비선형 관절강성 로봇 캘리브레이션 연구
Study on Nonlinear Joint Stiffness Robot Calibration

*주건 [1], #강희준 [2], 임현규 [3], 김동혁 [3], 김성락 [3]
*J. Zhou[1], #Hee-Jun Kang(hjkang@ulsan.ac.kr)[2], Hyun-Kyu Lim[3], Dong-Hyeok Kim[3], Sung-Rak Kim[3]

[1] 울산대학교 전기공학부대학원, [2] 울산대학교 전기공학부, [3] 현대중공업 기전연구소

Key words : Robot calibration, Nonlinear joint stiffness, serial robot

1. Introduction

The application of robot is extended in different fields, such as machining operations, performing operation in medical, industrial task. To perform these operations precisely, the demand for accurate and reliable positioning becomes significantly important. However, the absolute positioning capability of robot is limited by kinematic and non-kinematic effects. The kinematic errors may result from manufacturing imperfections, misalignments and encoder offsets. Kinematic model calibration called level 2 calibration [1], is developed to compensate kinematic parameter errors, which has been studied by a number of researchers and has been summarized in [1,3]. Non-kinematic errors may come from joint and link compliance, temperature variation, gear transmission and backlash. Among these error sources that have the most significant effect on robot accuracy are joint and link compliance which are responsible for 8-10% of position and orientation errors of the end-effector, while backlash and temperature effects contribute to the global error from 0.5-1.0% and 0.1% respectively [4]. So identifying compliance parameters gets more attentions in non-kinematic calibration fields. As reported by [5] that link flexibility is than joint flexibility error-below 5%, most of the study works assume that robot link is much stiffer than robot joint, ignoring the link deflection. Joint compliance is modeled as a linear torsional spring in previous research. While an experimental study in [2] shows that the real behavior of joint stiffness is nonlinear. So this paper presents a method to identify nonlinear joint stiffness to improve the positioning accuracy of industry robot.

This paper is organized as follows. Section 2 describes the modeling of nonlinear joint stiffness. Section 3 is devoted to develop a method for nonlinear joint stiffness identification. The experimental calibration result is presented in section 4. Discussion of the result and conclusions are given in section 5.

2. Modeling of nonlinear joint stiffness

In [2], the torque-torsion relation is defined as follows:

$$\tau_c(q) = a_{f1} \times q^3 + a_{f2} \times q + K_{sw}(q) \times q \text{ ,} \quad (1)$$

where the parameters are defined in [2]. This nonlinear function shows that joint stiffness is not a constant value. We model the nonlinear joint stiffness as in Fig. (1):

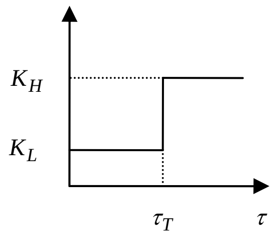

Fig. 1 Nonlinear joint stiffness model

As shown in Fig. (1), the nonlinear joint stiffness is modeled as a step function of torque.

3. Method for nonlinear joint stiffness identification

In section 2, we model the nonlinear joint stiffness as a step function of torque. In each step, joint stiffness is still linear. When we find the optimal transition torque, the error model can be given by the following equation (stiffness of joint 2 and joint 3 of 6 DOF robot are identified):

$$\begin{bmatrix} \Delta X_{LL} \\ \Delta X_{HH} \\ \Delta X_{HL} \\ \Delta X_{LH} \end{bmatrix} = J_{\phi} \times \Delta\phi + \begin{bmatrix} {}^{2}J_{stif}^{L} & 0 & {}^{3}J_{stif}^{L} & 0 \\ 0 & {}^{2}J_{stif}^{H} & 0 & {}^{3}J_{stif}^{H} \\ 0 & {}^{2}J_{stif}^{H} & {}^{3}J_{stif}^{L} & 0 \\ {}^{2}J_{stif}^{L} & 0 & 0 & {}^{3}J_{stif}^{H} \end{bmatrix} \begin{bmatrix} C_L^2 \\ C_H^2 \\ C_L^3 \\ C_H^3 \end{bmatrix} \quad (2)$$

where C is inverse of joint stiffness.

Genetic algorithm is used to search transition torque. The algorithm process is shown as follows:

1. Setting suitable genetic algorithm parameters.
2. Setting equation (2) as fitness function.
3. The iterative least square solutions of equation (2) is fitness value.
4. Searching transition torque that minimizes fitness value.

Table 1 Nominal kinematic parameters

	α_{i-1}	a_{i-1}	β_{i-1}	b_{i-1}	d_i	${}^{offset}\theta_i$
1	0	0	0	0	0.36	0
2	90	0.2	0(x)	0(x)	0(X)	0
3	0	0.56	0(x)	0(x)	0	0
4	90	0.13	0(x)	0(x)	0.62	0
5	-90	0	0(x)	0(x)	0	0
6	0	0	0(x)	0(x)	0.1(X)	0(X)
T	x	0	x	0	0	x

where x : non-selected/ X: dependency parameter/ lenth: meter/ angle: degree

4. Experimental results

Hyundai industry 6 DOF serial robot (HA006) is calibrated by the proposed method. The nominal kinematic parameters are shown in Table 1. Among the joints, the compliance errors of joint 2 and joint 3 are the most significant. So we just identify the nonlinear joint stiffness of joint 2 and joint 3. We use 45 robot points to calibrate the robot, and use 95 points (including the points used in calibration) to evaluate the calibrated robot parameters. The results and comparisons are shown in Table 2.

Table 2 Residual errors after calibration and after evaluation

Calibration (45 points)	Error_mean (mm)	Error_max (mm)
Before calibration	3.52	8.22
After calibration	0.115	0.24
	Error_mean (mm)	Error_max (mm)
Evaluation (95 points)	0.167	0.605

Conclusions

This paper presents a method for nonlinear joint stiffness included robot calibration. From the evaluation results, we clearly see that the calibrated robot has significant positioning accuracy within the work space. The mean error is 0.167 millimeter, the maximum error is 0.605 millimeter.

References

1. Z.S. Roth, Z.W. Mooring, B. Ravani, " An overview of robot calibration," IEEE Journal of Robotics and Automation, 3 (5) 377-385, 1987.
2. N. Kircanski and A. A. Goldenberg, " An experimental study of nonlinear stiffness, hysteresis, and friction effects in robot joint with harmonic drives and torque sensors," International Journal of Robotics Research, 1996.
3. J.M. Hollerbach, "A survey of kinematic calibration," The Robotics Review, MIT Press, Cambridge, Mass, 1988.
4. A.Y. Elatta, Li Pei Gen, Fan Liang Zhi, Yu Daoyuan and Luo Fei, "An overview of Robot calibration," Information Technology Journal 3 (1): 74-78, 2004.
5. Becquet, M., "Analysis of flexibility sources in robot structure," In proceeding of IMACS/IFAC International Symp. Modeling and Simulation of Distributed Parameters. Hiroshima, Japan, 419-424.