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A multilevel calibration technique for an industrial robot with parallelogram mechanism

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ABSTRACT

This paper presents a multilevel calibration technique for improving the absolute accuracy of an industrial robot with a parallelogram mechanism (ABB IRB2400). The parallelogram structural error is firstly modeled based on the partial differential of the position function of a general four-bar linkage and the linearization of the position constraints of the parallelogram mechanism, the model coefficients are fitted from experimental data. Secondly, an absolute kinematic calibration model is established and resolved as a linear function of all the kinematic parameters, as well as the base frame parameters and tool parameters. Finally, contrary to most other similar works, the robot joint space (rather than Cartesian space) is divided into a sequence of fan-shaped cells in order to compensate the non-geometric errors, the positioning errors on the grid points are measured and stored for the error compensation on the target points. After the multilevel calibration, the maximum/mean point positioning errors on 284 tested configurations (evenly distributed in the robot common workspace) are reduced from 1.583/0.420 mm to 0.172/0.066 mm respectively, which is almost the same level as the robot bidirectional repeatability.

1. Introduction

In recent years, industrial robots have been greatly used as orienting devices in industry, especially in the automotive, shipbuilding and aerospace manufacturing industries [1,2]. This is attribute to not only the continuous decrease of cost and its operational advantage compared with the traditional motion mechanisms, but also their flexibility for accomplishing on-line difficult tasks such as spot welding, picking and placing, drilling and cutting. Industrial robots have also been widely employed in inspection tasks for both the control and quality assurance of the manufacturing processes. Moreover, the flexible manufacturing systems constructed upon industrial robots are capable of adapting themselves to high-speed product upgrading in modern batch manufacturing mode. In a word, industrial robots already lead the development direction of future factories and will bring tremendous economic advantages to the manufacturers.

Although industrial robots have tremendous advantages, there still remains an urgent demand for improving the robot absolute accuracy in its extending application. In the conventional way, the robot is normally working on a point-to-point control mode, where the end-effector poses are manually taught for repetitive tasks, so the robot repeatability is all that matters while accuracy is not so important. But in the modern manufacturing sites, the robot has been taking on ever-more advanced tasks such as precision machining, high-accuracy (such as 0.1 mm) autonomous inspection and so on. Moreover, robot off-line programming has become one of the key techniques developed for improving the intelligence and efficiency of the industrial robot. Therefore, the robot accuracy has been elevated to an unprecedented level of importance [3].

As summarized in [4,5], the robot absolute accuracy is mainly influenced by the following factors: geometric errors (such as assembly misalignments, lateral and angular joint offsets, manufacturing accuracy, installation errors), non-geometric errors (such as link deflections, joint compliances, thermal deformations), and other errors (such as clearances, hysteresis and backlash, transducer resolution and nonlinearity). Geometric errors will cause the kinematic parameters to be slightly different from their nominal values which results in vast majority of the end-effector pose errors. Among these error factors, the geometric errors are generally modeled by a robot kinematic model and the non-geometric errors may be predictable by a structural or thermal model, but the other errors are random and cannot be easily modeled.

Robot calibration is a cost-effective way to improve the robot accuracy which is aimed at finding a mathematical model that can represent the robot better than the nominal kinematic model. The

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calibration process generally consists of the following three steps: (a) error parameters modeling, (b) end-effector pose measurement, (c) error parameters identification. Several researchers have focused on these issues involved in the robot calibration process. Stone [6], Mooring [7] and Hollerbach [8] have given comprehensive reviews on the fundamental and main aspects about kinematic calibration of robotic system in their books. Various measurement techniques such as laser tracker, CCD camera, telescoping ballbar and even special designed sensors have been employed for the calibration tasks [9,10]. All of these have made the calibration process more convenient and timesaving. Several researches have also focused on the implementation of fast and accurate parameters identification algorithms. Omodei et al. [11] have compared three different kinematic parameter identification algorithms (nonlinear least-square estimation, linear least-square estimation and extended Kalman filter estimation) for a SCARA manipulator, and gained the conclusion that the Kalman filter estimation is most fast and reliable. Moreover, recent studies have included explicitly non-geometric errors as well as geometric errors in calibration. Nubiola [12] proposed an absolute calibration method for an ABB IRB1600 robot using a laser tracker, which takes into account all possible geometric errors and compliance error. Santolaria et al. [13] have presented an empirical thermal error correction model for the typical arm coordinate measuring machine, which has shown an important accuracy improvement for arm operation at temperatures differ form 20 °C.

