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Determination of optimal samples for robot calibration based on error similarity

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Abstract Industrial robots are used for automatic drilling and riveting. The absolute position accuracy of an industrial robot is one of the key performance indexes in aircraft assembly, and can be improved through error compensation to meet aircraft assembly requirements. The achievable accuracy and the difficulty of accuracy compensation implementation are closely related to the choice of sampling points. Therefore, based on the error similarity error compensation method, a method for choosing sampling points on a uniform grid is proposed. A simulation is conducted to analyze the influence of the sample point locations on error compensation. In addition, the grid steps of the sampling points are optimized using a statistical analysis method. The method is used to generate grids and optimize the grid steps of a Kuka KR-210 robot. The experimental results show that the method for planning sampling data can be used to effectively optimize the sampling grid. After error compensation, the position accuracy of the robot meets the position accuracy requirements.

1. Introduction

The performance requirements for the new-generation aircraft assembly are higher than ever before. With high productivity, great flexibility, and low cost, articulated arm robots are used to improve assembly quality and production efficiency. Automatic drilling and riveting systems based on robots have been gradually implemented in Airbus and Boeing aircraft manufacturing systems.[1–5] Aircraft assembly requires equipment to have good absolute position accuracy (less than 0.5 mm). Therefore, it is necessary to improve the absolute position accuracy of industrial robots.

For ease of implementation and cost, the calibration method is more practical. Roth et al.[6] summarizes that robot calibration is an integrated process of modeling, measurement, identification, and implementation of a new model. One of the most difficult problems in robot calibration is choosing measurement samples to minimize the absolute position error based on an established error model. In fact, the sampling point locations have a great impact on the robot error compensation effect. Therefore, it is important to logically choose sampling points.

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There are many methods for robot calibration. In order to eliminate the singularity problem in the traditional D-H model proposed by Stone and Sanderson[7], several modeling methods including the S-model[8], the CPC (complete and parametrically continuous) kinematic model[9], and the modified D-H model[10] have been developed and used widely. A POE (product of exponentials) formula was used to calibrate serial robots[11], with which the singularity avoidance of the POE-based model was proved. A laser tracker was used for measurement and the robot parameter errors were identified.[12] A feasible low-cost vision-based measurement system using a single camera was developed for robot calibration methods and systems.[13] The Levenberg–Marquardt algorithm was used to identify the 25 unknown parameter errors described by the MD-H model.[14] Neural networks were also used to improve the poisoning accuracy of robot manipulators.[15] Park et al.[16] employed a stationary camera and a structured laser module (SLM) attached on a robot's end effector to measure the accurate position of the robot.[16] Several observability indexes were promoted to measure the goodness of a pose set based on analyzing the effects of noise and variance of parameters.[17]

From existing literature, most research focuses on model optimization, development of measuring equipment, and identification methods. Some methods use observability to judge the effectiveness of sampling points but not planning. In this study, a method is proposed for planning sampling points based on the error similarity compensation method.[18,19] In this method, sampling points are optimized while the accuracy is ensured. The number of sampling points is reduced to improve the implementation efficiency.

2. Error compensation method based on error similarity

2.1. Analysis of kinematics model error

The transformation matrix $\boldsymbol{T}_n$ that relates the tool frame {T} to the robot's base frame {B} can be represented as:

$$\boldsymbol{T}_n = \boldsymbol{A}_1\boldsymbol{A}_2\boldsymbol{A}_3 \ldots \boldsymbol{A}_n \tag{1}$$

$$\boldsymbol{A}_i = \mathrm{Rot}(Z, \theta_i) \cdot \mathrm{Trans}(0, 0, d_i) \cdot \mathrm{Trans}(a_i, 0, 0) \cdot \mathrm{Rot}(X, \alpha_i) \tag{2}$$

where $\boldsymbol{A}_i$ is the coordinate transformation matrix between joint $i-1$ and joint i, a_i is the length of the connecting rod of the ith joint, α_i is the torsional angle of the connecting rod of the ith joint, d_i is the joint deviation of the ith joint, and θ_i is the joint rotation angle of the ith joint, X is the X-axis of the link frame, Z is the Z-axis of the link frame.

According to Eq. (2), the description of $\boldsymbol{A}_i$ depends on its 4 parameters. For rotational freedom, θ_i is variable, and the other 3 parameters are fixed. For a revolute joint, the joint angle θ_i is the joint variable. According to the differential theory, the differentiation of Eq. (2) is:

$$\begin{aligned} \mathrm{d}\boldsymbol{A}_i &= \frac{\partial \boldsymbol{A}_i}{\partial a_i}\Delta a_i + \frac{\partial \boldsymbol{A}_i}{\partial \alpha_i}\Delta \alpha_i + \frac{\partial \boldsymbol{A}_i}{\partial d_i}\Delta d_i + \frac{\partial \boldsymbol{A}_i}{\partial \theta_i}\Delta \theta_i \\ &= \boldsymbol{A}_i \delta \boldsymbol{A}_i \end{aligned} \tag{3}$$

