Calibration of Parallel Manipulators using a New Measurement Device

Abdul Rauf †, Sung-Gaun Kim * and Jeha Ryu **

새로운 측정장비를 이용한 병렬구조 로봇의 보정에 관한

압둘 라우프 †, 김 성관 * and 류 제하 **

Key Words : HexaSlide Manipulator (헥사슬라이드), Identification Parameters (보정가능변수), Kinematic calibration (기구학적보정), Parallel robots (병렬기구로봇)

Abstract

Kinematic calibration is a process whereby the actual values of geometric parameters are estimated so as to minimize the error in absolute positioning. Measuring all components of Cartesian posture, particularly the orientation, can be difficult. With partial pose measurements, all parameters may not be identifiable. This paper proposes a new device that can be used to identify all kinematic parameters with partial pose measurements. Study is performed for a six degree-of-freedom fully parallel Hexa Slide manipulator. The device, however, is general and can be used for other parallel manipulators. The proposed device consists of a link with U joints on both sides and is equipped with a rotary sensor and a biaxial inclinometer. When attached between the base and the mobile platform, the device restricts the end-effector's motion to five degree-of-freedom and can measure position of the end-effector and one of its rotations. Numerical analyses of the identification Jacobian reveal that all parameters are identifiable. Computer simulations show that the identification is robust for the errors in the initial guess and the measurement noise.

1. Introduction

Parallel manipulators are preferred to serial manipulators for their better dynamic capabilities, increased rigidity and high positioning accuracy. The latter, however, may be deteriorated by factors like manufacturing tolerances, installation errors and link offsets resulting in different kinematic parameters from those of the nominal model. Kinematic calibration is a process by which the actual kinematic parameters are estimated and later used by the manipulator's controller. This compensates for the above sources of geometric errors and hence improves accuracy. Without calibration, the significance and veridicality of results for experimental robotics cannot be gauged. One may expect to spend most of experimental effort in calibration and less in actually running the experiments in control [1].

Kinematic calibration requires redundant sensory information. This information can be acquired by using external sensors [2-7], or by adding redundant sensors to the system [8-10], or by restraining the motion of the end-effector through some locking device [11-17]. The latter two are categorized as self-calibration schemes.

Classical methods of calibration require measurement of complete or partial postures of the end-effector using some external measuring devices. Numerous devices have been used for calibration of parallel manipulators. Zhuang et al. [2] used electronic Theodolites for the calibration of the Stewart platform along with standard measuring tapes. For a 3 degree-of-freedom (DOF) redundant parallel robot, Nahvi et al. [3] employed LVDT sensors. Laser displacement sensors were used to calibrate a delta-4 type parallel robot by Maurine [4]. Ota et al performed calibration of a parallel machine tool, HexaM, using a Double Ball Bar system [5]. Takeda et al. proposed use of low order Fourier series to calibrate parallel manipulators using Double Ball Bar system [6]. Besnard et al. [7] demonstrated that Gough-Stewart

† Abdul Rauf is with the Department of Mechatronics, Kwangju Institute of Science and Technology, Gwangju, Korea
E-mail : marauf@kjist.ac.kr
TEL : (062) 970-2425 FAX : (062) 970-2384

* Sung-Gaun Kim is with the Department of Mechatronics, Kwangju Institute of Science and Technology, Gwangju, Korea

** Jeha Ryu is with the Department of Mechatronics, Kwangju Institute of Science and Technology, Gwangju, Korea

platform could be calibrated using two inclinometers. All of the kinematic parameters can be identified when the Cartesian posture is completely measured. However, complete measurement of the Cartesian posture, particularly the orientation, can be difficult and expensive. With partial pose measurements, experimental procedure is simpler but some of the parameters may not be identified.

