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Absolute robot calibration with a single telescoping ballbar

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ABSTRACT

A novel 6D measurement system was recently proposed, comprising a single commercially available telescoping ballbar and two custom-made fixtures. One fixture is attached to the robot base and the other to the robot end-effector, and each having three magnetic cups. In each of 72 poses of the tool fixture, with respect to the base fixture, it is possible to measure six distances with the ballbar between the magnetic cups on the tool fixture and the magnetic cups on the base fixture, and thus calculate the pose with high accuracy. This paper is the first to present the successful use of this measurement system for absolute robot calibration. The robot calibrated is a Fanuc LR Mate 200iC six-axis industrial robot and the telescoping bar used is the QC20-W by Renishaw. The absolute position accuracy of the robot after calibration is validated with a Faro laser tracker in almost 10,000 robot configurations. Considering the validation data in only the front/up configurations, the mean absolute positioning error is improved from 0.873 mm to 0.479 mm. To allow a comparison, the robot is also calibrated using the laser tracker and the robot accuracy validated in the same 10,000 robot configurations.

1. Introduction

It is well-known that industrial robots are highly repeatable, but their nominal accuracy is relatively poor due to various sources of differences (errors) between the nominal robot model (used in the robot controller) and the real robot. These errors can be classified in five categories [1,2]: environmental (such as those caused by temperature drifts), parametric (for example, manufacturing and assembly errors), measurement (caused by the limited resolution of the motor encoders), computational (computer round-off and steady-state control errors) and application (such as installation errors).

Fortunately, the accuracy of an industrial robot can be improved through calibration [3]. The first step is to choose the mathematical model that will improve the representation of the position and orientation (pose) of the robot end-effector. This mathematical model is a function of the robot joint angles and takes into account the error parameters that need to be modeled. Models can be based on the Denavit–Hartenberg convention [4–6], Denavit–Hartenberg Modified convention [7] or other conventions that improve error parameter identification, such as the complete and parametrically continuous model (CPC) [8,9] or other models based on the product of exponentials (POE) [10,11].

Depending on the type of errors modeled, the calibration can be classified as level-1, where only joint errors are modeled; level-2 calibration, also known as kinematic calibration [12–14]; and level-3 calibration, also called a non-kinematic calibration, which models errors other than geometric defaults such as stiffness [15–18] and temperature [19].

The error parameters can be identified by measuring the *complete pose* or *partial pose* of the robot end-effector in a set of calibration robot configurations. Many measurement devices have been used for robot calibration or validation, such as: a touch probe and a reference artifact [20,21], a telescoping ballbar [22–26], a small-range 3D (position) measurement device (such as a camera-based system), [27] acoustic sensors [6], a large-range 3D measurement device (such as a laser tracker [17,18,28–30] or CMM [15,24,31]) and a 6D (complete pose) measurement device (such as a camera-based system [28,29,32] or a laser tracker with a 6D probe [33]).

In practice, the most critical issue is the choice of the measurement system, as the latter determines the efficiency and cost of the robot calibration process. For example, the so-called closed-loop method needs to be used if the robot tool is constrained to lie on a reference object of precisely known geometry [20,34]. Although the calibration algorithm might be more complex, this method is cheaper because it only needs a switch, such as a touch probe, to detect the contact with an obstacle and save the joint readings. On the other hand, open-loop calibration methods can be applied if a 3D or 6D measurement device is used. In general, these devices are either very expensive (such as laser trackers and CMMs), or

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not highly accurate (which is the case of some stereo cameras, also called optical CMMs).

In contrast, a new 6D measurement system based on a telescoping ballbar was recently proposed [35]. This new 6D measurement device has the advantage of being more accurate than laser trackers and yet cheaper than even the cheapest optical CMM. The principal disadvantage of this system is that it can only measure a limited number of poses (maximum 72), which is a relatively small working volume.

The goal of this work is to evaluate the use of this novel 6D measurement system for the absolute calibration of a small six-axis serial robot, a Fanuc LR Mate 200iC. The absolute calibration is validated with a laser tracker in nearly 10,000 arbitrary robot configurations.

The remainder of this paper is organized as follows: Section 2 presents the experimental setup, briefly outlines the 6D measurement system, and describes a new algorithm for setting up the world reference frame. Section 3 then describes the robot calibration model and the parameter identification procedure used. Section 4 presents the measurement procedure and the experimental results. Finally, conclusions are presented in Section 5.

2. Experimental setup and description of measurement system

The experimental setup is shown in Fig. 1. It consists of a Fanuc LR Mate 200iC six-axis industrial robot, a QC20-W telescoping ballbar from Renishaw, and custom-made base, and tool fixtures made of steel. A QC-5 tool changer from ATI is used for attaching the tool fixture to the robot flange.

