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# Working vs. operating space kinematic calibration of articulated industrial manipulators

Theissen Nikolas A.[1], Gonzalez Monica K.[1], and Archenti Andreas[1,2]

*[1]KTH Royal Institute of Technology, Department of Production Engineering, Manufacturing and Metrology Systems Division, Brinellvägen 68, 114 28 Stockholm, Sweden*
*[2]KTH Royal Institute of Technology, Department of Sustainable Production Development, Industrial Dependability Division, Kvarnbergagatan 12, 151 36 Södertälje, Sweden*

*theissen@kth.se*

## Abstract

Kinematic calibration improves the positioning accuracy of articulated industrial manipulators. Industrial manipulators with kinematic calibration are more likely to be successfully offline programmed. Almost all manufacturers offer this calibration service. The calibration provided by the robot manufacturer is a working space calibration, which means that it guarantees a positioning accuracy for all possible configurations. This approach seems reasonable for an unknown target operation and if only a single set of model parameters can be stored in the robot controller. However, nowadays robot controllers can store more than one set of model parameters to reflect the significantly different orientations in which industrial manipulators can be mounted, e.g., floor-, wall, or ceiling-mounted. Thus, this work investigates the variability of the mean and maximum positioning accuracy of industrial manipulators in four different operating space calibrations and compares them with the working space calibration provided by the robot manufacturer.

The article concludes with a discussion about potential improvements of existing kinematic calibration procedures.

Keywords: Robot, Calibration, Performance

## 1. Introduction

The demand for industrial robots has been increasing and can be considered significant, as shown by their market volume of approximately 13.2 billion USD in 2020 [1]. These industrial manipulators, or robots, are mainly articulated manipulators [5]. Wider implementation of offline programming and new applications, such as machining, requires a higher positioning accuracy of industrial robots [2]. The improvement of positioning and path positioning accuracy [3], i.e., a measure for the distance between the commanded and the attained position of a manipulator, is subject to the study of manipulator calibration [4]. Manipulator calibration, as described by Mooring in 1991, intends to improve the positioning accuracy by four steps; i) modelling the kinematics; ii) measuring the positioning accuracy of the actual robot; iii) identifying its model parameters, and iv) implementing the model parameters to optimize the capabilities of the manipulator [4]. The calibration provided by robot manufacturers, namely *Absolute Accuracy* (ABB), *High Accuracy* (KUKA) and *iRCalibration Signature* (FANUC), are working space calibrations [5]. It guarantees a positioning accuracy of approximately 0.5 mm on average and better than 1.0 mm at maximum for all configurations [2].

Robot controllers can increasingly store more than one set of kinematic model parameters, also called Denavit-Hartenberg (DH) parameters [4]. Therefore, this study quantifies the difference in positioning accuracy of an articulated industrial manipulator among four different Operating Spaces (OS) within its working space (WS) to highlight the potential improvement in positioning accuracy of OS calibration.

**Table 1: Nominal modified Denavit-Hartenberg parameters and elements of the parameter delta vector [6].**

| $Joint.$ | $d_i$ in m | $\alpha_i$ in m | $\alpha_i$ in rad | $\theta_i$ in rad |
|---|---|---|---|---|
| 1. | 0.7800 | 0.0000 | 0 | $\theta_1 + \delta\theta_1$ |
| 2. | $0.0000 + \delta d_2$ | $0.3500 + \delta a_2$ | $\frac{-\pi}{2} + \delta\alpha_2$ | $\theta_2 - \frac{\pi}{2} + \delta\theta_2$ |
| 3. | $0.0000 + \delta d_3$ | $1.1450 + \delta a_3$ | 0 | $\theta_3 + \delta\theta_3$ |
| 4. | $1.2125 + \delta d_4$ | $0.2000 + \delta a_4$ | $-\frac{\pi}{2} + \delta\alpha_4$ | $\theta_4 + \delta\theta_4$ |
| 5. | $0.0000 + \delta d_5$ | $0.0000 + \delta a_5$ | $\frac{\pi}{2} + \delta\alpha_5$ | $\theta_5 + \delta\theta_5$ |
| 6. | $0.2200 + \delta d_6$ | $0.0000 + \delta a_6$ | $-\frac{\pi}{2} + \delta\alpha_6$ | $\theta_6 + \pi$ |