Self-calibration schemes provide economic, automatic, noninvasive, and fast data measurement and are therefore preferred. Zhuang [8-9] proposed two rotary sensors at each universal joint of alternate legs of the Stewart platform and discussed formulation of measurement residual and identification Jacobian in detail. Wampler et al. calibrated Gough-Stewart platform using 5 sensors at passive joints of one leg [10]. Khalil and Besnard [11] showed that locking universal and/or spherical joints, with appropriate locking mechanisms, could calibrate the Stewart mechanism autonomously. Maurine et al. [12-14] extended the idea to calibrate HEXA-type parallel robot. Meggiolaro et al. [15] presented a calibration method using a single end-point contact constraint. This method is applied to a serial manipulator that has elastic effects due to end-point forces and moments. Rauf and Ryu [16], and Ryu and Rauf [17] proposed calibration procedures for parallel manipulators by imposing constraints on the end-effector. The problem of non-identifiable parameters becomes severe for the self-calibration schemes, particularly for the fully autonomous calibration schemes that rely on imposing constraints.

Zhuang et al. [2] formulated the cost function in terms of the inverse kinematic residuals that results in block diagonal identification Jacobian matrix and the identification can be performed without solving forward kinematics. Fassi et al. proposed a procedure for obtaining a minimum, complete, and parametrically continuous model for the geometrical calibration of parallel robots [18]. Iurascu and Park [19] formulated the kinematic calibration problem for closed chain mechanisms in coordinate-invariant fashion and solved directly the nonlinear constrained optimization problem of calibration. Daney et al. [20] presented variable elimination technique to improve the effectiveness of identification procedure when only partial pose information is available. Khalil et al. [21] presented an algorithm to calculate the identifiable parameters for robots with tree structures. Oilivers et al. [22] used singular value decomposition for the identification process and showed that this provides immunity to numerical redundancies that may result from partial pose measurements. Based on QR analyses of the identification Jacobian matrix, Besnard and Khalil [23] analyzed numerical relations between the identifiable and the non-identifiable parameters for different calibration schemes with case study on the Gough-Stewart platform that has 42 identification parameters. They showed that 3 parameters couldn't be identified when only position of the mobile platform is measured, 7 parameters are non-identifiable when two inclinometers are used, and the maximum number of identifiable parameters with self-calibration schemes realized by imposing constraints is 30.

This paper presents calibration of parallel manipulators using a new measuring device. The study is performed for a 6 DOF fully parallel Hexa Slide manipulator. The device, however, is general and can be employed for calibrating other parallel manipulators. The proposed device restricts the motion of the mobile platform to 5 DOF and can measure the position of the end-effector along with one of its rotations. Further details of the device will be provided in section 3. The device, thus, shares features of both the classical calibration schemes and the self-calibration schemes. Measurement of data can be automated thereby making the experimental procedure simple. QR analyses of the identification Jacobian reveal that with partial pose measurements from the device, all of the parameters can be identified.

This paper is organized as follows: Hexa Slide Manipulator (HSM) is introduced in Section 2. Section 3 discusses the calibration device along with measurement procedure and formulation. Results of computer simulations are presented in section 4 along with some discussions. Section 5 concludes the study and lays out directions of future work.

2. Description of the Mechanism

Schematic of the HSM, to which the proposed calibration scheme is applied, is shown in Fig. 1 and the geometric parameters are defined in Fig. 2. It is a 6-DOF fully parallel manipulator of PRRS type. In Fig. 2, A_{i0} and A_{i1} denote the start and the end points of the ith (i=1,2,…,6) rail axis. A_i denotes the center of ith universal joint and it lies on the line segment $A_{i0}A_{i1}$. Rail axes are identical and the nominal link length, ℓ, is same for all axes. The articular variable, λ_i, is the distance between the points A_{i0} and A_i. B_i denotes the center of spherical joint at the platform.

