A New Device and Procedure for Kinematic Calibration of Parallel Manipulators

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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 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. Intrinsic inaccuracies of the device can significantly deteriorate the calibration results. A measurement procedure is proposed and formulations of cost functions are discussed to prevent propagation of the inaccuracies to the calibration results.

Keywords: Hexa Slide Manipulator, Identification Parameters, Kinematic Calibration, Parallel Manipulators

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 significantly. 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 or autonomous calibration techniques.

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 platform could be calibrated using two inclinometers. All of the kinematic parameters can be identified when the Cartesian posture is completely measured. However, measuring all components 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 over classical calibration methods. Zhaung [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 procedure can be implemented 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 fully autonomous schemes is 30.

This paper presents a new measuring device for calibration of parallel manipulators. The study is performed for a 6 degree-of-freedom (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 degrees-of-freedom 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. Intrinsic inaccuracies of the device can significantly deteriorate the calibration results. A procedure for measuring postures is proposed and formulations of the cost function are discussed to avoid propagation of the device's intrinsic inaccuracies to the calibration results.

This paper is organized as follows: Hexa Slide Manipulator 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 discussion on some issues. Section 5 concludes the study.

2. DESCRIPTION OF THE MECHANISM

Schematic of the Hexa Slide mechanism (HSM), to which the proposed calibration scheme is applied, is shown in Fig. 1 and some details of the geometric variables are given in Fig. 2. It is a 6-degree-of-freedom fully parallel manipulator of PRRS type. In figure 2, A_{i0} and A_{i1} denote the start and the end points of the i^{th} (i=1,2,…,6) rail axis. A_i denotes the center of i^{th} universal joint and it lies on the line segment $A_{i0}A_{i1}$. All of the rail axes are identical and the nominal link length, ℓ, for each leg is equal. 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 a position vector of the mobile frame center in the base frame and with three Euler angles as

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

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 the cosine and sine respectively.

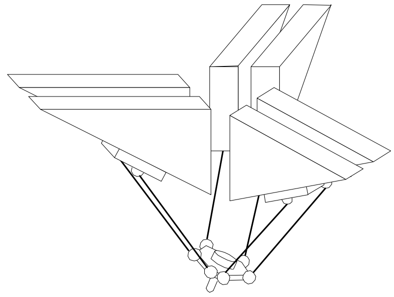

Fig. 1 Schematic of HSM

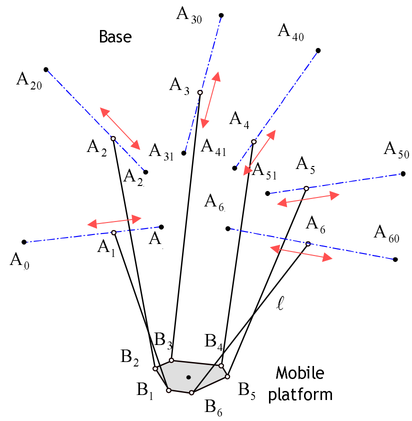

Fig. 2 Geometric parameters of the HSM

2.1 The Inverse Kinematics

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

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

where **a** is the unit vector along the direction of the rails.

2.2 The Forward Kinematics

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 according to the following algorithm [24]:

- Suppose $\mathbf{X}_g$, an initial posture (6x1 vector)
- Calculate $\mathbf{Q}_g$=IK($\mathbf{X}_g$)
- Update posture as: $\mathbf{X}_g = \mathbf{X}_g + \mathbf{J}_{inv}^{-1}(\mathbf{Q}_g - \mathbf{Q}_d)$
- Calculate $\mathbf{Q}_g$=IK($\mathbf{X}_g$)
- If $\|\mathbf{Q}_d - \mathbf{Q}_g\|$ > tolerance, goto step (iii)
- else $\mathbf{X}_g$ is the forward kinematics solution

where Q_d is the vector of measured articular variables, Q_g is the articular variable vector calculated from IK, J_{inv} is the inverse Jacobian and X_g is the solution posture. Note that the inverse of manipulator Jacobian used in the above computations needs to be transformed into the inverse Jacobian of Euler angles and this transformation depends on the choice of Euler angles used.

