Complete Parameter Identification of Gough-Stewart platform with partial pose measurements using a new measurement device

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Abstract: Kinematic calibration of Gough-Stewart platform using a new measurement device is presented in this paper. The device simultaneously measures components of position and orientation using commercially available gadgets. Additional kinematic parameters are defined to model the sources of inaccuracies for the proposed measurement device. Computer simulations reveal that all kinematic parameters of the Gough-Stewart platform and the additional kinematic parameters of the measurement device can be identified with the partial pose measurements of the device. Results also show that identification is robust for the initial errors and the noise in measurements. The device also facilitates the automation of measurement procedure.

Keywords: Gough-Stewart Platform, Identification Parameters, Kinematic Calibration, Parallel Manipulators

1. INTRODUCTION

The high accuracy of parallel manipulators, an inherent feature for which they are favored, may be decreased by fabrication tolerances and installation errors. With kinematic calibration, the actual values of geometric parameters describing robot manipulators are estimated and later updated in manipulators' control. Thus, kinematic calibration is critical for applications requiring high accuracy.

Calibration is at the heart of experimental and autonomous robotics. For experimental robotics, without careful controls and calibration, the significance or veridicality of results cannot be gauged. One may expect to spend most of experimental effort in calibration and relatively less in actually running the experiments. For autonomous robotics, a robot will need to develop and periodically update its internal model for best performance [1].

Schemes for kinematic calibration require redundant sensory information. This information can be acquired by adding redundant measurement devices to the system [2-4], or by restraining the motion of the end-effector through some locking device [5-11], or by using some external measurement devices [12-17]. The former two calibration schemes, relying on redundant sensors and constraints, are categorized as self-calibration schemes. The last one, acquiring redundant information through external measurement devices, is referred to as classical calibration schemes.

Self-calibration schemes provide economic, automatic, noninvasive, and fast data measurement and are therefore preferred over classical calibration methods. Zhuang [2, 3] proposed mounting two rotary sensors at universal joints of alternate legs of the Gough-Stewart platform for redundant information and discussed formulation of measurement residual and identification Jacobian in detail. Wampler et al. [4] calibrated Gough-Stewart platform using 5 sensors at passive joints of one leg. Khalil and Besnard [5] showed that locking universal and/or spherical joints, with appropriate locking mechanisms, could calibrate the Gough-Stewart mechanism autonomously. Maurine et al. [6-8] extended the idea of imposing constraint at joints to calibrate HEXA-type parallel robot. Meggiolaro et al. [9] presented a calibration method using a single end-point contact constraint. This method was applied to a serial manipulator having elastic effects due to end-point forces and moments. Rauf and Ryu [10], and Ryu and Rauf [11] proposed calibration procedures for parallel manipulators by imposing constraints on the end-effector.

Self-calibration schemes also have their limitations. Perhaps, the most serious problem is that of the non-identifiable parameters. Measurements of certain calibration schemes may not be sufficient to identify all kinematic parameters. Based on QR analyses of the identification Jacobian matrix, Besnard and Khalil [18] analyzed numerical relations between the identifiable and the non-identifiable parameters for different calibration schemes with case study on the Gough-Stewart platform having 42 identification parameters. They showed that the maximum number of identifiable parameters with self-calibration schemes realized by imposing constraints on joints is 30. Non-identifiable parameters may cause variation of accuracy with in the working volume of the manipulator. Another problem, while implementing the self-calibration schemes that rely on imposing constraints, is the back-drivability of the actuators. Restricting mobility of the end-effector requires some of the actuators to work in passive mode – not powered, yet providing sensor measurements. Errors in the nominal parameters appear as errors in the articular variables of the passive actuators, provided the actuators are backdrivabe. Actuators with high reduction ratio may not be able to exhibit this desired feature. For the calibration schemes with redundant sensors, problem of adding the extra sensor is not trivial and should be considered at the design stage. Also, additional sensors often need additional parameters.

Classical methods of calibration require measurement of complete or partial postures of the end-effector using some external measurement devices. Numerous devices have been used for calibration of parallel manipulators. Zhuang et al. [12] used electronic Theodolites for the calibration of the Gough-Stewart platform along with standard measurement tapes. For a 3 degree-of-freedom (DOF) redundant parallel robot, Nahvi et al. [13] employed LVDT sensors. Laser displacement sensors were used to calibrate a delta-4 type parallel robot by Maurine [14]. Ota et al. performed calibration of a parallel machine tool, HexaM, using a Double Ball Bar system [15]. Takeda et al. proposed use of low order Fourier series to calibrate parallel manipulators using Double Ball Bar system [16]. Besnard et al. [17] demonstrated that Gough-Stewart platform could be calibrated using two inclinometers.

