

Calibration Efficiency Analysis Based on Five Observability Indices and Two Calibration Models for a Six-Axis Industrial Robot

Ahmed Joubair, Albert Nubiola, and Ilian Bonev
Ecole de Technologie Supérieure

ABSTRACT

The purpose of this work is to evaluate the efficiency of several calibration methods applied to a six-axis industrial (serial) robot. Specifically, the absolute position accuracy of a Fanuc LR Mate 200 iC industrial robot is improved using two calibration models. The first model is purely kinematic, and takes into account all geometric parameters. The second model considers, in addition, five compliance parameters related to the stiffness in joints 2, 3, 4, 5, and 6. For both models, the so-called calibration (or identification) robot configurations are selected based on an observability analysis. For each model, the efficiency of five different observability indices are compared. The parameter identification is based on the forward kinematic approach, where only the residual of the calibration positions is minimized. The data collection process is completely automated, by using Matlab, a FARO laser tracker, communication modules, and a special end-effector with three optical targets (SMRs). The comparisons of the observability indices and of the two calibration models are made through an exhaustive experimentation (7000 measurements). Results show that the robot's mean position error is reduced from 0.622 mm (before calibration) to 0.250 mm, when using the kinematic model, and to 0.142 mm, when using the complete calibration model.

CITATION: Joubair, A., Nubiola, A., and Bonev, I., "Calibration Efficiency Analysis Based on Five Observability Indices and Two Calibration Models for a Six-Axis Industrial Robot," *SAE Int. J. Aerosp.* 6(1):2013, doi:10.4271/2013-01-2117.

INTRODUCTION

In the aerospace industry, industrial robots are mostly programmed off-line. Thanks to this programming method, shutting off the production for programming reasons is reduced significantly. However, off-line programming requires robots with high absolute accuracy. In other words, the robot end-effector should reach the desired locations, specified in the off-line programs, with errors as small as possible. The *pose* (position and orientation) errors occur because the robot controller uses the nominal kinematic model, which does not describe accurately the actual robot motion.

The sources of robot inaccuracy have been classified into two main categories [1]: kinematic errors (*e.g.* length of robot links and joint offsets) and non-kinematic errors (*e.g.* elasticity of links and thermal expansion of links).

The accuracy of a robot can be improved through a process known as robot calibration. Static robot calibration (referred to as *robot calibration* in this paper) consists of

developing a robot model which takes into consideration kinematic and/or non-kinematics errors, measuring several robot configurations (referred here as *calibration configurations*), and then identifying the values of the parameters of the calibration model. The identification process is achieved by minimizing residuals of poses (forward calibration) or actuated joints (reverse calibration), through optimization algorithms. A developed mathematical model allows to approximate as closely as possible the relationship between the pose of the robot end-effector and the *actuated joint variables* of that robot [1]. As a result, the end-effector pose errors are reduced, thereby the robot accuracy is improved.

Several modeling and parameter identification approaches have been proposed to improve robot kinematic models [2, 3, 4, 5, 6, 7, 8]. The identification process needs several measurements on joints (by using the robot's joint encoders), or on the end-effector (by using external coordinate measurement equipment). In previous studies, the data collection process has been achieved by using various

measurement instruments, such as laser trackers [9], CDD cameras [10, 11], CMMs [7, 12], inclinometers [13], ballbars [14], and laser interferometers [15].

During the data collection process, measurement noises usually occur and may affect significantly the parameter identification process. Furthermore, the robot calibration model does not include all sources of positioning errors. These unmodeled errors are also a source of parameter identification errors. Therefore, to minimize the impact of those two factors, the calibration configurations should be selected suitably. Most commonly, selecting an optimal set of calibration configurations is made possible by performing an observability analysis [16, 17, 18, 19], which is based on the singular value decomposition (SVD) of the *identification Jacobian matrix J*. Matrix **J** is composed of the derivatives of the end-effector position vector with respect to all the robot's independent parameters. The choice of the calibration configurations is performed by maximizing the values of the so-called *observability indices* (OIs), which are calculated from the singular values of the SVD. A high index value means that the position errors are mainly attributed to the modeled parameter errors, which imply that the effects of measurement noise and unmodeled errors (if applicable) are less significant. Consequently, the errors of parameter estimation are reduced.

