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Positional error similarity analysis for error compensation of industrial robots

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ABSTRACT

The purpose of this paper is to propose an error compensation method with error similarity analysis to improve the absolute positional accuracy of industrial robots. The positional error similarity is proposed with the analysis of the error model established by robot kinematic parameters, and is quantified with semivariogram function. Then an error compensation method is proposed base-on positional error similarity. The ordinary Kriging method is used to calculate the positional errors of the robot TCP. The error compensation is performed by modifying the position coordinates in the robot controlling commands. Experimental verification showed that the maximum positional error of the robot TCP was reduced by 75.36% from 1.2912 mm to 0.3182 mm.

1. Introduction

Industrial robots have been widely used in automated manufacturing of vehicles, aircrafts and even robots themselves. The accuracy of the robots is a very important factor to affect the quality of the products. Positional accuracy and repeatability are the most important criteria to judge the accuracy and precision of industrial robots. Although encoders and servo systems ensure the repeatability of the robot, they cannot compensate for the accuracy loss caused by the manufacturing errors of the components, the deflection caused by the robot's payload, backlash and so on. So the repeatability of an industrial robot is generally much better than the positional accuracy.

However, positional accuracy is more important than repeatability in some robot-based workcells which require high accuracy, such as robotic drilling systems for aircraft components. This is because these applications usually use off-line programming systems to generate the robot's trajectories. The trajectory generation is carried out by setting the nominal TCP (i.e. tool centre point) of the end effector to the specified positions on the nominal CAD models, so the quality of the processed products is mainly influenced by the positional accuracy of the robot. It is necessary to calibrate the robot so that the positional accuracy is able to meet the tolerance requirements of the products.

Kinematic calibration or error compensation is usually used to improve the robot positional accuracy. Many researchers have proposed calibration methods based on establishing kinematic error models. The model-based calibration methods focus on the position and posture relation between adjacent joints. Denavit–Hartenberg (D–H) model [1,2] is a traditional model to describe the joint relation with kinematic parameters, but it becomes singular if the adjacent joints are parallel. Many methods such as S-model [3] and complete and parametrically continuous (CPC) model [4] were proposed to solve this problem. Hayati [5] added a rotational parameter on the basis of D–H model and proposed modified D–H model, which is widely used in kinematic calibration by later researchers [6–10]. Besides, product of exponentials (POE) formula [11] was also used in the robot kinematic model to perform robot calibration [12,13].

The model-based calibration is mainly performed by measuring the positional errors of certain sample points and identifying the kinematic parameter errors [14]. The main methods to estimate the parameter errors include linear least square method [7,15], Levenberg–Marquardt (LM) method [16–18], Kalman filter [9,19] and artificial neural networks [20,21]. The model-based method can achieve a good calibration effect since the kinematic model is fitted to match the real one. But the kinematic parameter errors should be modified in the robot control system using most model-based methods, which is difficult and expensive for the unopened control systems.

Another feasible way is considering the robot positional errors as spatial data, i.e. positional errors are considered as attribute

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values corresponding to the spatial positions in the robot working envelope. Research showed that the robot positional errors of near positions have spatial similarity [22]. This property is similar to the spatial dependency of spatial data, so the positional errors can be estimated with spatial interpolation [23,24], which is mainly used in geographic information system (GIS).

A robot error compensation method with the analysis of the positional error similarity is proposed in this paper. Section 2 presents the positional error similarity based-on the analysis of the robot error model. An error modelling based-on error similarity and a compensation method with spatial interpolation are proposed in Section 3. The results of the experimental verification are shown in Section 4.

2. Error similarity of industrial robots

2.1. Positional error model based on kinematic parameters

There are several methods to describe the robot kinematic parameters in the existing literatures. As the most commonly used convention, the DH parameters were selected in this study. Thus each ith link can be defined by the link length a_i and the link twist α_i, and the ith joint can be defined by the joint distance d_i and the joint angle θ_i. An extra rotation parameter β_i proposed by Hayati [5] was also used to avoid singularity caused by two parallel joint axes.

The transformation between two adjacent link frames is defined in terms of the modified DH parameters as

$$\boldsymbol{A}_i = \text{Rot}(x, \alpha_{i-1})\text{Trans}(a_{i-1}, 0, 0)\text{Rot}(z, \theta_i)\text{Trans}(0, 0, d_i)\,\text{Rot}(y, \beta_i) \tag{1}$$

where $\boldsymbol{A}_i$ is a homogeneous matrix which refers to the transformation of the ith link frame relative to the $(i-1)$th link frame, $\text{Rot}(\cdot)$ represents rotation transformation matrix, and $\text{Trans}(\cdot)$ represents translation transformation matrix. For a 6-DOF (6-degree-of-freedom) manipulator, its forward kinematic model is defined as

$$\boldsymbol{T} = F(\boldsymbol{\theta}|\boldsymbol{\psi}) = \boldsymbol{A}_1\boldsymbol{A}_2\boldsymbol{A}_3\boldsymbol{A}_4\boldsymbol{A}_5\boldsymbol{A}_6 \tag{2}$$

where $F(\boldsymbol{\theta}|\boldsymbol{\psi})$ refers to a function calculating the forward kinematic matrix $\boldsymbol{T}$ with a group of joint angles $\boldsymbol{\theta}$, given a group of known kinematic parameters $\boldsymbol{\psi}$ (including $\boldsymbol{d}$, $\boldsymbol{a}$, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$).

