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Pose Accuracy Calibration of a Serial Five DOF Robot

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Abstract

Robot is widely used in industrial domain and pose accuracy of end-effector is an important indicator for judging robot performance. Calibration is a necessary for operating industrial robot and an effective and efficient means of accuracy improvement. This paper describes the development of a calibration procedure for a five degree of freedom serial robot using the laser tracker. The main goal of this paper is to utilize measurements relative to the end-effector of the robot to compensate errors. The robot kinematic model is computed to help identify the deviations. Robot parameter deviations can be identified so that the nominal parameters can be corrected. The experimental results are validated effectively.

Keywords: Serial robot; Degree of freedom; Calibration; Laser Tracker; Pose accuracy

1. Introduction

Robot is widely used in industrial domain, especially in the mechanical manufacturing, automobile industry, electronic industry, which can accomplish transport, welding, spray painting and assembling tasks substitute for workers. Most industrial robots are open chain mechanisms composed of links connected by prismatic or rotation joints. These serial manipulators have large workspace, high dexterity and good maneuverability. However, they exhibit poor precision for serial structure. Errors in end-effector position and orientation are the primary indication of robot performance. Over the past years, the need for precisely trajectory has grown substantially. To ensure robot routines which usually are generated by off-line programming, some kinds of calibration must be performed. Wide variety calibration methods have been developed in the past decade. The inverse calibration method is to estimate the end-effector error for the entire workspace by measuring discrete points. The goal of kinematic

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calibration method is identifying the deviations in the nominal parameters of the geometrical model of the robot. Linear displacement transducer, theodolite, 3D laser tracking system and CCD camera are used to calibrate the accuracy of robot [1].

The pose accuracy of end-effector is an important indicator for judging robot performance which is affected by various factors. To a large extent, robot inaccuracy is induced by geometric errors, loading errors, thermal errors and kinematic errors. The geometric errors come from manufacturing imperfection, misalignments, link offsets and joints wear. Loading errors are due to the flexibility of joint and link deflection under self-gravity and external payload. Thermal errors result from thermal distortion and expansion of robot components of internal and external heat sources such as motors, bearings and ambient temperature change. Kinematic errors are composed of sensor accuracy, controller discernibility. Geometric errors are the primary source of posing errors, which can be identified by kinematic calibration. Calibration is using advanced measurement method to identify the deviations in the nominal kinematic parameters of robot model based on model parameters identification method [2,3]. Then the absolute accuracy of robot is improvement through additional control algorithm or modified the original algorithm. A calibration method to identify these errors is the main subject of this paper. This paper presents a calibration method that use laser tracker for robot kinematic parameters deviation identification.

2. The object of this paper

The task of an industrial robot is to move a workpiece to another point and orientation to workspace. Robot is an arrangement of links connected with joints which can realize relative motion between the links. Joints can either be rotary which rotate about an axis, or be prismatic which can translate along an axis, or combination with these basic joints. A series of rigid links connected together through joints is modelled as a kinematic chain. In this research, the design index of the robot is shown in Table 1.

Table 1 Specifications of the robot

Index category	Index item	Design demand
speed	Highest rotation speed	$\geq$ 100°/s
size	Completely extend length	$\leq$ 710mm
	workspace	Approximately Radius=450mm sphere
Accuracy	Repeatability accuracy	$\leq \pm 2$ mm
weight	Total weight	$\leq$ 20kg
	load	$\leq$ 3.5kg

Under the premise of satisfy the workspace requirement and more load to weight ratio, we choose the structure of five links. For the rotary joint and prismatic joint with same size, Rotary joint can provide much larger workspace than prismatic joint. Moreover, rotary joint is easy installation and maintaining. We design the serial robot with five rotary joints which constructed of five revolute pair. The robot illustrated in Fig 1 was acquired for experimental research in this project. It is a five degree freedom serial robot which is rigidly mounted on the base and different end-effectors can be mounted to the flange.

3. Robot kinematic model

To predict the end-effector position and orientation, given the joints angle, the forward kinematic model is needed. Homogeneous matrix is set up in each joint to build the kinematic model of robot. Then the end-effector position and orientation can be determined.

