Journal of Institute of Control, Robotics and Systems (2014) 20(12):1267-1271
http://dx.doi.org/10.5302/J.ICROS.2014.14.8026 ISSN:1976-5622 eISSN:2233-4335

3 차원 미소변위센서 기반 로봇 캘리브레이션 성능 검토

Evaluation of Robot Calibration Performance based on a Three Dimensional Small Displacement Measuring Sensor

Hoai-Nhan Nguyen, 강 희 준*
(Hoai-Nhan Nguyen[1] and Hee-Jun Kang[1,*])
[1]School of Electrical Engineering, University of Ulsan

Abstract: There have been many autonomous robot calibration methods which form closed loop structures through the various attached sensors and mechanical fixtures. Single point calibration among them has been used for on-site calibration due to its convenience of implementation. The robot can reach a single point with infinitely many configurations so that single point calibration algorithm can be set up and easily implemented relative to the other methods. However, it is not still easy to drive the robots' sharp edge to its corresponding edge of the fixture. This is error-prone process. In this paper, we propose a 3 dimensional small displacement measuring sensor and a robot calibration algorithm based on this sensor. This method relieves the difficulty of matching two edges in the single point calibration and improves the resulting robot accuracy. Simulated study is carried out on a Hyundai HA06 robot to show the effectiveness of the proposed method over the single point calibration. And also, the resulting robot accuracy is compared with that from 3D laser tracker based calibration to show the dependency of robot accuracy on range of the workspace where the measurement data are collected.

Keywords: robot kinematic calibration, single point calibration, length based calibration, 3D laser based calibration, small displacement sensor

I. INTRODUCTION

Recently, robotic manipulators are widely used for the advanced manufacturing applications which require the high position accuracy of the robots. Therefore the manipulators should be undergone a calibration process to improve their position accuracy before utilizing. The improving robot accuracy has been performed by the conventional robot kinematic calibration method. A system of linear or non-linear differential equations is derived based on the measurements of robot end-effector position and its joint angle position [1-7]. A persistent problem is to find external sensors which can measure the robot position accurately and precisely. Therefore, in order to overcome this difficulty, the autonomous calibration method was proposed in many works as an alternative [8-14]. This method only utilizes the robot joint position and imposes the constraints on the robot end-effector such as plane constraints [10-12], single point constraint with force sensor [13], straight line constraint [14] and so on.

Among them, single point constraint without force sensor as shown in Fig. 1 is widely used in industry for on-site robot calibration. Single point based calibration has some advantages such as no use of expensive measuring device and ease to be implemented. But, it also has some shortcoming such as difficulty of matching the end-effector sharp edge to its corresponding fixture edge with the acceptable precision. Theoretically, due to the small deviation between the physical robot kinematics and the robot kinematic model built in its controller, it is very difficult to find the joint solutions for robot to reach a same point along many robot configurations. In practice, this job has been done for the skillful operator to match two edges with his eyes with teaching pendant operation. Therefore, this is error-prone process. In this paper, a low cost 3D small displacement measuring sensor is proposed to relieve the difficulty of this matching process and improve the resulting robot accuracy.

Simulated study is carried out on a Hyundai HA06 robot to show the effectiveness of the proposed method over the single point calibration. And also, the resulting robot accuracy is compared with that from 3D laser tracker based calibration to show the dependency of robot accuracy on range of the workspace where the measurement data are collected. The rest of the paper is organized as follows: Section 2 briefly explains the single point based robot calibration algorithm. Section 3 introduces the structure of a 3D small displacement sensor and its corresponding robot calibration algorithm. In section 4 the comparative evaluation of the calibration performances of three cases such as single point based calibration, a 3D small displacement sensor based calibration and the conventional laser tracker based calibration (this is included to explain the dependency of robot accuracy on range of the workspace where the measurement data are collected). Section 5 shows the conclusion of this paper.