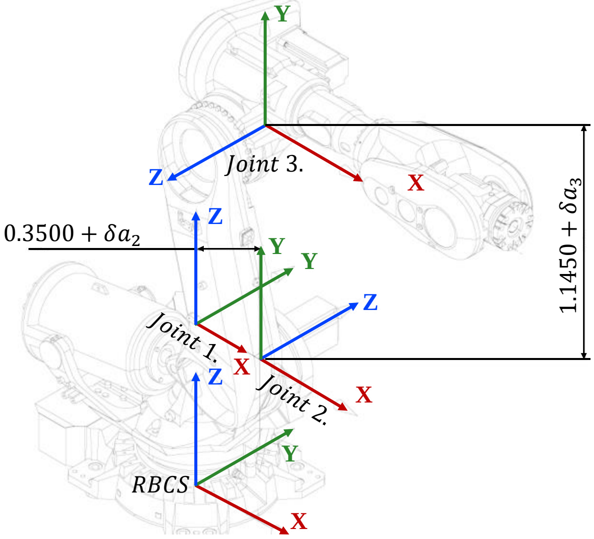


**Figure 1: Visualisation of the DH convention on the articulated manipulator.**

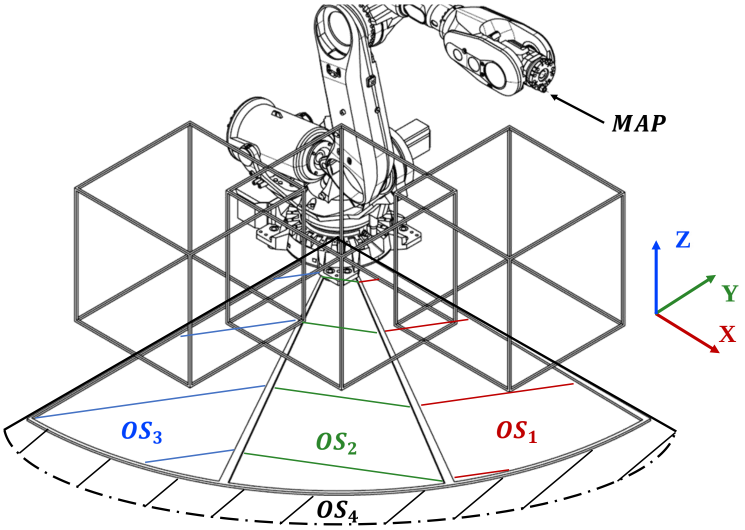


Figure 2: Visualisation of the conceptual measurement setup: The setup shows a large-sized articulated industrial robot and the different OSs. The Measurement Application Point (MAP) is visualised through a 1.5 ″ SMR on the manipulator's End Effector (EE).

## 2. Methodology

This study quantifies the difference between the positioning accuracy attained after kinematic calibration on an articulated industrial manipulator in four different OSs and the manufacturer's WS calibration. The calibration is based on 50 calibration configurations and validates the calibrated manipulator model in an additional 50 validation configurations for each OS measured using a Laser Tracker (LT).

### *2.1. Modelling*

The movement of an industrial robot is commonly defined by the successive positions attained by each joint, resulting in a specific End Effector (EE) pose, i.e., combined position and orientation. It is mainly expressed in terms of the actuated joint angles $\boldsymbol{\theta}$. The EE pose can be modelled using the Denavit-Hartenberg (DH) convention to relate joint space to Cartesian space through the kinematic model parameters [7]. The nominal kinematic parameters are depicted in Table 1, and the assignment of the coordinate systems to the joints is visualised in Figure 1. The nominal parameters are stated as scalar values. The calibration procedure aims to identify the actual scalar values of the DH parameters. Therefore, the calibrated kinematic robot model updates 19 model parameters by identifying a parameter delta vector $\boldsymbol{\Delta v} \in \mathbb{R}^{1\times 19}$.

$$\boldsymbol{\Delta v} = [\delta\theta_1 \quad \cdots \quad \delta\alpha_6] \qquad (1)$$