All kinematic parameters can be identified when the Cartesian posture is completely measured. However, measuring all components of the Cartesian posture, particularly that of the orientation, can be difficult and expensive. With partial pose measurements, experimental procedure is often simpler but some of the parameters may not be identified. Besnard and Khalil [18] showed that 3 parameters cannot be identified when only position of the end-effector is measured, and 7 parameters are non-identifiable when two inclinometers are used.

While measuring only position components or only orientation components may not be sufficient to identify all kinematic parameters as mentioned above, simultaneous measurement of position and orientation components, however, may suffice for the identification of all kinematic parameters. In this paper, a new measurement device is proposed for kinematic calibration of parallel manipulators. The proposed device simultaneously measures components of position and orientation using commercially available gadgets. Computer simulations reveal that measurements from the proposed device are sufficient to identify all kinematic parameters, including the additional parameters of the device. Simulations also show that calibration results are robust against the errors in initial guess and the measurement noise. The device also facilitates the automation of measurement procedure.

This paper is organized as follows: Description and kinematics of the Gough-Stewart platform is provided in Section 2. Section 3 describes the proposed measurement device and discusses its kinematics and kinematic parameters. Formulations for identification and simulation results are presented in section 4. Section 5 concludes the study.

2. THE PARALLEL MECHANISM

This section briefly describes the parallel robot, Gough-Stewart platform, to which the proposed calibration scheme is applied and presents its kinematics.

2.1 Description of the mechanism

Schematic of the Gough-Stewart platform is shown in fig. 1. It is a 6 DOF fully parallel PRRS type manipulator. Position and orientation of the end-effector is controlled by adjusting lengths of six actuators. Fig. 2 shows the frame assignment and some of the geometric parameters of the manipulator. In fig. 2, $\mathbf{A_i}$ denotes the center of the i^{th} (i=1,2,…,6) universal (U) joint at the base and $\mathbf{B_i}$ denotes the center of the i^{th} spherical (S) joint at the platform. Points O and P represent the origins of the base frame and the mobile frame respectively.

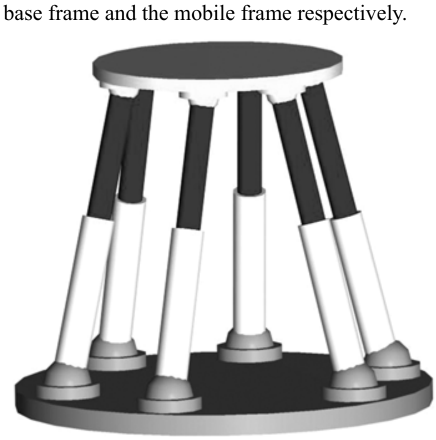

Fig. 1 Schematic of the Gough-Stewart platform

Posture of the end-effector (mobile frame) in Cartesian space is represented by position of the mobile frame's origin in the base frame and three Euler angles as

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

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 $\mathbf{R} = \mathbf{R}_{Y,\theta}\mathbf{R}_{X,\psi}\mathbf{R}_{z,\phi}$.

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

where C and S represent the cosine and sine respectively.

In joint space, posture can be represented by a vector of articular variables as

$$\mathbf{q} = \begin{bmatrix} q_1 & q_2 & q_3 & q_4 & q_5 & q_6 \end{bmatrix} \quad (3)$$