II. SINGLE POINT BASED ROBOT CALIBRATION METHOD

A calibration system which consists of a robot and a single point fixture is shown in Fig. 1. The robot moves its end-effector so that the end-effector sharp edge is matched to the edge of the

* Corresponding Author
Manuscript received July 7, 2014 / revised September 10, 2014 / accepted September 15, 2014
Hoai-Nhan Nguyen, 강희준: 울산대학교 전기공학부
(nhan.nguyenhoai@yahoo.com/hjkang@ulsan.ac.kr)
※ This work was supported by the Ministry of Knowledge Economy Under Robot Industry Core Technology Project.
※ 본 논문은 2014 ICROS 학술대회에서 초안이 발표되었음.

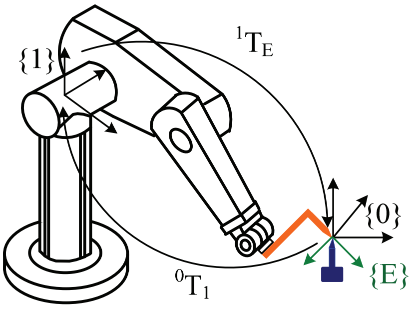

그림 1. 단일점기반 로봇 캘리브레이션 구성.

Fig. 1. A set up of the single point based calibration.

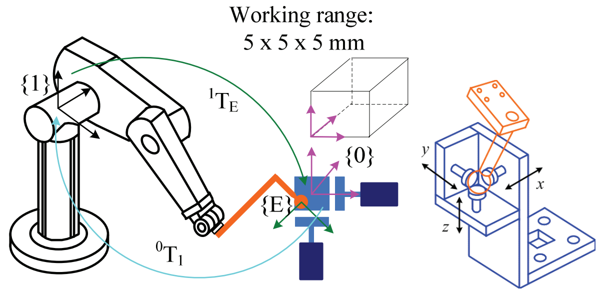

그림 2. 3D 미소변위센서 기반 로봇 캘리브레이션 구성.

Fig. 2. A set up of a calibration method using the 3D small displacement measuring sensor.

fixture. There are infinite robot configurations so that the both edges of the end-effector and the fixture are matched.

As shown in Fig. 1, the reference coordinate frame {0} is fixed at the edge of the fixture, the coordinate frame {E} is assigned at the edge of the robot end-effector. The robot link frames are fixed on its link based on Denavit-Hartenberg (DH) method. The kinematic model of a 6 degree of freedom robotic manipulator is described by a transformation matrix from reference frame {0} to the end-effector frame {E} as follows:

$$ {}^{0}_{E}\boldsymbol{T} = {}^{0}_{1}\boldsymbol{T}\,{}^{1}_{2}\boldsymbol{T}\,{}^{2}_{3}\boldsymbol{T}\,{}^{3}_{4}\boldsymbol{T}\,{}^{4}_{5}\boldsymbol{T}\,{}^{5}_{6}\boldsymbol{T}\,{}^{6}_{E}\boldsymbol{T} \quad (1)$$

For each of robot configurations, identification equations of robot parameters are formulated as follows [1]

$$\Delta \boldsymbol{X}_i = \boldsymbol{J}_i \Delta \boldsymbol{p} \quad (2)$$

where (3×1) vector of position error as $\Delta \boldsymbol{X}_i = \boldsymbol{X}_{i,m} - \boldsymbol{X}_{i,c}$, ('m' for measured, 'c' for computed); $\Delta \boldsymbol{p}$ is a (n×1) vector of robot parameter errors; $\boldsymbol{J}$ is a (3×n) error propagation matrix (or so called Jacobian matrix).

Here, the sharp edge of robot tip should be matched to the sharp edge of the fixture which is the origin of the base coordinate system. Therefore, $\boldsymbol{X}_{i,m} = \boldsymbol{0}$ for all the configurations of the robot.