The number of identifiable model parameters depends on the kinematic chain of the industrial manipulator, the modelling as well as the measurement approach. The delta parameter vector is identified using a linear least-squares parameterisation based on the position difference between the nominal kinematic model and the measurement from the LT $\boldsymbol{\Delta pos}$ and the identification Jacobian $\boldsymbol{J}(\boldsymbol{\Delta v}, \boldsymbol{\theta})$ [8]. Hereafter simply denoted as $\boldsymbol{J}$.

$$\boldsymbol{\Delta v} = (\boldsymbol{J}^T \boldsymbol{J})^{-1} \boldsymbol{J}^T \boldsymbol{\Delta pos} \qquad (2)$$

The identification procedure is based on [9]. Here $(\boldsymbol{J}^T \boldsymbol{J})^{-1} \boldsymbol{J}^T$ denotes the Moore-Penrose pseudoinverse of the identification Jacobian. The identification Jacobian quantifies the sensitivity of the position difference to the parameters of the delta vector and the manipulator's configuration. The nominal DH parameters are used to identify suitable manipulator measurement configurations according to [10].

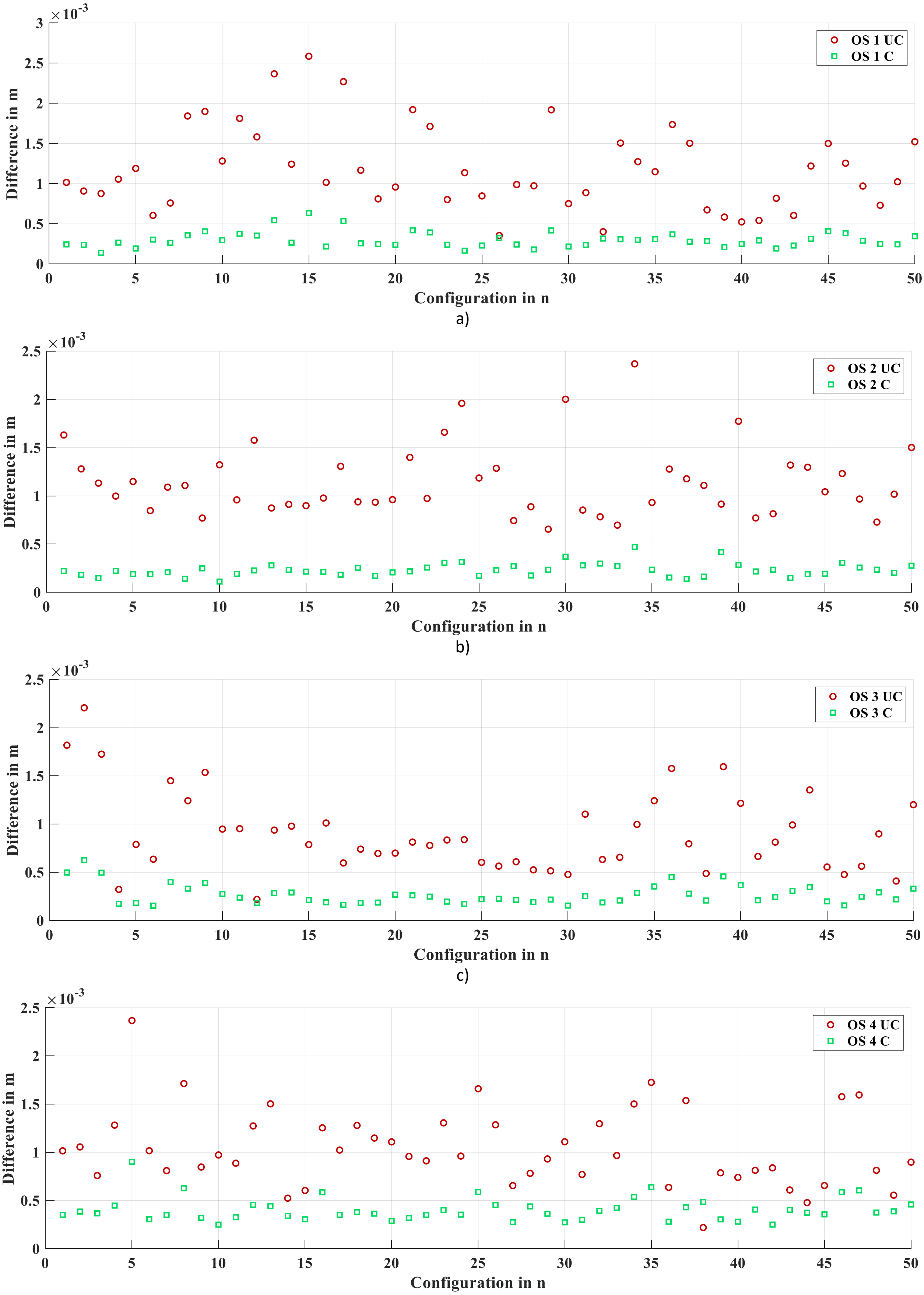
### *2.2. Measurement*

The conceptual measurement setup is shown in Figure 2. The setup comprises the following equipment: An articulated industrial robot, payload 300 kg and reach 2.7 m, with its corresponding controller (not included in the picture), a Leica AT901-LR LT (not included in the picture) with a 1.5 ″ Spherically Mounted Retroreflector (SMR). The position difference is measured at Measurement Application Point (MAP), also referred to as a point of interest. The MAP equals the translational transformation of the location of the SMR on the industrial manipulator relative to the manipulator's mechanical interface.