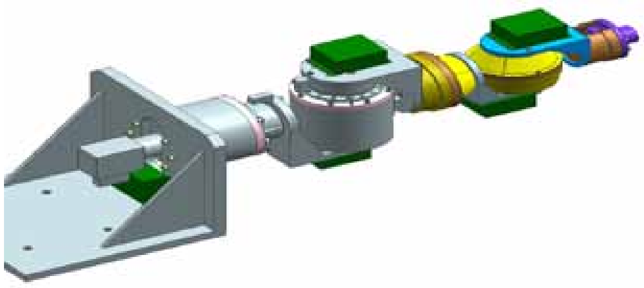

Fig.1. Configurations of the five rotary joints robot

A Denavit-Hartenberg parameters method is used to model the kinematic. First, a coordinate system is assigned to each joint of robot. Then using the matrix transformation characterized the associated parameters of robot. The coordinate system assigned to each joint is shown in Fig2. A set of four Denavit-Hartenberg parameters extracted from each joint is illustrated in Table 2. In DH model, the transformation matrix about the neighbouring links is illustrated in Eq1.

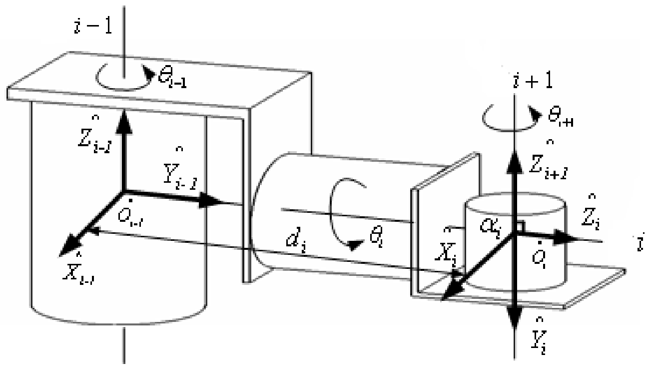

Fig.2. The Denavit-Hartenberg coordinate system for the 5-DOF robot

Table 2 The 5-DOF robot DH parameters

Link	angle	d_n(mm)	α_n(degree)	a_n(mm)
1	θ_1	268	90	0
2	θ_2	0	-90	0
3	θ_3	256.6	90	0
4	θ_4	0	-90	0
5	θ_5	176.5	90	0

$$
{}^{i-1}T_i=\begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & \alpha_{i-1} \\ \sin\theta_i\cos\alpha_{i-1} & \cos\theta_i\cos\alpha_{i-1} & -\sin\alpha_{i-1} & -d_i\sin\alpha_{i-1} \\ \sin\theta_i\sin\alpha_{i-1} & \cos\theta_i\sin\alpha_{i-1} & \cos\alpha_{i-1} & d_i\cos\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix}=\begin{bmatrix} {}^{i-1}\mathbf{L}_i & {}^{i-1}\mathbf{P}_i \\ 0 & 1 \end{bmatrix} \tag{1}
$$

Where, ${}^{i-1}L_i$ is 3 ×3 pose transformation matrix of the i^{th} coordinate system relative to $(i-1)^{th}$ coordinate. ${}^{i-1}P_i$ is vector of origin in i^{th} coordinate relative to $(i-1)^{th}$ coordinate. $\boldsymbol{\alpha_i}$ is link angle rotated about x_i axis from z_i to z_{i+1}; d_i is the distance translate along z_i axis from x_{i-1} to x_i; $\boldsymbol{\theta_i}$ is joint angle rotated about z_i axis from x_{i-1} to x_i.

For a five degree of freedom series robot, the overall transformation between the first link and the last is the matrix multiplication of all the DH transformation matrices as shown in Eq 2.

$$
{}^0T_5={}^0T_1{}^1T_2{}^2T_3{}^3T_4{}^4T_5 \tag{2}
$$

This robot transformation relates points expressed in the end-effector coordinate system to those of same points in the world coordinate system.

$$
{}^0\mathbf{T}_1=\begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad {}^1\mathbf{T}_2=\begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ \sin\theta_2 & \cos\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^2\mathbf{T}_3=\begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad {}^3\mathbf{T}_4=\begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ \sin\theta_4 & \cos\theta_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^4\mathbf{T}_5=\begin{bmatrix} \cos\theta_5 & -\sin\theta_5 & 0 & 0 \\ 0 & 0 & 1 & d_5 \\ \sin\theta_5 & \cos\theta_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad {}^0\mathbf{T}_5={}^0\mathbf{T}_1\,{}^1\mathbf{T}_2\,{}^2\mathbf{T}_3\,{}^3\mathbf{T}_4\,{}^4\mathbf{T}_5=\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

A simulation program was devised to compute the work volum of the end-effector through the use of forward kinematic model. From 10000 measurements of the end-effector pose, a visuralization of the end-effector work volum is pictured in Fig 3.