For m robot configurations, a system of 3m equations is formulated as follows:

$$\begin{bmatrix} \Delta \boldsymbol{X}_1 \\ \vdots \\ \Delta \boldsymbol{X}_m \end{bmatrix} = \begin{bmatrix} \boldsymbol{J}_1 \\ \vdots \\ \boldsymbol{J}_m \end{bmatrix} \Delta \boldsymbol{p}, \quad (3)$$

Or in short form, $\Delta \boldsymbol{X} = \boldsymbol{H} \Delta \boldsymbol{p}$

The vector of robot parameter errors $\Delta \boldsymbol{p}$ is obtained in the iterative least square method as follows.

1) Computes $\boldsymbol{X}_{i,com}$ and $\boldsymbol{H}$ for current parameters $\boldsymbol{p}$

2) $\Delta \boldsymbol{p} = (\boldsymbol{H}^T \boldsymbol{H} + \lambda \boldsymbol{I})^{-1} \boldsymbol{H}^T \Delta \boldsymbol{X}$ (singularity robust inverse) (4)

3) $\boldsymbol{p}_{i+1} = \boldsymbol{p}_i + \Delta \boldsymbol{p}$

4) Go to 1) until $\Delta \boldsymbol{p} \le \varepsilon$

III. A THREE DIMENSIONAL SMALL DISPLACEMENT SENSOR BASED ROBOT CALIBRATION METHOD

As mentioned in the single point based calibration method, it is difficult to match robot end-effector's sharp edge to the edge of the fixture. In order to overcome this difficulty, a 3 dimensional small displacement measuring sensor is devised as shown in Fig. 2.

The 3D small displacement measuring sensor is composed of 3 linear sensors such as LVDT(Linear Variable Differential Transformer) sensors. The precision of this is order of 0.05mm.

The linear sensors are arranged in mutually orthogonal way so that each sensor measures the displacement as x, y, z coordinates with respect to the base coordinate system {0}. The measuring device can operate within the volume of 5×5×5 mm^3 which is defined according to the maximum displacement of the used LVDT sensors.

With this arrangement, the device can measure a 3D coordinates of the center of the steel ball when the ball contact to the planes which is rigidly connected to the probe of three linear sensors. This ball is attached to the end-effector.

As shown in Fig. 2, the reference coordinates frame {0} is located at a position when all linear sensors are in zero indication, the coordinate frame {E} is attached at the center of the ball. The robot kinematic model is described by Eq. (1) and the identification equations of robot parameters are described by Eq. (2). Here, $\boldsymbol{X}_{i,m}$ is a vector of measured position of the ball by using the sensor, whereas $\boldsymbol{X}_{i,c}$ is a vector of computed position of the ball by using robot forward kinematics. The rest of the calibration algorithm just follows the iterative least square method as explained in Eq. (4).

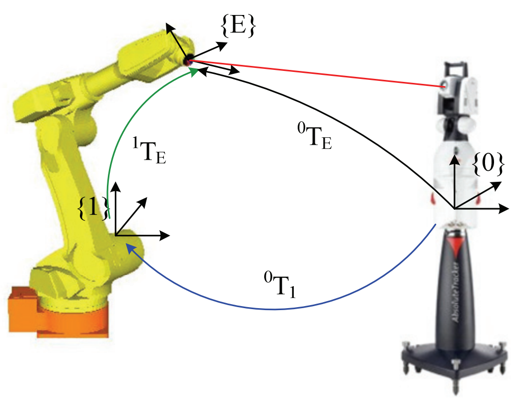

그림 3. 3D 레이저 트랙커 기반 로봇 캘리브레이션 구성.

Fig. 3. A set up of a calibration method using 3D laser tracker (using laser interference technology).

The calibration algorithm here is the same as the conventional laser tracker based robot calibration algorithm shown in Fig. 3. The difference among them is placed on what are the measured data. The measured data for single point calibration method is that $\boldsymbol{X}_{i,m} = \mathbf{0}$, where as those of other two method are that $\boldsymbol{X}_{i,m}$ is the measured values of each sensor. For other two 3D sensors, the range of workspace where measured data is collected from the 3D small displacement measuring sensor is much smaller than those from the laser tracker sensor.