2.3 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 HSM:

S Joints' location:	$\mathbf{B}$	3 parameters/chain
Slider Axis Start Point:	$\mathbf{A}_0$	3 parameters/chain
Slider direction vector:	$\mathbf{a}$	2 parameters/chain
Link Length:	ℓ	1 parameters/chain

Note that the unit vectors of the sliders' are specified by two components; say, the x and the y. This makes 9 parameters for each link chain and 54 parameters in total for the mechanism. Note that the **B** points are defined with respect to the PX'Y'Z' frame while the $\mathbf{A_0}$ points are defined with respect to the OXYZ frame. Note also that all parameters are measured in the units of length.

3. CALIBRATION DEVICE AND PROCEDURE

3.1 The Measurement Device

The device proposed in this paper mainly 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. Figure 3 shows labeled schematics of the proposed device.

Rotary sensor can measure rotation of the mobile platform about the local z-axis when attached to the mobile platform. Alternately, it can measure rotation of the mobile platform about the global z-axis if it is coupled to the base platform. Orientation of the platform should be defined in accordance with the installation of the device. Considering the Cartesian vector defined in equation 1, the rotary sensor should be attached to the mobile platform and measure angle ϕ - the rotation about local z-axis.

3.2 The 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 and will have 5 degrees-of-freedom. If L is the length of the link (between the upper and the lower U joint centers) and α and β are the angles measured by the inclinometer about X and Y axes respectively, the measured position of the mobile platform can then be given as

$$
\begin{aligned}
x_m &= L\cos(\alpha)\sin(\beta) \\
y_m &= -L\sin(\alpha) \\
z_m &= L\cos(\alpha)\cos(\beta)
\end{aligned}
\tag{4}
$$

Ranges of the measured angles will depend on the workspace of the HSM and the measurement range of the inclinometer.

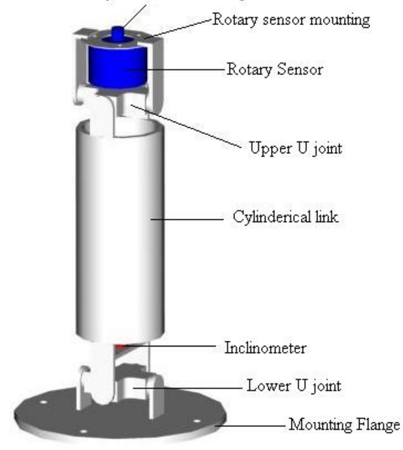

Fig. 3 Schematic of the proposed calibration device

3.3 The Identification Loop

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

$$du = J^{-1}dX \tag{5}$$

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. Equation 5 is solved iteratively with termination criterion specified on either du or dX. Effectiveness of the calibration procedure depends on the Identification Jacobian that is computed numerically.

In this case, four rows of the identification Jacobian are computed for each measurement as

$$
\begin{bmatrix} J_{i1} \\ J_{i2} \\ J_{i3} \\ J_{i4} \end{bmatrix} =
\begin{bmatrix}
\frac{\partial x^i}{\partial u^1} & \frac{\partial x^i}{\partial u^2} & \cdots & \frac{\partial x^i}{\partial u^{54}} \\
\frac{\partial y^i}{\partial u^1} & \frac{\partial y^i}{\partial u^2} & \cdots & \frac{\partial y^i}{\partial u^{54}} \\
\frac{\partial z^i}{\partial u^1} & \frac{\partial z^i}{\partial u^2} & \cdots & \frac{\partial z^i}{\partial u^{54}} \\
\frac{\partial \phi^i}{\partial u^1} & \frac{\partial \phi^i}{\partial u^2} & \cdots & \frac{\partial \phi^i}{\partial u^{54}}
\end{bmatrix}
\tag{6}
$$