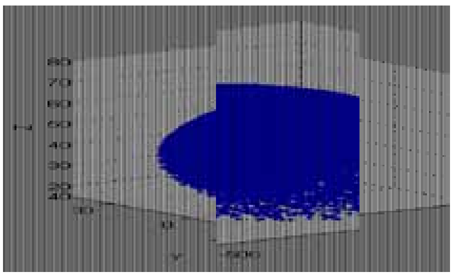

Fig. 3. Workspace of the end-effector through simulation

4. Experiment and Results

A laser tracker LTD 840 showned in Fig4 was used here to calibrate the pose errors of the robot. The laser tracker is composed of tracker head, retroreflector, controller, measurement software. There are a set of laser interferometer, two angluar tranceducer, two degree of freedom gimbal, motors and detector in the tracker head. Its accuracy is 0.075mm in 2m domain and not more than 0.015mm in 10m domain, which can meet the measurement accuracy demand[4,5]. The work principle schematic of the laser tracker is showninFig. The procedure of the calibration experiment is as follows. First, a target mirror was mounted to the tool flange of the robot. The measurement laser beam was directed to the target mirror located on the tool flange and the returning beam from the target mirror went parallel to the tracking mirror. Then the robot moved according to the preestablished program. As the movable target mirror changed its position, the tracking mirror rotated axes of the gimbal by motors to track the target mirror position. A Dopple frequency shift of the beam is occurred. The frequency shift translated through interferometry to a relative displacement reading. The pitch and yaw angle of the gimbal can be measured with angle encoder. At last, the measurement software compute the location of each point in the refence coordinate system[6]. The results of the calibration DH parameter are shown in Table 3.

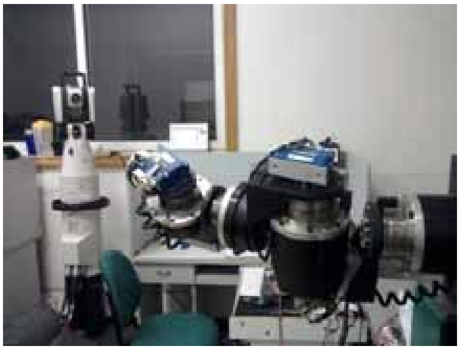

Fig.4. The schematic of the calibration with laser tracker

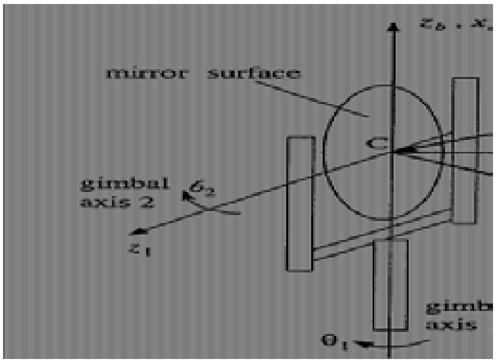

Fig.5. The work principle schematic of the laser tracker[3]

Table 3 Calibration result of the DH parameter

parameter	Design value	Calibration value	Deviation
d_1(mm)	268	265.9	2.1
d_3(mm)	256.6	255.47	1.13
d_5(mm)	176.5	178.64	-2.14
α_1(°)	90	90.859	0.859
α_2(°)	-90	-89.087	0.913
α_3(°)	90	91.039	1.039
α_4(°)	-90	-90.478	-0.748
a_1 (mm)	0	0.72	0.72
a_2(mm)	0	0.54	0.54
a_3(mm)	0	0.89	0.89
a_4(mm)	0	0.67	0.67

parameter	θ_1°	θ_2°	θ_3°	θ_4°	θ_5°
deviation	0.18	0.24	0.23	0.16	0.20

5. Conclusion

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