IV. COMPUTER SIMULATION STUDY

Simulated study of those calibrations above is performed for a 6 DOF Hyundai HA06 robot which has kinematic schematics as shown in Fig. 4. The coordinate frames are attached on the robot links as shown in Fig. 4. The nominal robot parameters are listed in the Table 1.

An assumed physical robot is generated by adding the link errors with the corresponding robot nominal parameters of Table 1. The physical robot parameters are listed in Table 2. The parameters in the second rows of Tables 1 and 2 depend on the location of the measurement device. Single point calibration method has limitation to identify the full parameters of the robot, because it uses the closed loop constraints. Therefore, it is assumed that the base parameters are known before calibration for simplicity. And the tool parameters also have dependency with some robot link parameters, so they are assumed to be fixed.

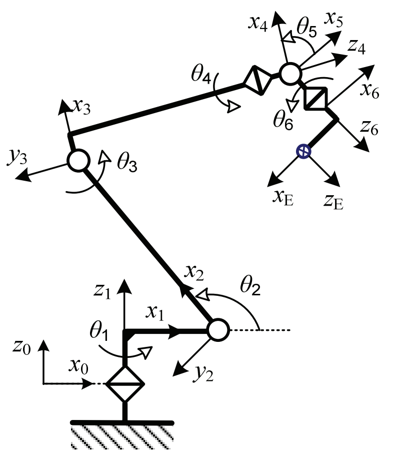

그림 4. HA06 로봇 및 관련 링크 좌표계 개략도.

Fig. 4. A schematic view of HA06 robot and its link frames.

표 1. HA06 로봇의 공칭 DH 파라미터.

Table 1. Nominal DH parameters of HA06 robot.

i	α [deg]	a [m]	β [deg]	B [m]	d [m]	$\Delta\theta$ [deg]
1	α_0	a_0	β_0	b_0	d_1	$\Delta\theta_1$
2	90	0.200	-	-	0	0
3	0	0.560	0	-	0	0
4	90	0.130	-	-	0.620	0
5	90	0	-	-	0	0
6	90	0	-	-	0.100	0
7	-	0.3	-	0.30	0.2	-

표 2. HA06 로봇의 가정된 실제 DH 파라미터.

Table 2. Assumed real DH parameters of the HA06 robot.

i	α [deg]	a [m]	β [deg]	b [m]	d [m]	$\Delta\theta$ [deg]
1	α_0	a_0	β_0	b_0	d_1	$\Delta\theta_1$
2	90.2	0.208	-	-	0	0.4
3	0.1	0.560	-0.3	-	0.001	0.2
4	89.9	0.128	-	-	0.621	0.3
5	-90.1	0.001	-	-	0.001	0.3
6	90.2	0.001	-	-	0.001	-0.4
7	-	0.3	-	0.30	0.2	-

The robot moves its end-effector to M configurations in the robot workspace. For each robot configuration (or a set of robot joint positions) the robot end-effector position is computed based on its forward kinematics and its assumed physical parameters. In the practical measurement process, the measurement noise always exists. Therefore, in order to simulate the real situation, the assumed measurement noise is added to the vector of robot end-effector position (computed position).

The measurement noise error depends on the measuring accuracy of the each measurement device. The noise error is assumed to have a normal distribution of zero mean and standard deviation σ. In this study, we use the range of confidence is 3σ. Then, we consider the noise error for the above mentioned sensors of the calibration methods.

For the single point based calibration method, the matching the end-effector sharp edge to the corresponding sharp edge of the fixture is error prone process. The matching error is assumed for two cases as follows: the first case, the large matching error of 0.4 [mm], the second case, the low matching error (equivalent to the accuracy of some precise measuring sensors) about 0.05 [mm].

In the robot calibrations using a 3D small displacement measuring sensor and a laser measuring device, the measuring error is assumed to be about 0.05 [mm] for the performance comparison. The measurement error and the corresponding standard deviations σ are listed in Table 3.