Posture of the mobile platform is represented with position of the mobile frame center in the base frame and three Euler angles as

$$X = \begin{bmatrix} x & y & z & \theta & \psi & \phi \end{bmatrix} \tag{1}$$

The Euler angles are defined as: ψ rotation about the global X-axis, θ rotation about the global Y-axis and ϕ rotation about the rotated local z-axis. Orientation is thus given by $R = R_{Y,\theta} R_{X,\psi} R_{z,\phi}$.

$$R=\begin{bmatrix} C\theta C\phi+S\theta S\phi S\psi & -C\theta S\phi+S\theta S\psi C\phi & S\theta C\psi \\ C\psi S\phi & C\psi C\phi & -S\psi \\ -S\theta C\phi+C\theta S\psi S\phi & S\theta S\phi+C\theta S\psi C\phi & C\theta C\psi \end{bmatrix} \quad (2)$$

where C and S represent cosine and sine respectively.

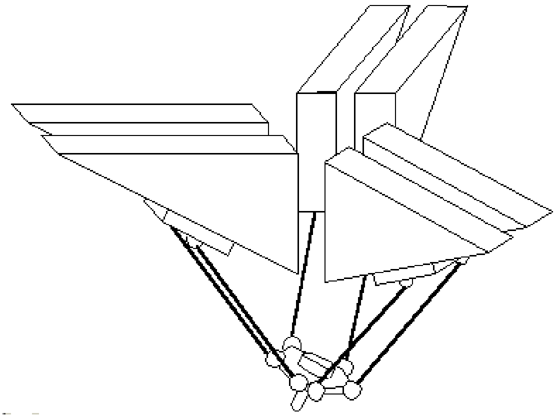

Fig. 1 Schematic of the HSM

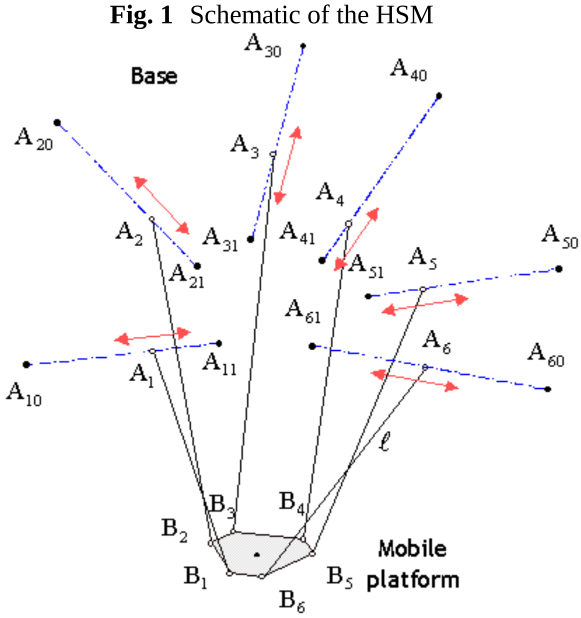

Fig. 2 Geometric parameters of the HSM

2.1 Kinematics of the HSM

The problem of inverse kinematics is to compute the articular variables for a given position and orientation of the mobile platform. For the HSM, the problem of inverse kinematics is simple and unique and is solved individually for each kinematic chain. Considering a single link chain, the inverse kinematics relation can be expressed as

$$\lambda=\mathbf{a}^{\mathrm{T}}\mathbf{A}_0\mathbf{B}-\sqrt{\ell^2-\|\mathbf{A}_0\mathbf{B}\|^2+\left(\mathbf{a}^{\mathrm{T}}\mathbf{A}_0\mathbf{B}\right)^2} \quad (3)$$

In forward kinematics, position and orientation of the mobile platform are computed for given values of articular variables. Forward kinematics may yield multiple solutions and is solved numerically using the manipulator Jacobian as [24]

$$X_{k+1}=X_k+J_f\left(\lambda-\lambda_k\right) \quad (4)$$

where J_f is the inverse manipulator Jacobian transformed into the Jacobian of the used Euler angles.

2.2 Frames and Identification Parameters

Origin of the base frame, O, is located at the center of the U joint near the base plate. The global Z-axis is directed along the negative direction of the gravity acceleration and the OXYZ system forms a right-handed system. Global X and Y-axes are defined parallel to the measurement axes of the biaxial inclinometer at zero reading. Origin of the mobile frame, P, is located at the center of the U joint with z-axis being collinear with the rotation axis of the rotary sensor. PX'Y'Z' also forms a right-handed system.

