Kinematic Calibration of Robot Arm Testbed for Decommissioning Application

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1. Introduction

Robotic technologies have been applied to address unique needs in the nuclear sector. In decommissioning applications, especially, the primary use of robotics is to reduce the radioactive dose levels to which workers are exposed and to help in handling heavy wastes and debris.

Examples of robots in decommissioning applications include Brokk, LMF, RODDIN and DAWN to name a few [1]. Recently, furthermore, an integrated robotic dismantling system has been proposed, where robot arms are used in cutting operations [2]. Robot arm is a key element in these robotic decommissioning applications.

To control robot arms precisely, we need to know the kinematic parameters of the robot arm. Even though we have nominal design values of the kinematic parameters, it is necessary to calibrate robot arms regularly because deviations occur in fabrication or robot arms are deformed in use.

Calibration requires external measurement systems to measure robot arm's pose accurately. Often these external pose measurement systems come with high expense.

This study introduces a practical and cost-effective kinematic calibration method for robot arm testbed. The method is applied to UR10 robot arm and the result is presented.

2. Methods and Results

In this section, the robot arm testbed and the concept of kinematic calibration are briefly described. A practical calibration method is proposed and the results are presented.

2.1 Robot Arm Testbed

The robot arm testbed considered in this study is UR10. UR10 is a six-jointed, collaborative industrial robotic manipulator manufactured by Universal Robots [1]. Table I summarizes UR10's specifications.

Table I. Technical Specifications of UR10 robot

Payload	10 kg
Reach	1300mm
Joint ranges	±360°
Repeatability	± 0.1mm
Weight	28kg

It is light weight and easy to program, and has various safety features for human-robot collaborative operations [3,4]. UR10 is packaged with a controller box (CB3) and a teaching pendant as shown in Figure 1 [1].

Fig. 1. UR10 robot with controller box and teaching pendant

2.2 Kinematic Calibration

This section provides an overview of the calibration process, and describes an implementation of the kinematic calibration process.

2.2.1 Calibration Process

The relationship between joint space configuration (θ_{joint}) and task space end effector configuration (P_{task}) is represented by Equation (1)

$$P_{task} = f(\eta, \theta_{joint}) \qquad (1)$$

where P_{task} is the end effector pose defined in task space, θ_{joint} is the vector of joint space displacements, and η is the set of parameters used in the model.

The calibration process can be summarized in the following steps

Step 1. Modeling: Define an appropriate functional form in Equation (1).

Step 2. Determine the parameter set, η, that makes the model from Step 1. matches the performance of the actual robot as closely as possible. This step can be further divided into 2 sub-steps: measurement and identification.

2.2.2 Modeling

The first step is the determination of a suitable functional form between the task space configuration and the joint space configuration in Equation (1). We adopted the Denavit-Hartenberg (DH) parameter model because UR10 calibration manual [5] contains the nominal design values of DH parameters (Table II), and it is the most popular method for manipulator kinematics modeling [6]. Figure 2 shows the joint and link assignment, and associated DH parameter frames.

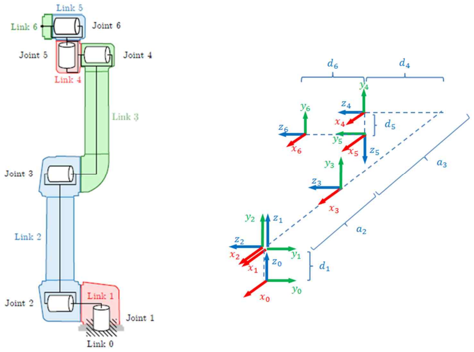

Fig. 2. UR10 robot schematic and DH parameter frames

Table II. Design values of DH parameters for UR10 robot

i	a_{i-1}[m]	d_i[m]	α_{i-1}[rad]
0	0	-	0
1	0	0.118	1.5708
2	-0.6127	0	0
3	-0.5716	0	0
4	0	0.1639	1.5708
5	0	0.1157	-1.5708
6	-	0.0922	-

2.2.3 Measurement

The second step in the calibration process is measurement. The goal of the measurement process is to accurately determine either the end effector pose, or some subset of the pose, for a set of robot joint configurations. A typical measurement data set is obtained by the following steps:

Step 1. Move the robot's end effector to some location in the task space, $P_{task,i}$

Step 2. Record the joint space configuration, $\theta_{joint,i}$, and then measure the end effector pose, $P_{measure,i}$, using an external measuring system with suitable precision.

Step 3. Repeat Step 1 and 2 until we get as many measurements as necessary

There are a few systems that have the necessary precision to make adequate pose or partial pose measurements. The UR10 manual suggests a practical method for calibration using a calibration plate shown in Figure 3 [5].

Fig. 3. Calibration plate with holes to align the end effector

Inspired by the calibration plate, we designed a small calibration zig that can be installed on a test table. Figure 4 shows the calibration zig design and the fabricated zig. The calibration zig has four holes for the robot tool flange so that, when the robot tool flange is inserted into one of the holes on the calibration zig, the end effector position is precisely known, within fabrication tolerance. The joint angles can be read from the teaching pendant. The control box computes estimated position of the end effector using the joint angles and factory-set DH parameters. The calibration zig can be installed on the bolting holes on the table, and we can get as many measurements as needed, without using an external measuring system. Figure 5 shows the calibration setup used in this study.

