Precision Engineering 40 (2015) 325–333

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Technical note

Non-kinematic calibration of a six-axis serial robot using planar constraints

Ahmed Joubair*, Ilian A. Bonev

École de technologie supérieure, Montreal, QC, Canada

ARTICLE INFO

Article history:
Received 12 March 2014
Received in revised form 9 October 2014
Accepted 2 December 2014
Available online 10 December 2014

Keywords:
Closed-loop calibration
Planar constraints
Non-kinematic model
Robot stiffness identification
Robot accuracy
Precision

ABSTRACT

This paper describes a non-kinematic calibration method developed to improve the accuracy of a six-axis serial robot, in a specific target workspace, using planar constraints. Simulation confirms that the stiffness of the robot, as well as its kinematic parameters, can be identified. An experimental validation shows that the robot's accuracy inside the target workspace is significantly enhanced by reducing the maximum distance errors from 1.321 mm to 0.274 mm. The experimental data are collected using a precision touch probe, which is mounted on the flange of a FANUC LR Mate 200iC industrial robot, and a high precision 9-in. granite cube. The calibration method makes use of a linear optimization model based on the closed-loop calibration approach using multi-planar constraints. A practical validation approach designed to reliably evaluate the robot's accuracy after calibration is also proposed.

1. Introduction

The accuracy of an industrial robot can be improved through a process known as robot calibration. This process consists of developing a mathematical robot model taking into account kinematic and/or non-kinematic errors affecting the robot's accuracy. The error values are estimated by means of an identification process using coordinate measurement data collected in several robot configurations (referred to here as *calibration configurations*).

Robot calibration approaches are divided into two main categories: static robot calibration, in which the effects of motion on robot accuracy are neglected; and dynamic robot calibration, in which the impact of the motion is considered. In this paper, only static calibration is considered. For simplicity, we refer to it simply as *robot calibration* in this paper.

Three main categories of (static) robot calibration are presented in the literature [1,2]. The first involves joint calibration, which is also called *first level calibration*. The objective of this category is to identify the right relationship between the actual joints' displacements and the joints' encoder signals. The second involves kinematic calibration, or *second level calibration*, where the robot's kinematic parameters are determined, such as in [3–5]. This approach neglects both the elasticity of the links/gearboxes and the backlash of the joints. These two sources of inaccuracy (elasticity and backlash) are taken into account in the *third level calibration*, where the kinematic parameters are also identified, as are the joint errors, such as in [6] where spring stiffness and links' gravity were considered.

The parameters are usually identified by minimizing the residuals of the end-effector poses (forward or open-loop calibration). With a mathematical calibration model that includes the parameter errors, it is possible to closely approximate the relationship between the end-effector poses and the actuated joint variables [2]. Such a model reduces the amplitude of the end-effector pose errors, which enhances robot accuracy as a result. External devices are required to measure the calibration poses or positions used in the parameter identification process. Furthermore, the measurement device should be accurate enough to calibrate a robot effectively (i.e. the uncertainty of the measurement device should be much better than the desired accuracy after calibration). Unfortunately, coordinate measurement devices with enhanced measurement uncertainty are significantly more expensive. For example, an optical CMM with an uncertainty of about ±100 μm [5], a laser tracker with an uncertainty of about ±40 μm [6], and a medium-sized CMM with an uncertainty of ±2.7 μm [7,8] cost around $45,000, $100,000, and at least $150,000 respectively.

Another calibration approach, so-called *inverse calibration*, is also proposed in the literature. This approach is based on minimizing the residual of the actuated joint values, where the measurement data used are collected from the robot's encoders. However, in this case, the calibration poses or positions are

* Corresponding author.
E-mail addresses: ahmed.joubair.1@ens.etsmtl.ca (A. Joubair), ilian.bonev@etsmtl.ca (I.A. Bonev).

http://dx.doi.org/10.1016/j.precisioneng.2014.12.002
0141-6359/

assumed to be known, which means implicitly that those poses or positions had been measured previously by external instruments.

The *closed-loop calibration* approach is proposed in the literature to avoid the need to use external measurement devices; the only data used are taken from the encoders of the robot's joints. Closed-loop calibration is based on constraining the movement of the end-effector. For example, the end-effector might be constrained to stay in a specific position or point toward the same point while the robot joint configurations change [9,10], or to lie on a specific surface, such as a cylinder [11] or a plane [12–18]. The main advantages of this approach are its low cost and the fact that it can be fully automated.

This paper focuses on the planar constraint approach. However, a single-plane constraint is not sufficient to calibrate a robot. An appropriate calibration (i.e. equivalent to an unconstrained calibration) needs at least three planes [12]. There are two main calibration models [13]. The first uses the plane equations, as in [12,14,15]. The second uses the normals of the planes [16–18]. Details of earlier work are presented below.

Zhong and Lewis [16] propose a constraint calibration method using three orthogonal planes. In this case, the encoder reading is triggered by a touch probe. Their method is based on the plane normals, which are obtained by calculating the cross-product of different sets of two vectors belonging to the same plane. Each pair of vectors is obtained from a set of three probed positions, and on this basis a linear identification system is developed. The position accuracy obtained after a PUMA 560 robot calibration was about 0.6 mm. More recently, Tang et al. [18] used the same approach (i.e. plane normals) with three planes in a study simulating the calibration of a serial polishing robot. Their simulation demonstrates that with this approach it is possible to reduce the robot's maximum pose error to about 17% and the average pose error to 24%.