The number of identification parameters depends on the way the reference frames are assigned. By assigning the reference frames properly, the complexity of the calibration problem can be reduced significantly. Fassi et al. discussed the manipulator under consideration for their study on identification of a minimum, complete and parametrically continuos model for geometrical calibration of parallel robots and concluded that 54 parameters are required, which is the same as considered in this study. Following are the minimum and independent identification parameters for a kinematic chain of the HSM:

S joints' location ($\mathbf{B}$) – 3 parameters/chain
Slider axis start point ($\mathbf{A}_0$) – 3 parameters/chain
Slider's direction vector ($\mathbf{a}$) – 2 parameters/chain
Link length (ℓ) – 1 parameter/chain

Note that the direction vectors of the sliders' are specified by two components; say, x and y. This makes 9 parameters for each kinematic chain and a total of 54 parameters. Note also that all parameters are measured in the units of length.

3. Calibration Device and Procedure

3.1 The Measurement Device

The proposed device consists of a link having U joints at both ends. At one end, after the U joint, a rotary sensor is attached such that its axis of rotation passes through the U joint center. At the other end, a flange is provided for mounting. Biaxial inclinometer is also mounted and it measures the rotations about X and Y-axes. The device can measure the position of the end-effector using the inclinometer's information. Fig. 3 shows labeled schematics of the proposed device.

3.2 Measurement Data

Mobile platform can only execute 5 DOF motions while the device is attached. It can then be positioned over a spherical surface with arbitrary orientation. If L is the length of the link, distance between the U joint centers, and α and β are the rotation angles of the inclinometer about X and Y axes respectively, position of the mobile platform can then be given as

$$x = -L\cos(\alpha)\sin(\beta)$$
$$y = L\sin(\alpha) \quad (4)$$
$$z = -L\cos(\alpha)\cos(\beta)$$

Note that the x, y, and z can be computed through forward kinematics for measured postures. For known x, y, and z, the angles can be calculated as

$$\alpha = \sin^{-1}(y/L)$$
$$\beta = \tan^{-1}(x/z) \quad (5)$$

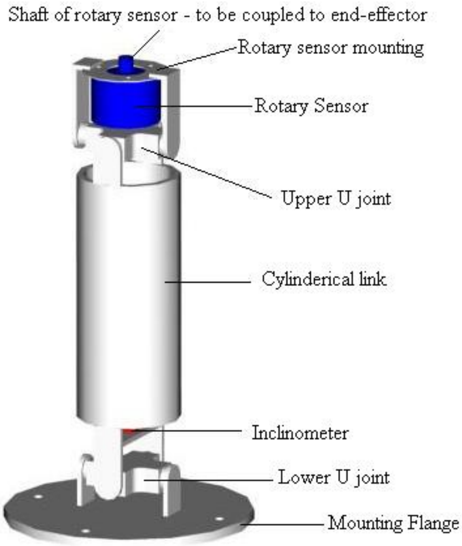

Fig. 3 Schematic of the proposed measurement device

3.3 The Identification Loop

Typically, solving the following system of equations with least squares performs identification for the calibration schemes.

$$du = J^{-1}dX \quad (6)$$

where J is the identification Jacobian, dX is the vector of error residuals, i.e. the cost function to be minimized, and du is the vector to update the nominal parameters. Termination criterion is specified on either du or dX, to solve (6) iteratively. Three rows of the cost function and the identification Jacobian are computed for each measurement as