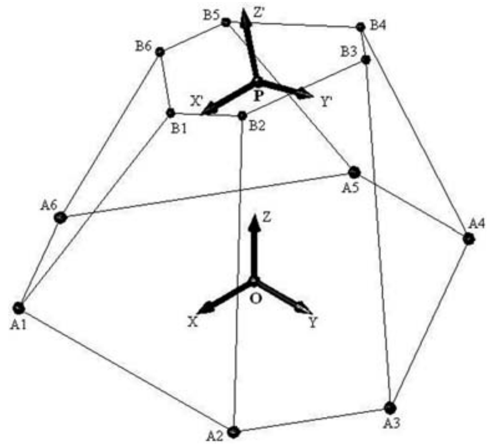

Fig. 2 Geometric parameters of the Gough-Stewart platform

2.2 Kinematic parameters of the mechanism

Masory et al. presented accurate and nominal kinematic models for calibration of Gough-Stewart platform [19]. In accurate model, they considered each kinematic chain as a serial manipulator and showed that it can be represented by 22 independent parameters, a total of 132 parameters for the mechanism. For the nominal model, considering joints as points and links as lines, each chain is modeled by 7 parameters, a total of 42 parameters for the mechanism. Generally, nominal model is considered for calibration of parallel manipulators. Fassi et al. [20] discussed the manipulator under consideration for their study on identification of a minimum, complete and parametrically continuous model for geometrical calibration of parallel robots and also showed that it can be represented by 42 independent parameters.

Following are the kinematic parameters for the Gough-Stewart platform:

- Center of U Joints at base ($\mathbf{A}$) - 3 parameters/chain
- Center of S Joints at platform ($\mathbf{B}$) - 3 parameters/chain
- Link Offset (L^{off}) - 1 parameter/chain

2.3 Kinematics of the mechanism

The problem of inverse kinematics is to compute the articular variables for a given posture (position and orientation) of the end-effector. For the manipulator, the problem of inverse kinematics is simple and unique and is solved individually for each kinematic chain. Considering a single link chain shown in fig. 3, the inverse kinematics relation can be expressed as

$L_i = \|\mathbf{R}\mathbf{B}_i + \mathbf{t} - \mathbf{A}_i\|$ (4)

where vector **t** and matrix **R** specify, respectively, the position and the orientation of the end-effector. The articular variable is then calculated as

$q_i = L_i - L_i^{off}$ (5)

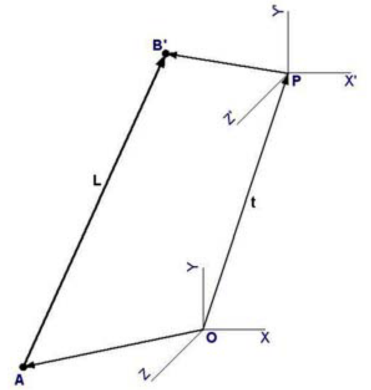

Fig. 3 Vector diagram for a kinematic chain

In forward kinematics, the position and the orientation of the mobile platform is computed for the given values of articular variables. Unlike inverse kinematics, forward kinematics is difficult and may yield many solutions. Forward kinematics of the Gough-Stewart can be solved numerically using iterative Newton's method [21]. As the forward kinematics may converge to other than the desired solution, it is required to check the solution of forward kinematics, say by its Euclidian distance to the nominal posture, for validity.

3. THE MEASUREMENT DEVICE

A device is proposed to provide partial pose measurements for the kinematic calibration of the parallel manipulators. This section describes the general features of the device and presents its kinematics.

3.1 Description

Labeled schematic of the proposed measurement device is shown in fig. 4. It is a 6 DOF device and 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. The rotary sensor can be coupled to the end-effector to measure one of its rotations. At the other end of the link, a flange is provided for mounting. It is assumed that the joints are perfect and, therefore, are modeled as points. As discussed earlier, it is typical to model joints as points and links as lines for calibration of parallel manipulators. The device is also equipped with a biaxial inclinometer that measures inclinations about two mutually perpendicular axes. Inclinometers are inertial devices that provide angular inclinations with respect to "true vertical" – the direction of gravity. The device is further equipped with an LVDT (Linear Variable Differential Transformer) to measure variable length of the link. The device can, therefore, simultaneously measure components of the position and orientation of the end-effector.

Biaxial inclinometers with resolution of 1 micro radian are commercially available. Commercially available optical encoders with the same resolution as that of the inclinometers can be used as rotary sensor. Precision LVDTs with wide variety of measurement ranges are also commercially available. Length of the link, the distance between the upper and the lower U joint centers, can be fabricated with precision to match accuracy of other components. The device can thus be realized with the commercially available gadgets. Although components of the device have been used for calibration of parallel manipulators, their combination assures much better results as compared to those of the individual components. The device also facilitates automated measurement procedure.