Acquiring the measurement data of the single point based calibration method is illustrated in Fig. 5. The robot end-effector

표 3. 가정된 가우시안 측정 잡음 및 그 표준편차.

Table 3. Assumed measurement noise and standard deviations.

Sensing Type	Gaussian noise : standard deviation σ [mm]
Single point	Case 1: Matching error ≈ 0.4 => σ = 0.4/3 = 0.133
	Case 2: Matching error ≈ 0.05 => σ = 0.05/3 ≈ 0.018
Small displacement	Measurement noise ≈ 0.05 => σ = 0.05/3 ≈ 0.018
Laser sensor	Measurement noise ≈ 0.05 => σ = 0.05/3 ≈ 0.018

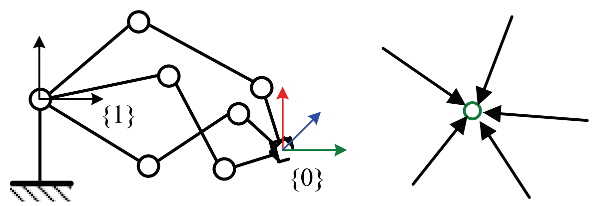

그림 5. 단일점 기반 캘리브레이션을 위한 데이터 취합.

Fig. 5. Data collection for single point based calibration.

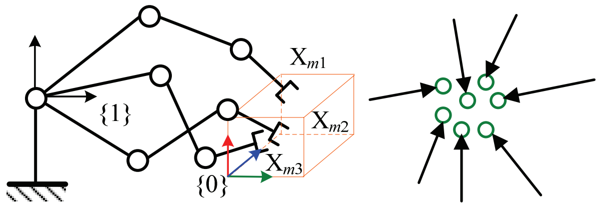

그림 6. 3D 미소변위센서기반 캘리브레이션을 위한 데이터 취합.

Fig. 6. Data collection for 3D small displacement sensor based calibration.

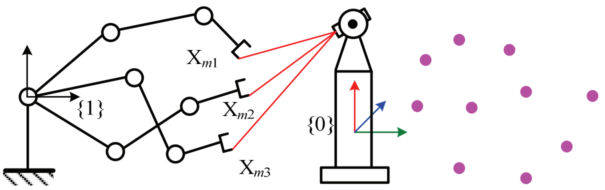

그림 7. 레이저트랙커기반 캘리브레이션을 위한 데이터 취합.

Fig. 7. Data collection for laser tracker based calibration.

is moved to many poses so that its sharp edge should be matched to the edge of the fixture.

Acquiring the measurement data of the calibration method using a 3D small displacement measuring sensor is shown in Fig. 6. The robot moves its end-effector to some poses inside the small cube so that this process relieves the difficulty of matching in single point calibration method.

Acquiring the measurement data of the calibration method using a laser tracker sensor is shown in Fig. 7. The robot moves its end-effector to arbitrary poses inside the robot workspace. The 3D coordinates of the robot endpoints are measured and recorded by using the laser tracker sensor.

표 4. 캘리브레이션에 사용된 위치를 이용한 로봇 정확도.

Table 4. Robot accuracy at measurement points used in calibration process.

Sensor types	measurement noise [mm]	Mean Error [mm]	Max. Error [mm]
Single point	σ = 0.133	0.2075	0.3718
	σ = 0.018	0.0491	0.0902
Small displacement sensor	σ = 0.018	0.0505	0.0858
Laser sensor	σ = 0.018	0.0254	0.0430

표 5. 타당성 검증을 위한 임의 위치에 대한 로봇 정확도.

Table 5. Robot accuracy at 30 arbitrary measurement points used for validation.