$$\begin{bmatrix} X_{i1} \\ X_{i2} \\ X_{i3} \end{bmatrix} = \begin{bmatrix} \alpha_m^i - \alpha_c^i \\ \beta_m^i - \beta_c^i \\ \phi_m^i - \phi_c^i \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} J_{i1} \\ J_{i2} \\ J_{i3} \end{bmatrix} = \begin{bmatrix} \frac{\partial \alpha^i}{\partial u^1} & \frac{\partial \alpha^i}{\partial u^2} & \cdots & \frac{\partial \alpha^i}{\partial u^{54}} \\ \frac{\partial \beta^i}{\partial u^1} & \frac{\partial \beta^i}{\partial u^2} & \cdots & \frac{\partial \beta^i}{\partial u^{54}} \\ \frac{\partial \phi^i}{\partial u^1} & \frac{\partial \phi^i}{\partial u^2} & \cdots & \frac{\partial \phi^i}{\partial u^{54}} \end{bmatrix} \quad (8)$$

where the superscripts m and c correspond respectively to the measured and the computed values. Also note that the forward kinematics may converge to other than the desired solution. Therefore, each measurement needs to be checked, say by its Euclidian distance to the nominal posture, before using it for the identification.

4. Simulations and Discussions

To study validity and effectiveness of the proposed calibration device and procedure, computer simulations have been performed. For simulations, four sets of geometrical parameters are used. The first set defines the exact geometric parameters and is used to generate the measurement data. The other sets are used as nominal geometric parameters that should be calibrated. Table 1 gives the exact values of the geometric parameters and Table 2 shows the errors in the nominal sets used. Note that all dimensions in Table 1 and Table 2 are linear and are measured in millimeters.

Simulations have been performed with length of the measurement device, the distance between U joint centers, being 750 millimeters. Postures were generated with ranges along X and Y-axes being ± 350 millimeters from the origin. Range for rotations was chosen to be $\pm 30^o$. 30 postures were selected for calibration computations when measurement noise was not considered and 60 postures were used for noisy measurements. Postures were selected from randomly generated valid set of postures by minimizing the condition of the identification Jacobian. Note that the condition number for the selected postures was around 900. QR analyses of the identification Jacobian showed that all of the parameters were identifiable.

Table 1 The Exact geometric parameters

#	1	2	3	4	5	6
A_{0x}	-735.9	-841.8	-110.1	110.2	839.7	729.7
A_{0y}	-552.2	-358.9	899.1	897.2	-355.6	-546.3
A_{0z}	261.4	259.9	253.4	251.8	256.3	253.9
B_x	-61.1	-170.8	-110.2	109.8	173.8	63.7
B_y	-161.7	28.8	137.1	137.2	28.8	-161.7
B_z	-16.1	-16.2	-16.1	-15.8	-16.1	-016.2
ℓ	994.7	994.8	994.6	994.7	994.8	994.7
a_x	750.2	749.8	0.2	-0.2	-749.7	-750.3
a_y	433.2	432.7	-866.2	-866.3	432.9	432.7

Table 2 Errors in the nominal parameters

Parameters	Maximum	Mean	σ
Nominal Set 1	1.8	0.8	0.87
Nominal Set 2	2.8	1.33	1.45
Nominal Set 3	9.2	4.99	5.28

Fig. 4 shows the initial and the final errors for individual parameters for the three nominal sets when measurement noise is not considered. In figures, initial and final errors are represented respectively by the height of '*' and 'o' from the datum (0-line). Note that the final errors' marks appear on the datum line for all cases revealing that all parameters are identifiable. Further, it can be concluded that identification is robust against the initial errors.

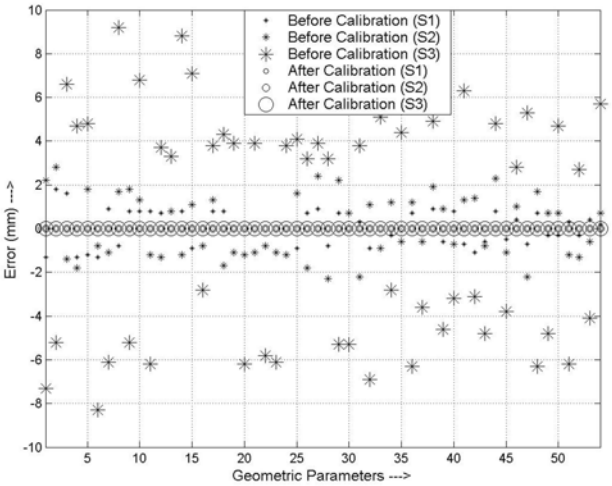

Fig. 4 Identification of three nominal sets (no noise)