Similarly, the cost function terms can be computed as

$$
\begin{bmatrix} X_{i1} \\ X_{i2} \\ X_{i3} \\ X_{i4} \end{bmatrix} =
\begin{bmatrix} x_m^i - x_c^i \\ y_m^i - y_c^i \\ z_m^i - z_c^i \\ \phi_m^i - \phi_c^i \end{bmatrix}
\tag{7}
$$

where the superscripts m and c correspond to measured and computed through forward kinematics respectively. Note that the measured components are computed based on measurements from the inclinometer according to equation 4. 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

In order to show 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.

Table 1 The exact geometric parameters

Chain	1	2	3	4	5	6
A_{ox}	-735.9	-841.8	-110.1	110.2	839.7	729.7
A_{oy}	-552.2	-358.9	899.1	897.2	-355.6	-546.3
A_{oz}	261.4	259.9	253.4	251.8	256.3	253.9
B_x	-061.1	-170.8	-110.2	109.8	173.8	063.7
B_y	-161.7	028.8	137.1	137.2	028.8	-161.7
B_z	-016.1	-016.2	-016.1	-015.8	-016.1	-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	0.80	0.87
Nominal Set 2	2.8	1.33	1.45
Nominal Set 3	9.2	4.99	5.28

Simulations have been performed with a link having length of 750 millimeters. Postures were generated with ranges along X and Y-axes being ± 400 millimeters from the origin. Range for rotations was chosen to be $\pm 35^o$. 25 postures were selected for calibration computations when measurement noise was not considered. When measurement noise was considered, 50 postures were used for the computations.

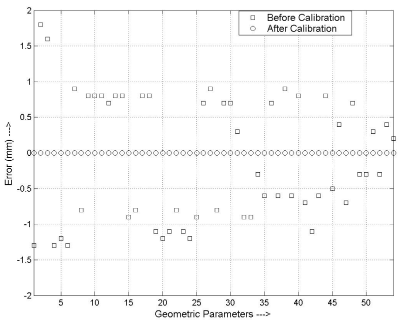

Fig. 4 Error comparison for nominal set #1 (No noise)

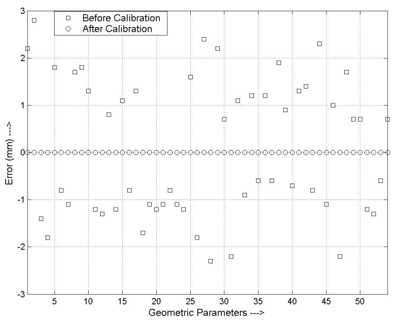

Fig. 5 Error comparison for nominal set #2 (No noise)

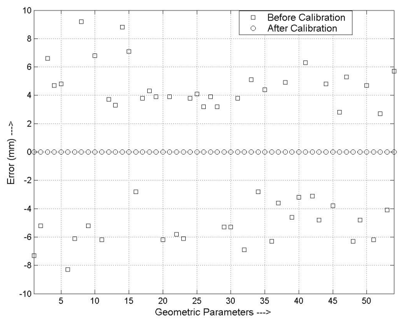

Fig. 6 Error comparison for nominal set #3 (No noise)

Figures 4 – 6 show the initial and the final errors for the 54 parameters individually for the three nominal sets of parameters when measurement noise is not considered. In figures, the height of '□' from the datum (0-line) represents the initial error while the final error is represented by the height of '○' from the datum. It can be concluded from figures that all parameters are identified. QR analyses also show that all parameters are identifiable. Also, the results show that convergence is robust against the initial errors.

For studying the effects of the measurement noise, uniformly distributed noise was added to the exact measurement data including the articular variables, the rotary sensor measurements and the angles measured by inclinometers.