The industrial manipulator is programmed to approach 100 configurations in each OS. There are four OSs in this investigation. The joint domains of the OSs are stated in Table 2. The distribution was meant to resemble overlapping cubes with a side length of one meter according to ISO 9283 [3], which is also visualised in Figure 2. OS 1 to 3 have similar joint angle domains for joint 1 of approximately 30 deg. OS 4 spans the whole domain of the configurations in OSs 1 to 3. Each OS has a similar condition number that ensures that the parameter identification includes a similar error associated with the matrix inversion. The manipulator moves with a velocity of 200 mms$^{-1}$ between the configurations and stops for 7.5 s at each measurement configuration. Then, the laser tracker takes a single stable measurement, i.e., there are 100 measured position differences for the 100 programmed calibrations. The transformation of the laser tracker data into the Robot Base Coordinate System (RBCS) is achieved through the circle point method [11]. In general, the preparation of the equipment, task programs, etc., has been conducted in accordance with ISO 9283:1998. Further information on kinematic calibration can be found in [12].

Table 2: Joint domains of the different OSs.

| $\boldsymbol{OS}$ | $\boldsymbol{\theta_1}$ $\boldsymbol{in\ deg}$ | $\boldsymbol{\theta_2}$ $\boldsymbol{in\ deg}$ | $\boldsymbol{\theta_3}$ $\boldsymbol{in\ deg}$ | $\boldsymbol{\theta_4}$ $\boldsymbol{in\ deg}$ | $\boldsymbol{\theta_5}$ $\boldsymbol{in\ deg}$ | $\boldsymbol{\theta_6}$ $\boldsymbol{in\ deg}$ |
|---|---|---|---|---|---|---|
| $OS_1$ | $-1$<br>$\cdots$<br>$-30$ | $-10$<br>$\cdots$<br>$35$ | $-10$<br>$\cdots$<br>$28$ | $-90$<br>$\cdots$<br>$90$ | $-90$<br>$\cdots$<br>$90$ | $-180$<br>$\cdots$<br>$180$ |
| $OS_2$ | $-31$<br>$\cdots$<br>$-60$ | $-10$<br>$\cdots$<br>$35$ | $-10$<br>$\cdots$<br>$28$ | $-90$<br>$\cdots$<br>$90$ | $-90$<br>$\cdots$<br>$90$ | $-180$<br>$\cdots$<br>$180$ |
| $OS_3$ | $-61$<br>$\cdots$<br>$-90$ | $-10$<br>$\cdots$<br>$35$ | $-10$<br>$\cdots$<br>$28$ | $-90$<br>$\cdots$<br>$90$ | $-90$<br>$\cdots$<br>$90$ | $-180$<br>$\cdots$<br>$180$ |
| $OS_4$ | $-1$<br>$\cdots$<br>$-90$ | $-10$<br>$\cdots$<br>$35$ | $-10$<br>$\cdots$<br>$28$ | $-90$<br>$\cdots$<br>$90$ | $-90$<br>$\cdots$<br>$90$ | $-180$<br>$\cdots$<br>$180$ |



a)

b)

c)

d)