Uniformly distributed random noise was added to the exact measurements including the articular variables, the rotary sensor measurements and the angles measured by inclinometers, to study noise effects. Fig. 5 compares errors in the kinematic chains before and after identification for different values of measurement noise and Table 3 compares the mean values of the errors in position and orientation for 50 randomly selected postures. Nominal set 2 was used for the results shown below. Note that although the results are presented in millimeters/microns and degrees, the simulations computations were performed in meters and radians. Therefore, while the random noise added to variables measured linearly corresponds to micrometers, it corresponds to micro radians for the angular variables. From Table 3, it can be seen that error in position is 3-4 times higher than the measurement noise.

Table 3 Effects of measurement noise

	Initial Error	Error after Calibration		
		5μ	10μ	50μ
Position	3.10mm	19.6μ	32μ	169μ
Orientation	0.76°	0.004°	0.005°	0.045°

Important to note that while measuring data, the mobile platform will be capable of only 5 DOF motions. One of the six actuators, therefore, is required to operate in passive mode. Passive mode requires the actuators to give position information while not powered. Actuators may not work efficiently in passive mode. Back drivability is a significant problem while implementing the fully autonomous calibration schemes that require some of the actuators to operate in passive mode. To avoid this problem, LVDT can be added to the device. In that case, the constant value L should be replaced by L_m^i for computing position in (4).

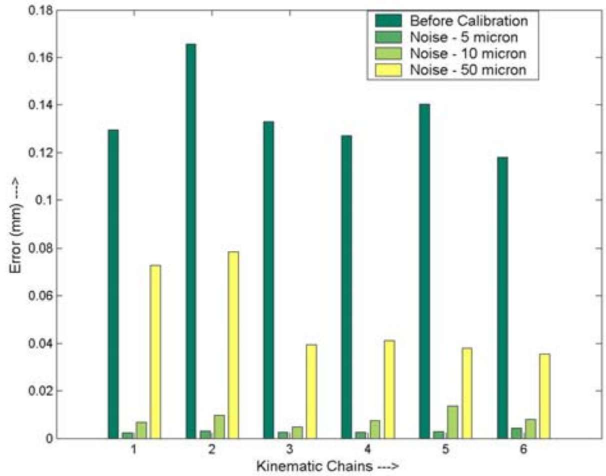

Fig. 5 Errors in kinematic chains (measurement noise)

Also, the inaccuracies in the measuring device will adversely affect the calibration results. The problem can be addressed either by introducing additional calibration parameters or by devising suitable measurement scheme.

5. Conclusions and Future Work

A new device is proposed for calibration of parallel manipulators that can identify all kinematic parameters with partial pose measurements. Formulation for the proposed device is discussed for a six DOF fully parallel Hexa Slide manipulator. The device is general and can be used for other parallel manipulators. Computer simulations show that the calibration results are robust against errors in the initial guess and the measurement noise.

Fabrication of the proposed device is under progress and future work includes experimental verification. Automation of the experimental procedure is also an important issue for future work.

References

(1) Hollerbach, J.M. and Wampler C. W., 1996, "The calibration index and taxonomy for robot calibration methods", The International Journal of Robotic Research, Vol. 15, No. 6.

(2) Zhuang H., Yan J., and Masory O., 1998, "Calibration of Stewart platforms and other parallel manipulators by minimizing inverse kinematic residuals", Journal of Robotic Systems 15(7).

(3) Nahvi, A., Hollerbach J. M., and Hayward V., 1996, “Calibration of parallel robot using multiple kinematic closed loops”, Proceedings of IEEE Conference on Robotics and Automation.

(4) Maurine P., and Dombre E., 1996, “A calibration procedure for the parallel robot Delta 4”, Proceedings of IEEE International Conference on Robotics and Automation.