Figures 7 – 9 compare the errors the kinematic chains before and after the identification. Nominal set 2 was used for the results shown below. Table 3 compares the mean values of the errors in the position and in the orientation for 50 randomly selected postures. Note that the linear values in Table 3 are in microns and the angular values are in degrees. Although the results are presented in millimeters or microns and degrees for convenience, 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 variable.

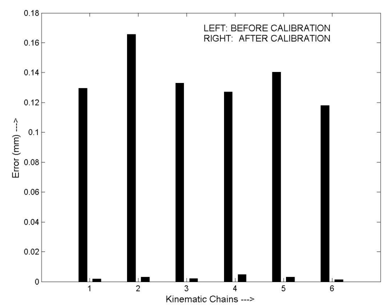

Fig. 7 Errors in kinematic chains – 5 micron noise

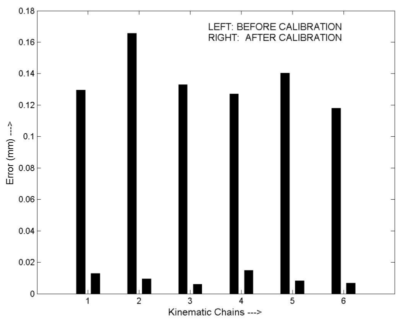

Fig. 8 Errors in kinematic chains – 10 micron noise

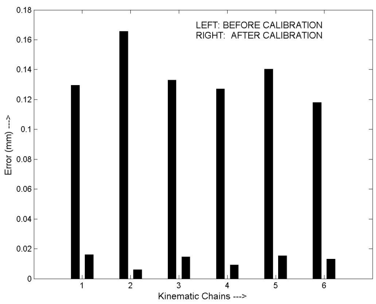

Fig. 9 Errors in kinematic chains – 20 micron noise

Table 3 Effects of measurement noise

	Initial Error	Error after Calibration		
		5 μ	10 μ	20 μ
Position	2.39 mm	3.5 μ	12 μ	25 μ
Orientation	0.61 deg	0.0024°	0.005°	0.007°

Note that the above simulations and discussions hold true for the case of the ideal device. Now, we discuss some of the important practical problems and layout their solutions.

While measuring data, the mobile platform will be capable of only 5 degrees-of-freedom 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 the measured position in equation 4.

It is assumed that the two inclinometers are perpendicular and measure rotation about the X and the Y-axes. In practical case, they may not be truly perpendicular leading to erroneous computation of the measured position. Although the values of y and z may be inaccurate, the length of the device will still be the same. Therefore, to solve this problem, we propose a procedure in which measurements are performed in two steps. First, over a spherical surface and then by keeping the end-effector at a fixed position.

For measurements over the spherical surface, cost function is defined in terms of link length instead of the Cartesian position components as

$$\begin{bmatrix} X_{i1} \\ X_{i2} \end{bmatrix} = \begin{bmatrix} L - L_c^i \\ \phi_m^i - \phi_c^i \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} J_{i1} \\ J_{i2} \end{bmatrix} = \begin{bmatrix} \frac{\partial L^i}{\partial u^1} & \frac{\partial L^i}{\partial u^2} & \cdots & \frac{\partial L^i}{\partial u^{54}} \\ \frac{\partial \phi^i}{\partial u^1} & \frac{\partial \phi^i}{\partial u^2} & \cdots & \frac{\partial \phi^i}{\partial u^{54}} \end{bmatrix} \tag{9}$$