**Figure 3: Positioning accuracy for the 50 validation configurations for OSs 1 to 4, i.e., a) – d), for the uncalibrated (UC) and calibrated (C) industrial manipulator.**

**Table 3: Mean $\overline{\Delta pos}$, standard deviation $\sigma_{\Delta pos}$, and maximum $max\ (\Delta pos)$ positioning accuracy for the uncalibrated industrial manipulator in the OSs.**

| | $\boldsymbol{OS_1}$ | $\boldsymbol{OS_2}$ | $\boldsymbol{OS_3}$ | $\boldsymbol{OS_4}$ | $\boldsymbol{WS}$ |
|---|---|---|---|---|---|
| $\overline{\Delta pos}\ in\ mm$ | 1.18 | 1.14 | 0.91 | 1.07 | – |
| $\boldsymbol{\sigma}_{\Delta pos} in\ mm$ | 0.52 | 0.36 | 0.41 | 0.45 | – |
| $\max(\Delta pos)\ in\ mm$ | 2.59 | 2.37 | 2.21 | 2.59 | – |

**Table 4: Mean $\overline{\Delta pos}$, standard deviation $\sigma_{\Delta pos}$, and maximum $max\ (\Delta pos)$ positioning accuracy for the calibrated industrial manipulator in the OSs and the WS according to the manufacturer.**

| | $\boldsymbol{OS_1}$ | $\boldsymbol{OS_2}$ | $\boldsymbol{OS_3}$ | $\boldsymbol{OS_4}$ | $\boldsymbol{WS}$ |
|---|---|---|---|---|---|
| $\overline{\Delta pos}\ in\ mm$ | 0.32 | 0.25 | 0.25 | 0.41 | 0.32 |
| $\boldsymbol{\sigma}_{\Delta pos} in\ mm$ | 0.16 | 0.11 | 0.15 | 0.18 | 0.13 |
| $\max(\Delta pos)\ in\ mm$ | 0.63 | 0.47 | 0.62 | 0.90 | 0.59 |

## 3. Results

The magnitude of the positioning accuracy of the uncalibrated and calibrated industrial manipulator can be seen in Figure 3, Table 3, and Table 4. Figure 3 shows the positioning accuracy for each configuration in each OSs, while Table 3 and Table 4 summarise the statistical moments of the data. OS 4 has a significantly higher positioning accuracy than OS 1 to 3. These observations imply that the smaller the OS the smaller the positioning accuracy and its standard deviation, cf. OS 1 to 3. This appears plausible, as the smaller the OS the less inaccurate the industrial manipulator model may be represented by the linearisation for the model parameter identification. Other factors such as gravity and thermo-elasticity have been controlled for in the experiments.

Nevertheless, this gain in positioning accuracy is difficult to quantify as it depends on the calibration procedure. This statement can be corroborated by Table 4 which shows that the manufacturer's calibration is significantly more accurate for the WS than the proposed calibration for solely OS 4, which is approximately one fourth in size compared with the WS.

There is only one uncertainty contributor associated with the measurement which is the measurement instrument uncertainty of the laser tracker. Based on the in-built evaluation capability provided by the manufacturer, the uncertainty budget for the measurement equals $\pm 15\ \mu m$, at a coverage factor of $k = 1$. The measurement instrument uncertainty is considered as a normal distribution.

## 4. Conclusion

This work presents a comparison of OS and WS calibration. The comparison shows that an improvement in positioning accuracy can be achieved for smaller OS. This result seems plausible as the kinematic manipulator model needs to be linearised over a smaller domain. Nevertheless, it is not straightforward to quantify the relationship between the size of the OS and the positioning accuracy. This work is serves as a quantitative reference to those who intend to achieve a wider implementation of offline programming and new applications such as machining through OS calibrations. Further future work shall focus on providing quasi-static kinematic calibration, i.e., the measurement of industrial manipulators under slow movement to reduce the time required for the measurement phase to facilitate OS calibration.

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