The positional error of TCP can be considered as the result caused by the errors of the kinematic parameters, since 80–90% of the positional error is caused by kinematic parameter errors [25,26]. Thus, the positional error model of an arbitrary position $\boldsymbol{P}_i$ in the robot working envelope can be defined as

$$\Delta\boldsymbol{P}_i = \frac{\partial\boldsymbol{P}_i}{\partial\boldsymbol{\theta}}\Delta\boldsymbol{\theta} + \frac{\partial\boldsymbol{P}_i}{\partial\boldsymbol{d}}\Delta\boldsymbol{d} + \frac{\partial\boldsymbol{P}_i}{\partial\boldsymbol{a}}\Delta\boldsymbol{a} + \frac{\partial\boldsymbol{P}_i}{\partial\boldsymbol{\alpha}}\Delta\boldsymbol{\alpha} + \frac{\partial\boldsymbol{P}_i}{\partial\boldsymbol{\beta}}\Delta\boldsymbol{\beta} \tag{3}$$

where $\boldsymbol{P}_i$ is the position vector (i.e. the 1st to the 3rd elements of the 4th column of the forward kinematic matrix $\boldsymbol{T}$) and $\Delta\boldsymbol{P}_i$ is the positional error vector of $\boldsymbol{P}_i$. For a 6-DOF manipulator, each of the parameter error vectors (i.e. $\Delta\boldsymbol{\theta}$, $\Delta\boldsymbol{d}$, $\Delta\boldsymbol{a}$, $\Delta\boldsymbol{\alpha}$ and $\Delta\boldsymbol{\beta}$) has 6 elements.

2.2. Qualitative analysis of error similarity

For manipulators with rotary joints, we can assume that only the joint angle θ_i is variable and the other kinematic parameters are constant. According to the kinematic model in Eq. (2), the change of the TCP positions depends on the change of the joint angles. Generally the kinematics parameter errors are also considered as constant values, thus the change of the TCP positional errors also depends on the change of the joint angles, according to Eq. (3).

Based on the above assumptions, it can be seen from Eq. (3) that the positional error $\boldsymbol{P}_i$ is composed of a series of elementary functions of the kinematic parameters and their errors. For 6-DOF manipulators with rotary joints, the positional error $\boldsymbol{P}_i$ is continuous since it is a function with respect to the joint angles. Therefore, when two joint configurations are similar, the corresponding robot positions and positional errors are also similar.

In addition, for 6-DOF industrial robots with rotary joints, the waist, shoulder and elbow joints (θ_1, θ_2 and θ_3) contribute primarily to the position of the TCP, while the pitch, roll and yaw joints (θ_4, θ_5 and θ_6) contribute primarily to the posture of the TCP. Therefore the waist, shoulder and elbow joints show a larger effect on the robot positional error than that of the pitch, roll and yaw joints [27]. In general, there is multi-solution issue in solving inverse kinematics from Cartesian to joint space. Under certain constraints of the joint angles of the robot, such as restricting the "status" value of KUKA industrial robots [28], the robot configurations can be uniquely identified, i.e. the waist, shoulder and elbow joints can be similar when the positions of the TCP are similar. Then, if the orientations of the TCP are similar, the corresponding robot configurations are similar, thus the positional errors are similar. If the orientations are not similar, the positional errors cam be similar as well because the positional errors caused by the pitch, roll and yaw joints are small.

Thus, we can qualitatively assume that, under certain constraints, there is similarity between the positional errors of adjacent positions in both joint space and working space. The "similarity" mentioned here means that if the positional error of a position in the robot working space is relatively large (or relatively small), the positional error of the adjacent position trends to be relatively large (or relatively small).

2.3. Quantitative analysis of error similarity

The error similarity illustrated above can be displayed quantitatively by means of semivariogram function in spatial statistics [29]. The semivariogram of the robot positional errors is half of the variance of the increment between two positional errors in the working space. In practice, the semivariogram is usually calculated by the following equation with a group of samples:

$$\gamma(\boldsymbol{h}) = \frac{1}{2N(\boldsymbol{h})}\sum_{i=1}^{N(\boldsymbol{h})}\left[\boldsymbol{e}(\boldsymbol{P}_i) - \boldsymbol{e}(\boldsymbol{P}_i + \boldsymbol{h})\right]^2 \tag{4}$$

where $\gamma(\boldsymbol{h})$ is called the experimental semivariogram, $N(\boldsymbol{h})$ is the number of the sample pairs which distance is $\boldsymbol{h}$, and $\boldsymbol{e}(\boldsymbol{P}_i)$ represents the positional error of the sample point $\boldsymbol{P}_i$. A semivariogram curve can be fitted by calculating several semivariogram value related to different distance $\boldsymbol{h}$, and the semivariogram properties can be analyzed. A typical graph of the semivariogram curve is shown in Fig. 1, where C_0 and C are the semivariogram and covariance of two observations of the positional errors at the same point, respectively. The range a is the minimum distance corresponding to the maximum semivariogram value $(C_0 + C)$. There exists a relationship between the semivariogram and the covariance function [30]:

$$\gamma(h) = Cov(0) - Cov(h) = \sigma^2 - Cov(h) \tag{5}$$

where $Cov(h)$ is the covariance between the positional errors of two positions with a distance of h, and σ^2 is the covariance of the positional errors at the same position, which is equal to the semivariogram parameter C.

The semivariogram curve shows some properties of the