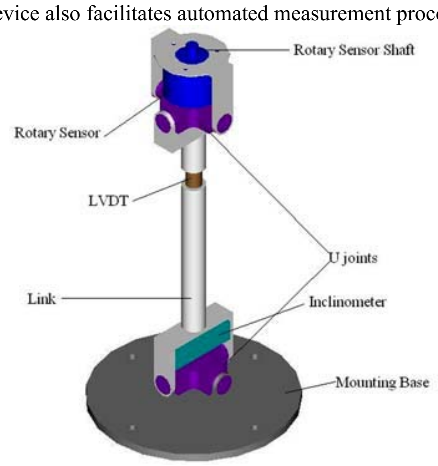

Fig. 4 Schematic of the proposed measurement device

3.2 Additional Identification Parameters

Modeling the significant error sources of the measurement device can help achieve better calibration results. Origins of the base and the mobile platforms are assigned at the centers of the upper and the lower U joints. Position of the centers of the U joints, therefore, need not to be considered as additional kinematic parameters. Following two parameters are considered as the additional identification parameters.

- Fixed length of the link (D_0)

- Angle between the measurement axes of the biaxial inclinometer (γ)

Note that the total length of the device refers to the distance between the upper and lower U joint centers and is given as the sum of the fixed length and the length measurement provided by the LVDT.

$D = D_0 + D_m$ (6)

where D_m refers to the measured length.

3.3 Kinematics of the measurement device

Relations between the components of the Cartesian posture and the variables measured by the gadgets installed on the measurement device are developed in this subsection. As mentioned earlier, origin of the base frame, O, is located at the center of the U joint of the proposed measurement device near the base plate. The global Z-axis is directed along the negative direction of the gravity acceleration and the OXYZ forms a right-hand system. Global X-axis is defined parallel to the first measurement axes of the biaxial inclinometer. Origin of the mobile frame, P, is located at the center of the U joint near platform with z-axis being collinear with the rotational axis of the rotary sensor. PX'Y'Z' also forms a right-hand system. If D is the length of the link, distance between the upper and the lower U joint centers, and α and β are the inclination angles of the link about the X and the Y axes respectively, position of the end-effector can then be given as

$$x = D\cos(\alpha)\sin(\beta)$$
$$y = D\sin(\alpha) \quad (7)$$
$$z = D\cos(\alpha)\cos(\beta)$$

Alternatively, if the position of the end-effector is given, say computed through the forward kinematics, inclination angles of the link can be computed as

$$\alpha = \sin^{-1}(y/D)$$
$$\beta = \tan^{-1}(x/z) \quad (8)$$

Equations (7) and (8) are valid for the case when the measurement axes of the biaxial inclinometer are truly perpendicular. If γ is the actual angle between the measurement axes of the inclinometer (nominal value of γ being $\pi/2$), the system of equations presented in (7) can be rewritten as

$$x = DS\gamma\left((C\beta - 1)C\gamma S\alpha + C\alpha S\beta\right)$$
$$y = D\left(C\gamma C\alpha S\beta + S\alpha\left(C^2\gamma C\beta + S^2\gamma\right)\right) \quad (9)$$
$$z = D\left(C\alpha C\beta - C\gamma S\alpha S\beta\right)$$

Numerical techniques can be used to compute α and β from equation (9), with initial guess from equation (6), for given position of the end-effector.

4. FORMULATION AND SIMULATIONS

4.1 The Identification Loop

Typically, solution of the non-linear optimization problem of identification is obtained by solving iteratively the following system of equations with least squares

$$\mathbf{du} = \mathbf{J}^{-1}\mathbf{dX} \quad (10)$$

where $\mathbf{J}$ is the identification Jacobian, $\mathbf{dX}$ is the vector of residual errors, i.e. the cost function to be minimized, and $\mathbf{du}$ is the vector to update the nominal parameters. Termination criterion is specified either on $\mathbf{du}$ or $\mathbf{dX}$. Fig. 5 shows the typical flow chart to implement (10). In the figure, $\mathbf{V}^m$ is the vector of articular variables, $\mathbf{U}^k$ is the vector of identification parameters at kth iteration, $\mathbf{X}^m$ is the vector of measured variables, and $\mathbf{X}^k$ is the vector of computed variables at kth iteration.

