mm/s			
x	8,293	8,169	0,124
y	-349,925	-350,209	0,284
z	82,212	81,944	0,268
3 mm/s			
x	7,744	7,581	0,163
y	-349,736	-350,153	0,417
z	81,982	81,877	0,105
4 mm/s			
x	7,744	7,61	0,134
y	-349,736	-350,130	0,394
z	81,982	81,883	0,099
5 mm/s			
x	7,595	7,542	0,053
y	-349,94	-350,210	0,270
z	82,212	81,944	0,268
6 mm/s			
x	8,364	8,29	0,074
y	-349,696	-350,141	0,445
z	81,984	81,85	0,134
7 mm/s			
x	8,293	8,223	0,07
y	-349,925	-350,211	0,286
z	82,212	81,93	0,282
8 mm/s			
x	7,944	7,678	0,266
y	-349,932	-350,224	0,292
z	82,212	81,953	0,259
9 mm/s			
x	7,595	7,65	-0,055
y	-349,94	-350,213	0,273
z	82,212	81,957	0,255
10 mm/s			
x	7,666	7,624	0,042
y	-349,711	-350,128	0,417
z	81,984	81,844	0,14

Thanks to this solution, a computational basis for a digital twin of the tested device was developed. The program was written using the Python language. The input data are always actual readings from the device's encoders, and the mathematical model is based on a simple kinematics task. On the rigid contact head, the differences between the digital twin and the actual reading oscillate within 0.5 mm (the maximum reading is 0.596 mm). However, this is a result without robot correction and without head correction, which will ultimately be performed using an artificial neural network (ANN), which in this case will allow learning from the robot's input data. Fast Artificial Neural Network (FANN) is a library implementing ANN, which will be programmed in Python. The principle of operation of ANN is based on approximating a given function. In other words, they learn the given function by observing examples of its operation. According to previous work carried out at the Coordinate Metrology Laboratory, the assumed mathematical model made the measuring head error dependent on the vector of approach to the measuring point. In the case of industrial robots, we are dealing with a situation similar to that of coordinate machines equipped with a rotary tilt head, where it is possible to control the orientation of the measuring head. Therefore, it will be important that the approaches are presented in the head system and not in the main robot system. The model itself will be adopted as a function R3→R1, where the input parameters will be the coordinates of the approach vector, and the result will be the deviation. For this task, programs will be written that will construct spheres, then calculate their parameters along with deviations and determine the approach vector during measurement. Measuring a sphere of known diameter will allow for an average head correction of 50%, which has already been proven[9] by one of the authors of this paper.

4. Conclusions

This article is the first stage of a series of publications aimed at developing a digital twin of the UR3 cobot for measurement applications, followed by modeling its correction. Further work will determine the kinematic errors of the device. A CAA correction matrix will be developed, and both the head and the entire system will be adjusted. The points will be sent to a database where they will be sorted and sent to metrology software for the application of validated algorithms for the construction of geometric elements, i.e., PC Dmis or PolyWorks. In this work, preliminary tests were carried out and assumptions were made by the authors regarding the operation of such a system. Tests were performed on the influence of speed on the repeatability of readings, and indirectly, the accuracy of the digital twin was also determined. The data show only constant spreads, which did not increase or decrease with changes in speed (Table 2).

The collected data is of a kinematic nature (axis positions), spatial (TCP position), and dynamic indirect (the effect of speed and overload on stopping). , it constitutes the first reference data set for: verification of the UR3 kinematic model, analysis of contact point repeatability, identification of axes sensitive to speed changes. At this stage, the digital twin represents the robot in a simplified form, but already allows for comparison of the virtual model's behavior with the real object.

This article is a starting point for the next stages of work, which will include: the use of a dedicated measuring head, detailed analysis of measurement errors, dynamic modeling of the robot, coupling the digital twin with online data, and validation of the digital twin in real measurement tasks.

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