Five OIs are proposed in literature and are referred to as O_1 , O_2 , ..., O_5 . The choice of the appropriate O_1 for a specific robot calibration is not obvious and is addressed in a very few studies, with contradictory conclusions. According to Sun and Hollerbach [16], O_3 is the best choice, while Home and Notash [20] do not recommend this OI. More recently, the first four OIs were compared, for 2-DOF serial robot, by Zhou *et al.* [21], and the conclusion was that the O_4 index is the best OI. However, these studies were not performed on six-axis serial robots. To our knowledge, no study has been made on the comparison of the OIs for a serial six-axis robots.

Therefore, the main objective of this work is to compare the efficiency of the five OIs in the case of a serial six-axis robot. This comparison is applied on two calibration models. The first model uses only geometric parameters, which allow to identify the base frame with respect to the world frame and the parameters of the Modified Denavit-Hartenberg (D-HM) model. The second calibration model considers five compliance parameters, in addition to the geometric parameters of the first model. A second objective of this work is to compare the efficiency of both calibration models.

The parameter identification is achieved by minimizing the residual of the end-effector positions, which are measured by using a laser tracker. The measurement targets are three spherically-mounted reflectors (SMRs), suitably placed on a special triangular end-effector to have at least one target visible for a large number of a dissimilar robot configurations.

The remainder of this paper is organized as follows. The next section presents the five OIs, followed by the calibration models. Next, the algorithm for selecting the calibration configurations, and the parameter identification process are described. Then, the selection of the calibration sets and the experimental study are presented. Finally, our conclusions are given in the last section.

OBSERVABILITY INDICES

The OIs allow quantifying the efficiency of the parameter identification, with respect to the used calibration configurations. The calculation of the OIs is based on the singular values, σ_i , in the diagonal matrix **D**, which is generated by SVD of the identification Jacobian matrix. In other words,

$$\mathbf{D} = \begin{bmatrix} \sigma_1 & 0 & \cdots & 0 \\ 0 & \sigma_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_m \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 \end{bmatrix}, \quad (1)$$

where $\sigma_1 \geq \sigma_2 \geq \sigma_m \geq 0$ are the singular values of **J**, arranged in descending order (m is the number of parameters to be identified).

The matrix **J** represents the relationship between the errors of the calibration positions, $d\mathbf{X}$, and the parameter errors, Δ :

$$d\mathbf{X} = \mathbf{J} \Delta. \quad (2)$$

The commonly used OIs are developed by assuming that all the parameters are identifiable and independent, *i.e.* the number m of non zero singular values σ_i (the rank of **J**) is equal to the number of parameters to be identified. Therefore, the parameter errors are observable from the errors of the used calibration positions. Five OIs, O_1 , O_2 , O_3 , O_4 , and O_5 , are proposed in [17], [19], [18], again [18], and [16], respectively, and are calculated as follows:

$$O_1 = \frac{(\sigma_1 \sigma_2 \dots \sigma_m)^{\frac{1}{m}}}{\sqrt{n}}, \quad (3)$$

$$O_2 = \frac{\sigma_m}{\sigma_1}, \quad (4)$$

$$O_3 = \sigma_m, \quad (5)$$

$$O_4 = O_2 \times O_3 = \frac{\sigma_m^2}{\sigma_1}, \quad (6)$$

$$O_5 = \frac{1}{\frac{1}{\sigma_1} + \frac{1}{\sigma_2} + \dots + \frac{1}{\sigma_m}}, \quad (7)$$

where n is the number of calibration configurations,

ROBOT CALIBRATION MODELS

The Fanuc LR Mate 200 iC robot (Figure 1) is composed of six revolute joints, which link the flange frame F_6 to the base frame F_0 . Two additional frames are also taken into account: the tool frame F_{tool} and the world frame F_{world} .