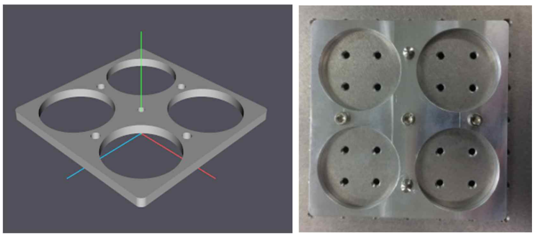

Fig. 4. Calibration zig: design(left) and fabricated zig(right)

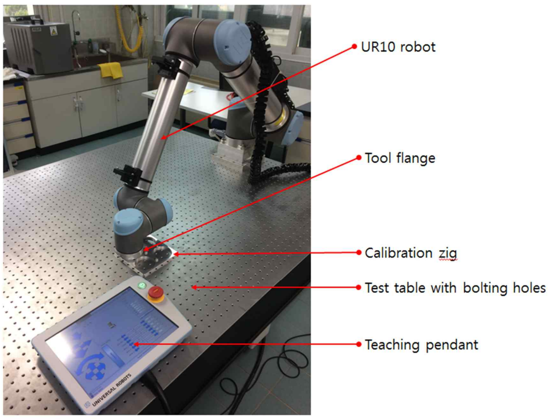

Fig. 5. Calibration test setup

2.2.4 Identification

The parameter identification process is to determine the parameter set, η, that minimizes the following position errors for i = 1, … , N

$$\delta P_i = |P_{measure,i} - P_{model,i}(\eta, \theta_{measure,i})|$$

where N is the number of measurements, $P_{measure,i}$ is a measured pose and $P_{model,i}(\eta, \theta_{measure,i})$ is the pose predicted by the model in Equation (1) at the *i*-th measurement location, i.e. $f(\eta, \theta_{measure,i})$.

We collected data using the calibration zig, and an iterative least square optimization algorithm (i.e., leastsq in Python 3.5) was applied to find a solution. The iterative optimization solves highly nonlinear error minimization problem, yielding a locally optimal solution. Thus the identified DH parameters may not be the globally optimal solution, which should be noted.

The identification process was run twice. At first, robot's factory-set DH parameters were identified, which are used in the control box for UR10 control.

Then the DH parameters were recalibrated to determine actual DH parameters.

It turned out that the identified factory-set DH parameters (Table III) are different from the design values of DH parameter in Table II. Figure 6 visualizes the result. The green dots represent estimated positions of the end effector using the nominal DH parameters (Table II). The blue dots represent the end effector positions displayed on the teaching pendant. The red dots represent the end effector positions using the estimated factory-set DH parameters.

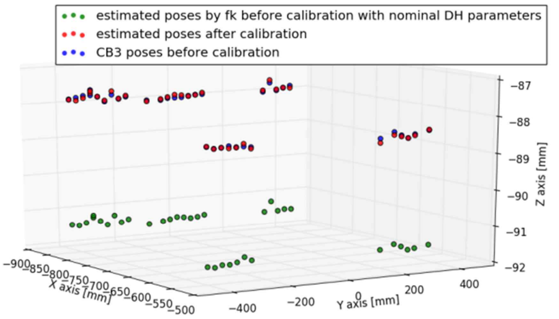

Fig. 6. Identification of Factory-set DH parameters

Table III. Factory-set DH parameters for UR10 robot

i	a_{i-1}[m]	d_i[m]	α_{i-1}[rad]
0	0	-	-4.296 E-05
1	0	0.135696	1.591
2	-0.611987	0	8.140 E-03
3	-0.571337	0	6.556 E-03
4	0	0.165331	-1.557
5	0	0.115795	1.567
6	-	0.096037	-

After identifying the factory-set DH parameter values, actual DH parameter values are identified. Figure 7 and Table IV summarize the result. The red dots represent the true end effector positions. The green dots represent estimated positions of the end effector using the identified factory-set DH parameters (Table III). The yellow dots represent the end effector positions displayed on the teaching pendant. The blue dots represent the end effector positions using the identified actual DH parameters (Table IV)

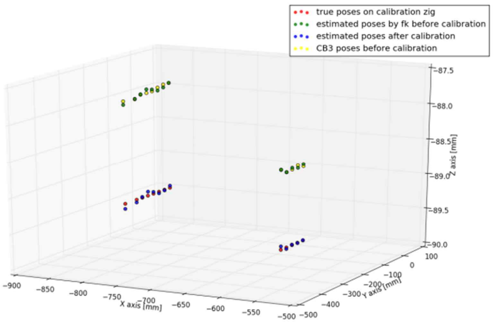

Fig. 7. Identification of actual DH parameters

Table IV. Actual DH parameters for UR10 robot

	a_{i-1}[m]	d_i[m]	α_{i-1}[rad]
0	0	-	-4.296 E-05
1	0	0.128833	1.591
2	-0.614911	0	8.140 E-03
3	-0.569829	0	6.556 E-03
4	0	0.165330	-1.557
5	0	0.115192	1.586
6	-	0.093927	-

3. Conclusions

In this study we introduced a kinematic calibration method for robot arm testbed. The method was tested on a test setup with UR10 robot arm. Using an iterative optimization algorithm, a set of local optimal parameters that minimizes the end effector position errors is determined.

The calibration method is practical for lab-scale test setups, and does not require expensive external pose measurement systems. The results are reasonably accurate but the accuracy is affected by some of the factors including but not limited to:

(1) the calibration zig, test table fabrication tolerance
(2) human errors in placing the end effector into the holes in the zig
(3) the optimization algorithm used
(4) selection of unknowns
(5) the stiffness of robot arm testbed

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