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Full length Article

Modeling and calibration of high-order joint-dependent kinematic errors for industrial robots

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ABSTRACT

Robot positioning accuracy is critically important in many manufacturing applications. While geometric errors such as imprecise link length and assembly misalignment dominate positioning errors in industrial robots, significant errors also arise from non-uniformities in bearing systems and strain wave gearings. These errors are characteristically more complicated than the fixed geometric errors in link lengths and assembly. Typical robot calibration methods only consider constant kinematic errors, thus, neglecting complex kinematic errors and limiting the accuracy to which robots can be calibrated. In contrast to typical calibration methods, this paper considers models containing both constant and joint-dependent kinematic errors. Constituent robot kinematic error sources are identified and kinematic error models are classified for each error source. The constituent models are generalized into a single robot kinematic error model with both constant and high-order joint-dependent error terms. Maximum likelihood estimation is utilized to identify error model parameters using measurements obtained over the measurable joint space by a laser tracker. Experiments comparing the proposed and traditional calibration methods implemented on a FANUC LR Mate 200*i* robot are presented and analyzed. While the traditional constant kinematic error model describes 79.4% of the measured error, the proposed modeling framework, constructed from measurements of 250 poses, describes 97.0% of the measured error. The results demonstrate that nearly 20% of the kinematic error in this study can be attributed to complex, joint-dependent error sources.

1. Introduction

Industrial robots are highly flexible and repeatable automation platforms effective for a number of manufacturing tasks [1]. In some applications, a robot is programmed through a "teach" mode [2], in which the robot is manually positioned through a series of points. The robot can return to any of those points, within its repeatability, at any time by recalling them from memory. For these applications, repeatability is the critical design parameter while accuracy is not as critical. In other manufacturing applications, such as deburring and light machining, the robot will be commanded to arbitrary positions and orientations [3], thus, its repeatability and accuracy are both important. However, robot accuracy can be an order of magnitude worse than its repeatability due to various sources of errors such as component manufacturing and assembly errors, as well as joint deflection errors [4–6]. Thus, a rapid and effective method for calibrating robots is essential.

Research regarding robot calibration has been studied and well-developed over the past three decades. While the majority of the work focuses on kinematic model-based calibration, non-kinematic errors (such as elastic deformation) also play an important role in reducing robot accuracy [7]. In [8], kinematic calibration methods were classified into open-loop, closed-loop and screw-axis measurement methods. In open-loop methods, external metrology systems are used to take measurements. Two examples of open-loop calibration methods are given in [9,10], in which a laser tracker and a single telescoping ballbar, respectively, were used for data collection. In closed-loop methods, external measurement devices are not needed. The robot endpoint is attached to the ground such that a mobile closed-loop kinematic chain is formed if the robot is redundant to the endpoint constraint. Then kinematic model parameters are identified using joint angle readings. The methodology and applications of this methodology are given in [11]. In screw-axis measurement methods, kinematic errors are calibrated by determining the actual transformation relationship between consecutive joints. A typical screw-axis measurement method is Circle Point Analysis (CPA) [12], two examples of which are given in [13,14].

Although a wealth of research has been conducted in robot kinematic calibration, a majority of the work only considers ideal rigid body motion and consists of identifying constant joint offsets. While a joint-independent error kinematic model may be sufficient to describe geometric errors resulting from structural errors in the robot assembly (e.g., link-length or alignment errors), many complex kinematic errors,

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such as periodic gear errors, cannot be sufficiently captured. Strain wave gearings, commonly used in industrial robots due to their high reduction ratio, light weight and compact size [15,16], are known to have complicated position-dependent errors caused by manufacturing tolerances, alignment errors and the gear tooth placement errors on both the circular and flexible splines [17]. Flexing of bearings will also result in non-parallel coupling of gearboxes, causing the end effector to be out of plane, higher at some positions and lower at other positions [18]. Assembly inaccuracies, gear tooth errors and wear combine to cause position dependent and periodic kinematic errors [19]. The small magnitude of the kinematic errors in strain wave gearings will be amplified by serial links to the end effector, resulting in large, very complex robot errors. More precise models are needed to better describe these complex kinematic errors and, thus, improve post calibration performance.

A new robot kinematic calibration method capable of capturing both fixed and complex kinematic errors is developed in this paper. Six Degree of Freedom (DoF) error transformation matrices between consecutive joints, having joint-dependent error terms modeled by high-order polynomials, are used to construct a joint-dependent kinematic error model capable of describing complex geometric errors [20]. A laser tracker, having the advantages of rapid measurement speed and the ability to gather most, if not all, of the measurements in a single setup, is used for data collection. Then, error model parameters are identified with a maximum likelihood estimation algorithm [21], and a gradient search inverse kinematic compensation algorithm [22] is used for compensation.

The rest of this paper is organized as follows. Section 1 categorizes and models different robot kinematic errors. Section 2 proposes a high-order, joint-dependent kinematic error model. Identification and compensation methods are provided in Section 3. Section 4 provides the experimental results for a FANUC LR Mate 200*i* robot. Circle Point Analysis is also implemented as a representative traditional calibration method. A comparison of CPA with the proposed method is described and analyzed in Section 5. The paper is summarized and conclusions are drawn in Section 6.