For the measurements with fixed position, the cost function is expressed as

$$\begin{bmatrix} X_{i1} \\ X_{i2} \\ X_{i3} \\ X_{i4} \end{bmatrix} = \begin{bmatrix} x^f - x_c^i \\ y^f - y_c^i \\ z^f - z_c^i \\ \phi_m^i - \phi_c^i \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} J_{i1} \\ J_{i2} \\ J_{i3} \\ J_{i4} \end{bmatrix} = \begin{bmatrix} \frac{\partial x^i}{\partial u^1} & \frac{\partial x^i}{\partial u^2} & \cdots & \frac{\partial x^i}{\partial u^{54}} \\ \frac{\partial y^i}{\partial u^1} & \frac{\partial y^i}{\partial u^2} & \cdots & \frac{\partial y^i}{\partial u^{54}} \\ \frac{\partial z^i}{\partial u^1} & \frac{\partial z^i}{\partial u^2} & \cdots & \frac{\partial z^i}{\partial u^{54}} \\ \frac{\partial \phi^i}{\partial u^1} & \frac{\partial \phi^i}{\partial u^2} & \cdots & \frac{\partial \phi^i}{\partial u^{54}} \end{bmatrix} \tag{11}$$

where the superscript f refers to the fixed position. Note that position can be fixed using the inclinometers' information. For the postures where values of both axes of the inclinometer read zero, the fixed position can be given as $\begin{bmatrix} 0 & 0 & -L \end{bmatrix}$. Note that this position will be not be effected by non-perpendicularity of the measurement axes of inclinometer. Experimental procedure can be laborious, as the articular variables may need to be adjusted many times before the desired inclinometers' readings are achieved. The problem can be solved by adding appropriate control logic or by using a blocking device to fix the device at desired position. The locking mechanism, if used, should be rigid enough to avoid any significant structural deformations while the manipulator is moved to different measuring postures. Mobile platform will have only 3 degrees-of-freedom when locking device is employed and then 3 actuators will be required to operate in passive mode.

Biases in the link length and the inclinometers' measurements can also contribute to errors. Defining the cost functions of equations (8) and (10) as difference of the computed postures can eliminate these errors. The relative cost function, for the two types of measurements, will be

$$\begin{bmatrix} X_{i1} \\ X_{i2} \end{bmatrix} = \begin{bmatrix} L_c^j - L_c^k \\ \phi_m - \phi_c \end{bmatrix}; \; j \neq k \tag{12}$$

$$\begin{bmatrix} X_{i1} \\ X_{i2} \\ X_{i3} \\ X_{i4} \end{bmatrix} = \begin{bmatrix} x_c^j - x_c^k \\ y_c^j - y_c^k \\ z_c^j - z_c^k \\ \phi_m - \phi_c \end{bmatrix}; j \neq k \tag{13}$$

Simulations were performed for both cases with 30 postures selected over the hemisphere and 10 postures selected with the fixed position for studying identification without considering measurement noise. In both cases, the results were the same, as presented before in figures 4 – 6, meaning that all parameters were identified. For analyses with measurement noise, 60 postures over spherical surface and 20 with fixed position were studied. When the offsets of the inclinometer and the link length were not considered, using equations (8) and (10), simulation results show that the error in position and orientation, although higher from the values presented in Table 3, was still of the same order as that of the introduced measurement noise. Note that the errors in orientation are considerably lesser than that of the position. Introducing offsets in inclinometer measurements and in link length deteriorates the results significantly. Using the relative cost functions, as defined in equations (12) and (13), can reject the offsets' effects. However, its convergence takes longer time and the results are poor as compared to the first cases. However, the error in position after calibration was reduced by 30 times and error in orientation by about 50 times, which is still quite significant. Note that "lsqnonlin" of MATLAB was used for simulations when cost functions was expressed according to equations (12) and (13).

5. CONCLUSIONS AND FUTURE WORK

A new device is proposed for calibration of parallel manipulators that can identify all kinematic parameters while measuring the pose partially. Formulation for the proposed device is discussed for a six-degree of freedom 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.

Intrinsic inaccuracies of the device can significantly deteriorate the calibration results. Propagation of these inaccuracies to the calibration results can be prevented by measuring postures in a particular way and defining the cost function as difference of computed postures.