Sensor types	measurement noise [mm]	Mean Error [mm]	Max. Error [mm]
Single point	σ = 0.133	0.4615	0.9016
	σ = 0.018	0.2878	0.4507
Small displacement sensor	σ = 0.018	0.2782	0.5072
Laser sensor	σ = 0.018	0.1658	0.3065

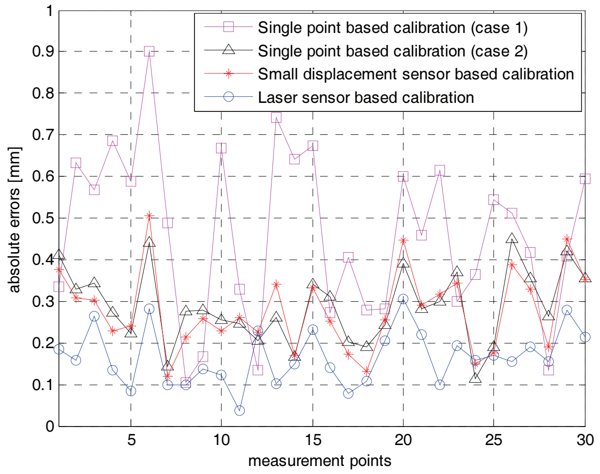

그림 8. 타당성 검증을 위하여 임의의 30 측정 위치에 대한 로봇 정확도.

Fig. 8. Robot accuracy at 30 measurement points used for validation.

The calibration results for HA06 robot by applying the calibration methods are shown in details in Table 4.

The single point based calibration method is performed in two cases of measurement noise standard deviations σ = 0.133 mm and σ = 0.018 mm. Other methods use the sensors which have measurement noise standard deviation σ = 0.018 mm.

The robot accuracy computed with used points in calibration is normally higher than the accuracy computed with arbitrary points. Therefore, the robot accuracy is validated on a set of arbitrary points inside robot workspace. These arbitrary points are completely different to the ones used in calibration. The validation results are shown in Table 5. The robot position accuracy for validation is shown in Fig. 8.

From the validated calibration results seen in Table 5 and Fig. 8, there are two aspects to be addressed. Firstly, the assumed matching error with σ to be 0.133 mm is small enough so that a human operator barely obtains this matching accuracy with his eyes. Nonetheless, its resulting robot accuracy is quite poor compared with that of 3D small displacement sensor calibration. If the matching accuracy in single point calibration is the same level in 3D small displacement sensor calibration, their resulting robot accuracy is the same level. But, it couldn't be obtained by a human operator without help of a certain sensor. It means that the effectiveness of the proposed 3D small displacement sensor is validated, because it is not difficult to be made and it could be easily implemented for robot calibration.

Secondly, it is very important to note how much the set of locations of measured data inside the robot workspace affect the robot accuracy.

The measured data in both single point based calibration and 3D small displacement calibration are located in very small region inside the workspace, whereas the measured data in laser tracker based calibration are located in wide region as big as the workspace. Here, it can be seen from Table 5 and Fig. 8 how data is measured inside the workspace makes the big difference of robot accuracy. The data set from the wider range of workspace leads twice better robot accuracy than the data set from the small region. (E_{mean} from laser tracker: about 0.025mm, E_{mean} from other two: about 0.050mm). As a matter of fact, the effect of data selection on the resulting robot accuracy is ongoing research for the authors. From the recent investigation, the measured data set must be selected in direction for joints to move bigger variation. It will be investigated more and reported later.

V. CONCLUSION

In this paper, a 3 dimensional small displacement measuring sensor is introduced and its resulting robot calibration algorithm is explained. This method relieves the difficulty of matching two edges in the single point calibration and improves the resulting robot accuracy. Simulated study is carried out on a Hyundai HA06 robot to show the effectiveness of the proposed method over the single point calibration. And also, the resulting robot accuracy is compared with that from 3D laser tracker based calibration to show the dependency of robot accuracy on range of the workspace where the measurement data are collected. In this case, the data set from the wider range of workspace leads twice better robot accuracy than the data set from the small region (E_{mean} from laser tracker: about 0.025mm, E_{mean} from other two: about 0.050mm).

REFERENCES

[1] W. Veitschegger and C. H. Wu, “Robot accuracy analysis based on kinematics,” *IEEE Jour. of Robotics and Auto*., vol. 2, pp. 171-179, 1986.