(5) Ota, H., Shibukawa, T., Tooyama, T. and Uchiyama, M., 2000, “Forward kinematic calibration method for parallel mechanism using pose data measured by a double ball bar system”, Proceedings of the Year 2000 Parallel Kinematic Machines International Conference.

(6) Takeda Y., Shen G., and Funabashi H., 2002, “A DBB-based kinematic calibration method for in-parallel actuated mechanisms using a Fourier series”, Proceedings of DETC’02.

(7) Besnard S., and Khalil W., 1999, “Calibration of parallel robots using two inclinometers”, Proceedings of IEEE International Conference on Robotics and Automation.

(8) Zhuang H. and Liu L., 1996, “Self-Calibration of a class of Parallel Manipulators”, Proceedings of IEEE International Conference on Robotics and Automation.

(9) Zhuang H., 1997, “Self-calibration of parallel mechanisms with a case study on Stewart platforms”, IEEE Transactions on Robotics and Automation, Vol. 13, No. 3.

(10) C. W. Wampler, J. M. Hollerbach, and T. Arai, 1995, “An implicit loop method for kinematic calibration and its application to closed-chain mechanisms”, IEEE Transactions on Robotics and Automation, vol. 11, No. 5.

(11) W. Khalil and S. Besnard, 1999, “Self calibration of Stewart-Gough parallel robots without extra sensors”, IEEE Transactions on Robotics and Automation, Vol. 15, No. 6.

(12) Maurine, P., Abe, K. and Uchiyama, M., 1999, “Towards more accurate parallel robots” Proceedings of IMEKO-XV World Congress, Osaka, Japan, Volume X.

(13) Maurine, P., Uchiyama, M., and Abe, K. 1998, “A fully-autonomous procedure for kinematic calibration of HEXA parallel robots”, Proceedings of China-Japan Bilateral Symposium on Advanced Manufacturing Engineering, Huangshan City, China.

(14) Maurine, P., Liu. D. M. and Uchiyama, M., 1998, “Self Calibration of a new HEXA parallel robot”, Proceedings of the 4th Japan-France Congress and 2nd Asia-Europe Congress on Mechatronics, Kitakyushu, Japan.

(15) Meggiolaro M. A., Scriffignano G., and Dubowsky S., 2000, “Manipulator calibration using a single end-point contact constraint”, Proceedings of DETC 2000, ASME, Baltimore, MD.

(16) Rauf, A., and Ryu, J., 2001, “Fully autonomous calibration of parallel manipulators by imposing position constrain”, Proceedings of IEEE International Conference on Robotics and Automation, Seoul.

(17) Ryu, J., and Rauf, A., 2001, “A new method for fully autonomous calibration of parallel manipulators using a constraint link”, Proceedings of AIM’01 conference, Italy.

(18) Fassi, I., and Legnani, G., 2002, “Automatic identification of a minimum, complete and parametrically continuos model for the geometrical calibration of parallel robots”, Proceedings of the Workshop on fundamental issues and future research directions for parallel mechanisms and manipulators, Quebec, Canada.

(19) Iurascu, C. C. and Park, F. C., 1999, “Geometric algorithm for parallel mechanism machine tool”, Proceedings of IEEE International Conference on Robotics and Automation.

(20) D. Daney, I. Z. Emiris, 2001, "Robust parallel robot calibration with partial information." Proceedings of IEEE International Conference on Robotics and Automation, Seoul.

(21) Khalil, W., Gautier, M., and Enguehard, Ch, 1991, “Identifiable parameters and optimum configurations for robots calibration” Robotica.

(22) M. P. Oliviers, J. R. Rene Mayer, 1995, "Global Kinematic Calibration of a Stewart Platform", ASME Dynamic Systems and Control Division, vol. 57(1).

(23) Besnard S, Khalil W., 2001, "Identifiable parameters for parallel robots kinematic calibration", Proceedings of IEEE International Conference on Robotics and Automation, Seoul, May.

(24) Merlet, J-P., 1997, Les robots paralleles, 2nd ed., Hermes, Paris.