It is virtually impossible to establish a complete kinematic identification model that considers all the error sources contributing to the end-effector pose error. Many recent research efforts have been focused on the modeless method which does not need any kinematic error model. Alici et al. [14] presented a systematic approach for representing and estimating the Cartesian positioning errors of robot manipulators with analytical functions such as Fourier polynomials and ordinary polynomials, which has shown effective enough to improve robot accuracy. Bai [15] proposed a modeless method to divide the robot workspace into a sequence of small cubic cells, and positioning errors on the grid points are measured and then used to estimate the positioning error on any target point in the robot workspace. The modeless calibration methods are conceptually simple and remarkably effective, and moreover, do not need any complicated parameters identification algorithms. However, there is generally a trade-off between the volume of the calibration workspace and the measurement workload, i.e., more grid point-measurements are needed for a larger calibration workspace or a more accurate calibration result. Also for a fixed calibration workspace, more cells are needed if higher calibration accuracy is desired, and more measurements and memory are required.

The robotic system researched in this paper is an ABB IRB2400 industrial robot, which is not a purely open-loop structure, but rather contains a parallelogram mechanism in order to increase its structural rigidity. In previous work about the kinematic identification of robot manipulators with parallelogram mechanisms, the kinematic parameters pertaining to the four-bar mechanism were either not taken into account or simply modeled by adding a passive joint chain in the robot kinematic transformation chain [14], which could not illustrate the essential relationship between the errors in passive joint angles and other parallelogram structural errors.

In this paper, we have explored the error sources of an industrial robot with a parallelogram mechanism and proposed a multilevel calibration method for improving its absolute accuracy. The error sources are divided into three levels and a source-oriented calibration method is developed to compensate each level of error. Level 1 is defined as “joint level”, and the error in the parallelogram mechanism is mainly calibrated. A joint angular error model is established and the model coefficients are fitted from the experimental data. Level 2 is the absolute kinematic level, and a linear kinematic error calibration model that takes into account all the kinematic parameters, as well as base parameters and tool parameters has been established. Level 3 is defined as non-geometric level which aims at compensating the non-geometric errors. In this level, we divided the joint space (rather than Cartesian space) of the robot into a sequence of fan-shaped cells, the positioning errors on the grid points are measured and stored for the error compensation at the target points. This is contrary to most other similar work. Finally, the multilevel compensation method has been validated in 284 robot configurations and the three levels of calibration methods are applied one by one. The results show that the robot absolute positioning accuracy has been improved gradually and steadily with these three error compensation steps, and finally increased to almost the same level as the robot bidirectional repeatability.

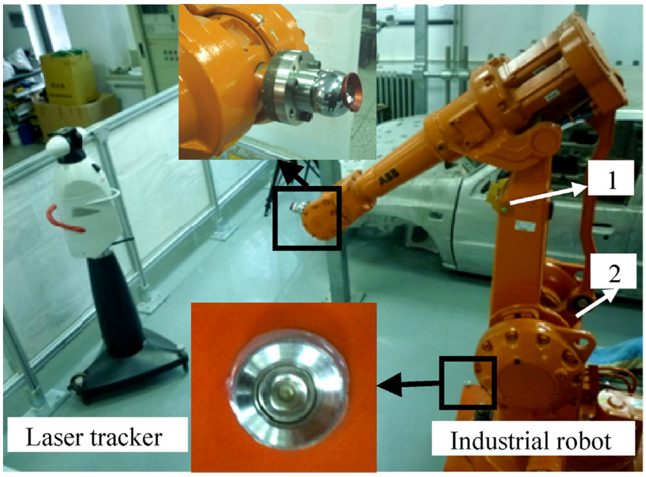

Fig. 1. Experimental setup with the ABB IRB2400 robot and Leica laser tracker.

The remainder of the paper is organized into the following five sections. Section 2 presents first an introduction for the robot kinematic model. Section 3 presents a deep analysis of the structural error behavior of the robot parallelogram. Section 4 provides the error model of the robot system and the error parameter identification method. Section 5 introduces the error compensation method based on grid division in the robot joint workspace and describes briefly the principle of interpolation method. Experimental verification of the multilevel error compensation method is given in Section 6 and conclusions are finally given in Section 7.

2. Experimental setup and kinematic model

Fig. 1 shows the experimental setup that was used for measuring the positioning performance of the ABB IRB2400/10 robot with a Leica AT901 laser tracker. In order to obtain the optimal measuring accuracy, the laser tracker works with the laser interferometer option and the spherically mounted reflector (SMR) is maintained never losing the beam during the position measurement. According to the specification, the typical measurement uncertainty (deviation between the measured and the nominal coordinate of a tested point) of the laser tracker is ±15 μm + 6 μm/m. As for the IRB2400 robot, its unidirectional repeatability is specified to be 0.060 mm. However, following the method suggested in [16], we evaluated that the robot's bidirectional repeatability can be as much as 0.157 mm using a Renishaw laser interferometer *XL*80. The bidirectional repeatability serves as the upper bound for the robot positioning error compensation results. The position commands sent to the robot controller are the joint values using the RAPID instruction *MoveAbsJ*, and all the measurements were performed