[2] S. Hayati, K. Tso, and G. Roston, “Robot geometry calibration,” *Proc. IEEE Int. Conf. on Robotics and Automation*, vol. 2, pp. 947-951, 1988.

[3] W. Khalil, J. L. Caenen, and Ch. Enguehard, “Identification and calibration of the geometric parameters of robots,” *The First Int. Symposium on Experimental Robotics I*, pp. 528-538, 1990.

[4] R. P. Judd and A. B. Knasinski, “A technique to calibrate industrial robots with experimental verification,” *IEEE Transactions on Robotics and Automation*, vol. 6, no. 1, pp. 20-30, 1990.

[5] G. Duelen and K. Schroer, “Robot calibration method and results,” *Robotics and Computer Integrated Manufacturing*, vol. 8, pp. 223-231, 1991.

[6] I. W. Park, B. J. Lee, and J. H. Kim, “Laser-based kinematic calibration of robot manipulator using differential kinematics,” *IEEE/ASME Trans. on Mechatronics*, vol. 17, no. 6, pp. 1059-1067, 2012.

[7] H. N. Nguyen, J. Zhou, H. J. Kang, H. K. Lim, and S. H. Ryu, “Robot calibration using a 3 dimensional small displacement measuring sensor,” *Proc. of the 27th ICROS Annual Conference*, pp. 325-326, Daegu, Korea, May 2014.

[8] D. J. Bennett and J. M. Hollerbach, “Autonomous calibration of single-loop closed kinematic chains formed by manipulators with passive endpoint constraints,” *IEEE Trans. on Robotics and Automation*, vol. 7, pp. 597-606, 1991.

[9] X. L. Zhong and J. M. Lewis, “A new method for autonomous robot calibration,” *Proc. of IEEE Int. Conf. on Robotics and Automation*, vol. 2, pp. 1790-1795, 1995.

[10] W. Khalil, Ph. Lemoine, and M. Gautier, “Autonomous calibration of robots using planar points,” *Int. Symp. on Rob. and Manuf.*, Montpellier: France, vol. 3, pp. 383-388, 1996.

[11] M. Ikits and J. M. Hollerbach, “Kinematic calibration using a plane constraint,” *Proc. IEEE Int. Conf. Robot Auto.*, pp. 3191-3196, 1997.

[12] H. Zhuang, S. H. Motaghedi, and Z. S. Roth, “Robot calibration with planar constraints,” *Proc. IEEE Int. Conf. on Rob. and Aut.*, vol. 1, pp. 805-810, 1999.

[13] M. A. Meggiolaro, G. Scriffignano, and S. Dubowsky, “Manipulator calibration using single endpoint contact constraint,” *Biennial Mechan. Conf.*, Baltimore, Maryland, ASME, pp. 1-9, 2000.

[14] H. J. Kang, J. W. Jeong, S. W. Shin, Y. S. Suh, and Y. S. Ro, “Autonomous kinematic calibration of the robot manipulator with a linear laser-vision sensor,” *LNCS: Adv. Intelligent Comp., Theories and App.*, Springer Berlin Heidelberg, vol. 4682, pp. 1102-1109, 2007.

Hoai-Nhan Nguyen

received the B.S. degrees from Faculty of Mechanical Engineering, University of Technology of Ho Chi Minh City, Viet Nam, in 2004. He is currently working toward the combined Master and Ph.D. degree in School of Electrical Engineering, University of Ulsan, Korea. His research interests are Robotic manipulator calibration, Mechanism analysis, Robot design and control.

Hee-Jun Kang

received the B.S. degree in Mechanical Engineering from Seoul National University, Korea in 1985. He received the M.S. and Ph.D. degrees in Mechanical Engineering from the University of Texas at Austin, USA in 1988 and 1991, respectively. Since March in 1992, he has been a Professor of School of Electrical Engineering in University of Ulsan, Ulsan, Korea. His current research interests are Sensor based robotic application, Robotic manipulator calibration, Haptics, Robot fault diagnosis, and Mechanism analysis.