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.

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REFERENCES

[1] Hollerbach, J.M. and Wampler C. W., “The calibration index and taxonomy for robot calibration methods”, The International Journal of Robotic Research, Vol. 15, No. 6, December 1996.

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

[3] Nahvi, A., Hollerbach J. M., and Hayward V., “Calibration of parallel robot using multiple kinematic closed loops”, pp. 407-412, IEEE 1994.

[4] Maurine P., and Dombre E., “A calibration procedure for the parallel robot Delta 4”, IEEE International Conference on Robotics and Automation, pp. 975-980, 1996.

[5] Ota, H., Shibukawa, T., Tooyama, T. and Uchiyama, M., “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, p 57-62, September 2000.

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

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

[8] Zhuang H. and Liu L., “Self-Calibration of a class of Parallel Manipulators”, IEEE Int. Conference on Robotics and Automation, pp. 994-999, 1996.

[9] Zhuang H., “Self-calibration of parallel mechanisms with a case study on Stewart platforms”, IEEE Trans. On Robotics and Automation, Vol. 13, No. 3, pp. 387-397, 1997.

[10] C. W. Wampler, J. M. Hollerbach, and T. Arai, “An implicit loop method for kinematic calibration and its application to closed-chain mechanisms”, IEEE Transactions on Robotics and Automation, vol. 11, No. 5, pp. 710-724, Oct 1995.

[11] W. Khalil and S. Besnard, “Self calibration of Stewart-Gough parallel robots without extra sensors”, IEEE Transactions on Robotics and Automation, Vol. 15, No. 6, pp. 1116-1121, Dec 1999.

[12] Maurine, P., Abe, K. and Uchiyama, M., “Towards more accurate parallel robots” IMEKO-XV World Congress, Osaka, Japan, Volume X (1999/6/13-18), 73-80.

[13] Maurine, P., Uchiyama, M., and Abe, K. “A fully-autonomous procedure for kinematic calibration of HEXA parallel robots”, Proceedings of 1998 China-Japan Bilateral Symposium on Advanced Manufacturing Engineering, Huangshan City, P. R. China, (1998/10/5-10), 161-166.

[14] Maurine, P., Liu. D. M. and Uchiyama, M., “Self Calibration of a new HEXA parallel robot”, Proceedings of the 4th JAPAN-FRANCE CONGRESS & 2nd ASIA-EUROPE CONGRESS on MECHATRONICS, Kitakyushu, Japan, p 290-295 October 1998.

[15] Meggiolaro M. A., Scriffignano G., and Dubowsky S., “Manipulator calibration using a single end-point contact constraint”, Proceedings of DETC 2000, ASME, Sep. 10-14, DETC2000/MECH-14129, Baltimore, MD, 2000.

[16] Rauf, A., and Ryu, J., “Fully autonomous calibration of parallel manipulators by imposing position constrain”, Proceedings of IEEE international conference on Robotics and Automation, Seoul, Korea, May 2001.

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

[18] Fassi, I., and Legnani, G., “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, October 2002.

[19] Iurascu, C. C. and Park, F. C., “Geometric algorithm for parallel mechanism machine tool”, Proceedings of IEEE International Conference on Robotics and Automation, p 1752-1757, May 1999.

[20] D. Daney, I. Z. Emiris, "Robust parallel robot calibration with partial information." In IEEE International Conference on Robotics and Automation (ICRA), 21-26 May 2001, Korea, Seoul.

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

[22] M. P. Oliviers, J. R. Rene Mayer, "Global Kinematic Calibration of a Stewart Platform", ASME Dynamic Systems and Control Division, vol. 57(1), pp 129--136, 1995 IMECE.

[23] Besnard S, Khalil W., "Identifiable parameters for parallel robots kinematic calibration", In IEEE International Conference on Robotics and Automation (ICRA), 21-26 May 2001,Korea, Seoul.

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