where Δa_i is the micro offset of a_i, $\Delta\alpha_i$ is the micro offset of α_i, Δd_i is the micro offset of d_i, $\Delta\theta_i$ is the micro offset of θ_i . $\delta\boldsymbol{A}_i$ is the error matrix of $\boldsymbol{A}_i$:

$$\delta\boldsymbol{A}_i = \begin{bmatrix} 0 & -\delta z_i^A & -\delta y_i^A & -\mathrm{d}x_i^A \\ \delta z_i^A & 0 & -\delta x_i^A & -\mathrm{d}y_i^A \\ \delta z_i^A & \delta x_i^A & 0 & -\mathrm{d}z_i^A \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

in which $\mathrm{d}x_i^A$, $\mathrm{d}y_i^A$, $\mathrm{d}z_i^A$ are the position errors of frame $\{i\}$ with respect to frame $\{i-1\}$. δx_i^A, δy_i^A, δz_i^A are the orientation errors of frame $\{i\}$ with respect to frame $\{i-1\}$.

With consideration of the error, the transformation model between the robot coordinate system and the tool coordinate system is established:

$$\begin{aligned} \boldsymbol{T}_n + \mathrm{d}\boldsymbol{T}_n &= (\boldsymbol{A}_1 + \mathrm{d}\boldsymbol{A}_1)(\boldsymbol{A}_1 + \mathrm{d}\boldsymbol{A}_1)\ldots(\boldsymbol{A}_n + \mathrm{d}\boldsymbol{A}_n) \\ &= \prod_{i=1}^{n}(\boldsymbol{A}_i + \mathrm{d}\boldsymbol{A}_i) \end{aligned} \tag{5}$$

If we ignore the differential higher-order term, we can obtain:

$$\begin{aligned} \mathrm{d}\boldsymbol{T}_n &= \boldsymbol{T}_n \cdot \sum_{i=1}^{n}(\boldsymbol{U}_{i+1}^{1} \cdot \delta\boldsymbol{A}_i \cdot \boldsymbol{U}_{i+1}^{1}) \\ &= \boldsymbol{T}_n \cdot \delta\boldsymbol{T}_n \end{aligned} \tag{6}$$

where $\delta\boldsymbol{T}_n$ is the error matrix of $\boldsymbol{T}_n$, and $U_i^1 = A_1A_2\cdots A_n$. According to differential kinematics,

$$\begin{aligned} \delta\boldsymbol{T}_n &= \sum_{i=1}^{n}(\boldsymbol{U}_{i+1}^{-1} \cdot \delta\boldsymbol{A}_i \cdot \boldsymbol{U}_{i+1}) \\ &= \begin{bmatrix} 0 & -\delta z_n & \delta y_n & \mathrm{d}x_n \\ \delta z_n & 0 & -\delta x_n & \mathrm{d}y_n \\ -\delta y_n & \delta x_n & 0 & \mathrm{d}z_n \\ 0 & 0 & 0 & 0 \end{bmatrix} \end{aligned} \tag{7}$$

in which $\mathrm{d}x_n$, $\mathrm{d}y_n$, $\mathrm{d}z_n$ are the position errors of frame {n} with respect to frame {0}. δx_n, δy_n, δz_n are the orientation errors of frame $\{n\}$ with respect to frame {0}.

The position and orientation errors vectors of the end effector are expressed as:

$$\boldsymbol{d}_n = [\,\mathrm{d}x_n, \quad \mathrm{d}y_n, \quad \mathrm{d}z_n\,]^{\mathrm{T}} \tag{8}$$

$$\boldsymbol{\delta}_n = [\,\delta x_n, \quad \delta y_n, \quad \delta z_n\,]^{\mathrm{T}} \tag{9}$$

2.2. Robot position error similarity

Each component of the position error vector $\boldsymbol{d}^n$ is described by a series functions composed of the kinematic parameters:

$$\begin{cases} \mathrm{d}x_n = \mathrm{d}x(\theta_1, \theta_2, \ldots, \theta_n) \\ \mathrm{d}y_n = \mathrm{d}y(\theta_1, \theta_2, \ldots, \theta_n) \\ \mathrm{d}z_n = \mathrm{d}z(\theta_1, \theta_2, \ldots, \theta_n) \end{cases} \tag{10}$$

Each function is composed of algebraic functions and trigonometric functions. Therefore, there is a degree of similarity between the pose errors when the joints configurations are close. The similarity is related to the deviation of each joint angle between configurations. Robot inverse kinematic analysis has shown that the pose of a robot and its joint angles are connected by a functional relation. Therefore, the pose errors of a robot also exhibit similarity.

When a robot is in a specific pose, its position error $\boldsymbol{d}_n$ can be treated as a three-dimensional vector in the base coordinate system. The concept of error similarity has been proposed by