The tool and base fixtures each consist of three equidistant magnetic cups for 0.5 in. precision steel balls. The tool fixture, including the tool changer and the adaptors, weighs approximately 2.7 kg, which is within the 5 kg rated payload of the robot. The base fixture is attached to a ball-in-socket pivoting platform (AP180 from Thorlabs) that can be locked into a large range of orientations.

The telescoping ballbar chosen for testing, the QC20-W, is the latest telescoping ballbar from Renishaw since it is compact and wireless. Renishaw's ballbars are also by far the most popular, many thousands of units having been sold. The nominal length of the QC20-W is 100 mm. The extension bars and calibrator allow highly accurate measurement of lengths near 100 mm, 150 mm, and 300 mm.

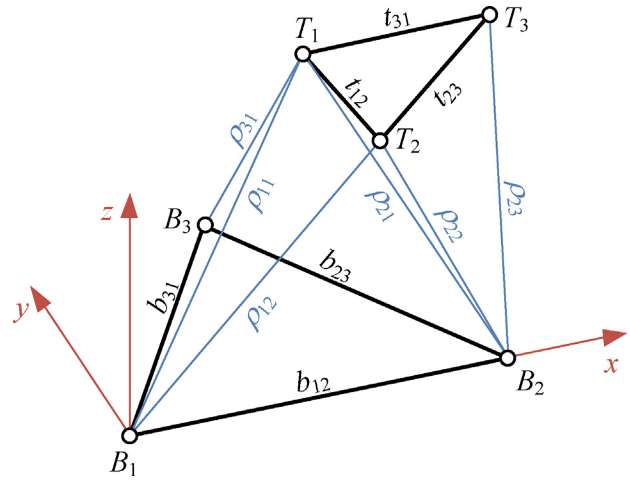
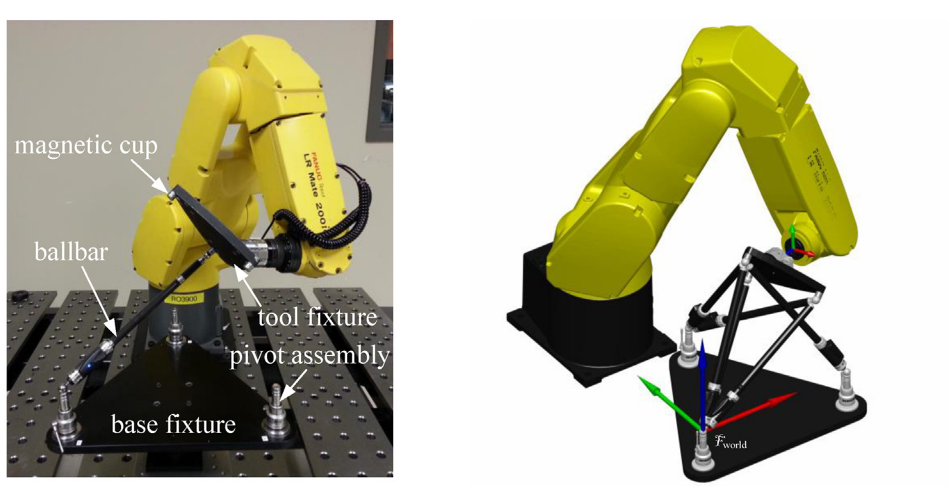


Fig. 2. Illustration of one of the 3–3 hexapod designs used.

As described in Ref. [35], several authors have proposed the use of six custom-made telescoping ballbars arranged as the legs of a hexapod for continuous 6D motion measurement. However, it is obviously preferable (and much cheaper) to use off-the-shelf telescoping ballbars such as the QC20-W. The problem with such ballbars is that their measurement range is very limited (only ±1 mm in the case of the QC20-W). To overcome this problem, and be able to measure a large number of discrete poses, the use of the so-called 3–3 hexapod design was proposed in [35] (Fig. 2). The main advantage of the 3–3 hexapod design is that no 3D measurement device is necessary in order to measure the relative positions of the three base and three tool attachment points. The telescoping ballbar itself can be used to measure the distances between the attachment points, with high accuracy. The nominal lengths provided with the standard QC20-W kit were chosen, 300 mm (the longest) for the distance between the base attachment points and 150 mm for the distance between the tool fixture attachment points. Legs of equal nominal length were chosen, and since the longer the legs the larger the measurement range of the device, this length was 300 mm.

The main idea behind this novel 6D measurement device and method is that the 3–3 hexapod can be assembled in various configurations, thus allowing the measurement of several poses. To allow simpler and more robust computations of these poses (i.e. to



(a) experimental setup (b) composite image of the six "leg" measurements

Fig. 1. Experimental setup for measuring the pose of the robot end-effector.