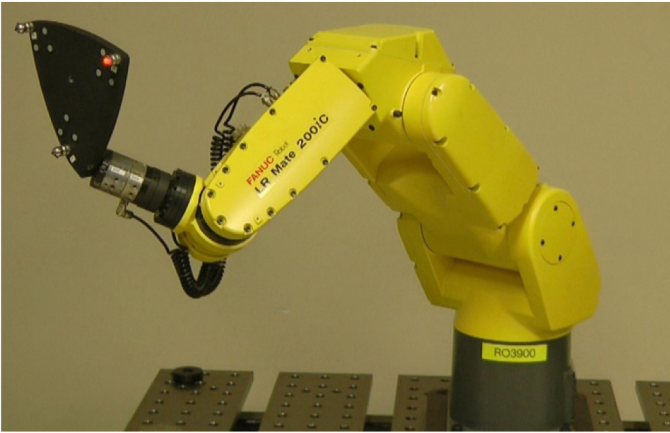


Figure 1. The Fanuc LR Mate 200 iC industrial robot used, with its end-effector with three measurement targets (SMRs).

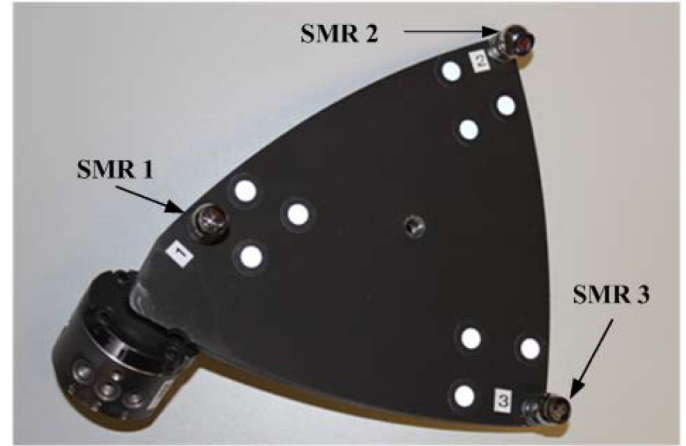


Figure 2. Robot's end-effector with SMRs.

Robot Kinematic Model

The robot's kinematic model is established by using the Modified D-H M notation [22]. Given the vector q of the active-joint variables ($\theta_1, \theta_2, \dots, \theta_6$), the end-effector's pose is represented as follows:

$$H(q) = A_0^{\text{world}} A_1^0 A_2^1 A_3^2 A_4^3 A_5^4 A_6^5 A_{\text{tool}}^6, \quad (8)$$

where

$$A_0^{\text{world}} A_1^0 = \text{Trans}(x_w, y_w, d_1 + z_w) \text{Rot}(x, \alpha_w) \text{Rot}(y, \beta_w) \text{Rot}(z, \gamma_w + \theta_1) \quad (9)$$

and, for $i > 2$,

$$A_i^{i-1} = \text{Rot}(x, \alpha_i) \text{Trans}(a_i, 0, 0) \text{Rot}(z, \theta_i) \text{Trans}(0, 0, d_i). \quad (10)$$

Finally, A_{tool}^6 is the transformation matrix representing the pose of frame F_{tool} with respect to frame F_6 .

Robot Stiffness Model

In addition to the kinematic model taking into account the D-H M parameters and the six parameters identifying frame F_0 , the second calibration model considers five compliance parameters. Recall that only static errors are modeled without any external force applied on the robot structure or end-effector. Therefore, only the gravity effects of the links and the weight of the tool on the gearboxes are taken into consideration. Thus, an elasticity model of the gearboxes of joints 2, 3, 4, 5, and 6 is developed. Each gearbox i is modeled as a linear torsional spring, by using one parameter, which represents the constant compliance k_i . Torsional, traction and compression effects are neglected. Considering that the deformations are quite small, the superposition theory