2. Robot kinematic error modeling

2.1. Characterization of robot kinematic errors

Let $\mathbf{T}_i^{i-1}$ represent a transformation from Frame i−1 to Frame i and parameterize $\mathbf{T}_i^{i-1}$ according to the Denavit–Hartenberg (DH) convention [23] as,

$$\mathbf{T}_i^{i-1} = \mathbf{T}_{RZ}(\theta_i)\mathbf{T}_{TZ}(d_i)\mathbf{T}_{TX}(a_i)\mathbf{T}_{RX}(\alpha_i), \tag{1}$$

where $\mathbf{T}_{Rj}$ is a rotation matrix about axis j, $\mathbf{T}_{Tj}$ is a translation matrix along axis j, and θ_i, d_i, a_i and α_i are model parameters. Using the DH frame assignment convention, a rotary joint can be written as

$$\mathbf{T}_i^{i-1} = \mathbf{T}_{RZ}(q_i)\mathbf{T}_{d_i,a_i,\alpha_i}, \tag{2}$$

where q_i is the joint command of link i and,

$$\mathbf{T}_{d_i,a_i,\alpha_i} = \mathbf{T}_{TZ}(d_i)\mathbf{T}_{TX}(a_i)\mathbf{T}_{RX}(\alpha_i), \tag{3}$$

is a fixed homogeneous transformation. Robot kinematic errors (e.g., link length error, misalignment, pitch error) will cause differences between the actual and nominal transformations. Appropriate mathematical descriptions of those errors are essential in the construction of robot kinematic error models. Several robot kinematic error sources are described and their corresponding error models are constructed as follows.

1) Rotating center offset errors
The nominal transformation $\mathbf{T}_i^{i-1}$ starts from the rotating center of Frame $i-1$. Existence of assembly errors will cause an offset between the actual and nominal rotating center. In this case, the actual transformation from Frame $i-1$ to Frame i, $\tilde{\mathbf{T}}_i^{i-1}$, is

$$\tilde{\mathbf{T}}_i^{i-1}(q_i) = \mathbf{E}_{RC,i}\mathbf{T}_i^{i-1}(q_i), \tag{4}$$

where $\mathbf{E}_{RC,\,i}$ is a fixed error translational transformation describing the ith joint rotating center offset,

$$\mathbf{E}_{RC,i} = \begin{bmatrix} 1 & 0 & 0 & \delta_{RC,X,i} \\ 0 & 1 & 0 & \delta_{RC,Y,i} \\ 0 & 0 & 1 & \delta_{RC,Z,i} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{5}$$

and $\delta_{RC,j,i}$ is the translational error along the jth axis. Fig. 1(a) gives a geometric description of a rotating center offset where Frame $X_{i\text{-}1}Y_{i\text{-}1}Z_{i\text{-}1}$ denotes the nominal Frame $i-1$ and Frame $X'_{i-1}Y'_{i-1}Z'_{i-1}$ denotes the actual Frame $i-1$.

2) Mastering errors
The location of the zero position, referred to as mastering, is set by aligning the robot through one of several procedures such as zero degree or single axis mastering. However, a robot might lose the mastering data and remastering can introduce a small change in the zero location. With this fixed small change, the actual transformation is

$$\tilde{\mathbf{T}}_i^{i-1}(q_i) = \mathbf{T}_i^{i-1}(q_i + \Delta q_{i0}) = \mathbf{T}_{RZ}(q_i + \Delta q_{i0})\mathbf{T}_{d_i,a_i,\alpha_i}, \tag{6}$$

where Δq_{i0} is a fixed mastering error for joint i. Fig. 1(b) shows the transformation due to mastering errors.

3) Link length and assembly errors
Imprecise manufacturing of link parts and assembly misalignment errors will cause a fixed offset of the nominal link lengths (i.e., d_i and a_i) and angles between joints (i.e., q_i and α_i). The resulting transformation due to the errors in the link lengths and angles between joints can be represented by

$$\begin{aligned}\tilde{\mathbf{T}}_i^{i-1}(q_i) &= \mathbf{T}_{RZ}(q_i + \Delta q_{ia})\mathbf{T}_{TZ}(d_i + \Delta d_i)\mathbf{T}_{TX} \\ &\quad (a_i + \Delta a_i)\mathbf{T}_{RX}(\alpha_i + \Delta\alpha_i), \\ &= \mathbf{T}_{RZ}(q_i + \Delta q_{ia})\mathbf{T}_{d_i,a_i,\alpha_i}\mathbf{E}_{LA,i},\end{aligned} \tag{7}$$

where Δq_{ia}, Δd_i, Δa_i and $\Delta\alpha_i$ are fixed link length and assembly errors and $\mathbf{E}_{LA,i}$ is a fixed link length and assembly error transformation,

$$\mathbf{E}_{LA,i} = \left(\mathbf{T}_{d_i,a_i,\alpha_i}\right)^{-1}\mathbf{T}_{TZ}(d_i + \Delta d_i)\mathbf{T}_{TX}(a_i + \Delta a_i)\mathbf{T}_{RX}(\alpha_i + \Delta\alpha_i). \tag{8}$$

Fig. 1(c) describes the transformations due to these errors using the DH convention.

4) Pitch errors
Pitch error is an error in the gearing that is caused by the runout of the gear flank groove. The pitch error will affect the nominal gear ratio such that the nominal joint command, q_i, will be amplified or attenuated. Further, the gear teeth may not be ideally evenly distributed; therefore, the pitch error may also be a function of the gear angle. In this case, the actual transformation will be

$$\tilde{\mathbf{T}}_i^{i-1}(q_i) = \mathbf{T}_{RZ}(r(q_i)q_i)\mathbf{T}_{d_i,a_i,\alpha_i}, \tag{9}$$

where $r(q_i)$ is a joint-dependent correcting ratio for pitch error. Fig. 1(d) illustrates the transformation due to pitch errors.

5) Strain wave gearing errors
Strain wave gearings are widely used in robotic transmission systems. A strain wave gearing, shown in Fig. 2, is comprised of three components: a flexible spline, a wave generator and a circular spline. The wave generator, inserted into the flexible spline, will rotate as the input. Although strain wave gearings have the advantages of