Besnard et al. [14] propose a calibration method using four orthogonal planes, which are known with an accuracy of 0.02 mm. This approach consists of minimizing the errors of those plane equations. The measurement trigger is a mechanical dial gauge with a retractable stem having a repeatability of 0.02 mm. The authors applied the approach on a PUMA 560, and results in an accuracy after calibration of 0.57 mm. The validation process after calibration is based on the *distance-to-plane errors* (i.e. evaluation of the distance between the validation positions and the corresponding planes). The same method was used by Hage et al. [15] to calibrate a Stäubli TX90 robot. The planes of a 150 mm cube were known with an accuracy of 0.02 mm, and the data collection trigger was a Renishaw probe. After calibration, the mean value of the distance-to-plane errors for the four planes used were: 0.41 mm, 0.05 mm, 0.08 mm, and 0.34 mm.

As we have shown, the planar constraint approach has been used in several research studies. However, only kinematic calibration is considered in those studies. To the best of our knowledge, there has been no research exploring non-kinematic calibration using planar constraints. Furthermore, the validation process in nearly all the existing experimental research is somewhat deficient, as errors are measured only with respect to the planar surfaces that were used in the calibration process.

In this paper, a FANUC LR Mate 200iC six-axis serial robot equipped with a high-precision Renishaw touch probe is calibrated using a non-kinematic model by probing four orthogonal planes of a commercially available 9-in. datum cube made of granite. Our validation process is based not only on the distance-to-plane method, but also on the standard approach to assessing the accuracy of coordinate measurement machines: 2-in. datum spheres separated by precisely known distances are probed in order to evaluate their diameters and the distance between each pair, in several configurations.

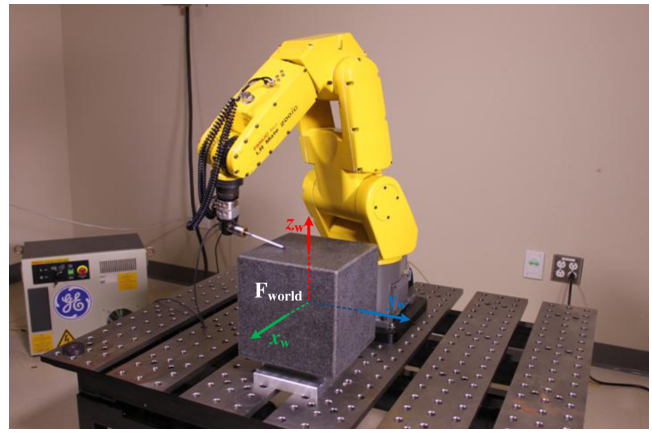

Fig. 1. The FANUC LR Mate 200iC industrial robot with the probe and the calibration cube.

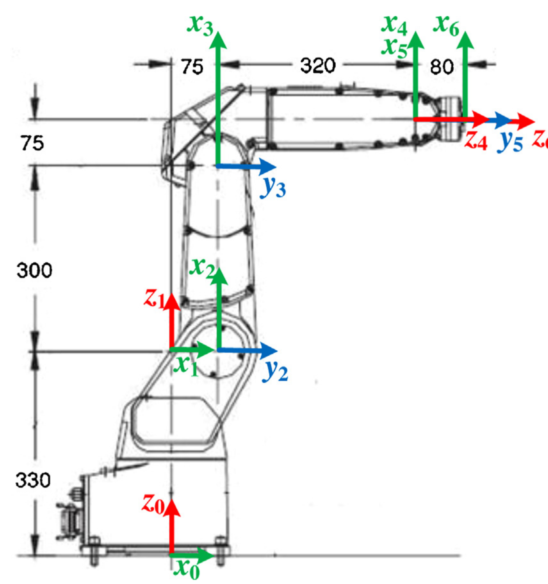

Fig. 2. The kinematic model of the FANUC LR Mate 200iC industrial robot.

2. Robot calibration model

The FANUC LR Mate 200iC (Fig. 1) is a 6-DOF serial industrial robot with six revolute joints. Seven reference frames are associated with the robot (Fig. 2), according to the Modified Dennavit–Hartenberg approach [19]: the base reference frame (F_0) and the six frames associated with the joints (F_1, F_2, ..., F_6), where F_6 represents the tool flange reference frame. Two additional frames are also considered: F_{tool}, which is associated with the touch probe and F_{world}, which is associated with the granite cube (Fig. 1).

2.1. The robot's world and tool reference frames

As shown in Fig. 1, F_{world} is chosen to be in the center of the cube and to have approximately the same orientation as F_0. The orientation (ϕ_{bx}, ϕ_{by}, ϕ_{bz}), described in *XYZ* fixed Euler angles, and the translation $\mathbf{t}_0 = [x_b, y_b, z_b]^T$ of frame F_0 with respect to frame F_{world}, are identified by the calibration process.

The origin of frame F_{tool} is the center of the probe's ruby ball, and its orientation is the same as that of the tool flange reference frame (F_6). It is important to note that our calibration process uses only the position of the end-effector. Therefore, only the translation $t_{\text{tool}} = [x_t, y_t, z_t]^T$ of frame F_{tool} with respect to frame F_6 is identified.