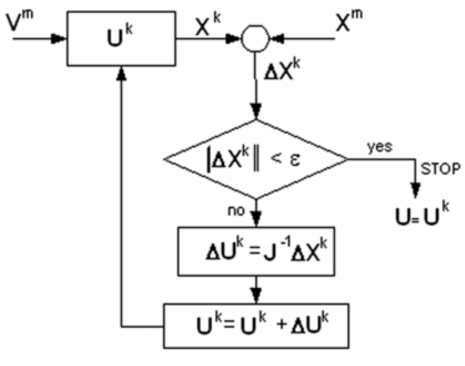

Fig. 5 The identification loop

For the proposed calibration scheme, the cost function and the identification Jacobian are computed as

$$\mathbf{dx}^i = \begin{bmatrix} \alpha_m^i - \alpha_c^i \\ \beta_m^i - \beta_c^i \\ \phi_m^i - \phi_c^i \end{bmatrix}; \mathbf{dX} = \begin{bmatrix} \mathbf{dx}^1 & \mathbf{dx}^2 & \cdots & \mathbf{dx}^M \end{bmatrix} \quad (11)$$

$$\mathbf{j}^i = \begin{bmatrix} \frac{\partial \alpha^i}{\partial u^1} & \frac{\partial \alpha^i}{\partial u^2} & \cdots & \frac{\partial \alpha^i}{\partial u^N} \\ \frac{\partial \beta^i}{\partial u^1} & \frac{\partial \beta^i}{\partial u^2} & \cdots & \frac{\partial \beta^i}{\partial u^N} \\ \frac{\partial \phi^i}{\partial u^1} & \frac{\partial \phi^i}{\partial u^2} & \cdots & \frac{\partial \phi^i}{\partial u^N} \end{bmatrix}; \mathbf{J} = \begin{bmatrix} \mathbf{j}^1 & \mathbf{j}^2 & \cdots & \mathbf{j}^M \end{bmatrix} \quad (12)$$

where the subscripts m and c correspond respectively to the measured and the computed values, i indicate the number of measurement, M refers to the total number of measurements and N represents the number of kinematic parameters. Note that the kinematic parameters include two additional parameters for the calibration device in addition to the kinematic parameters of the Gough-Stewart platform.

4.2 Simulation Parameters

Computer simulations have been performed to study the validity and the effectiveness of the proposed calibration scheme. 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 shows the errors in the nominal sets used and Table 2 shows the nominal values for the link length and the angle between the measurement axes of the biaxial inclinometer. Exact values for the link length and γ used are 850 mm and 90^o.

Postures were generated with ranges along X and Y-axes being $\pm$400 millimeters from the origin. Range for rotations was chosen to be $\pm$ 40^o. Postures were selected from randomly generated valid set of postures by minimizing the condition number of the Identification Jacobian matrix. For the simulation results presented below, 60 postures were used.

Table 1 Errors in platform parameters

Parameters	Maximum (mm)	Mean (mm)	σ (mm)
Nominal Set 1	4.65	1.31	1.65
Nominal Set 2	12.35	5.18	5.89
Nominal Set 3	18.44	6.96	7.76

Table 2 Errors in platform parameters

Parameters	Link Length	γ
Nominal Set 1	850.2	89.5
Nominal Set 2	849.3	90.7
Nominal Set 3	848.7	91.0

4.3 Simulation Results

Identification results are compared for the initial and final errors in individual parameters, and in kinematic chains. Also, for a set of 50 random postures, average errors in position and orientation before and after the calibration are compared. Comparison of the individual parameters includes the kinematic parameters of the measurement device. Figures 6 – 8 show the calibration results for the three nominal sets of parameters. In the figures, magnitudes of errors in the nominal parameters are represented by the distances of ‘ • ’ from the datum (zero-line) while magnitudes of errors in the calibrated parameters are represented by the distance of ‘ × ’. Note that except for the last parameter that is expressed in degrees, the other parameters are in millimeters. In the figures, all '×' marks appear on the datum line revealing that all kinematic parameters are identifiable. The convergence is achieved for quite large values of initial errors, which means that the identification with the proposed device is robust for the errors in the initial guess.

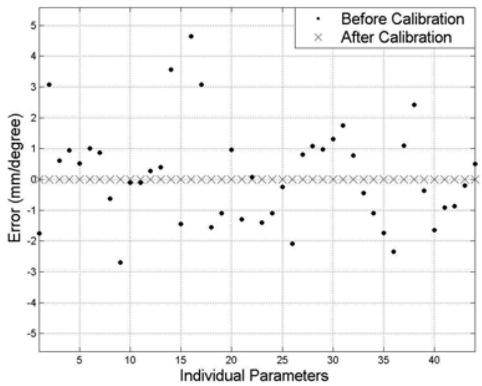

Fig. 6 Errors in individual parameters (Nominal Set 1)

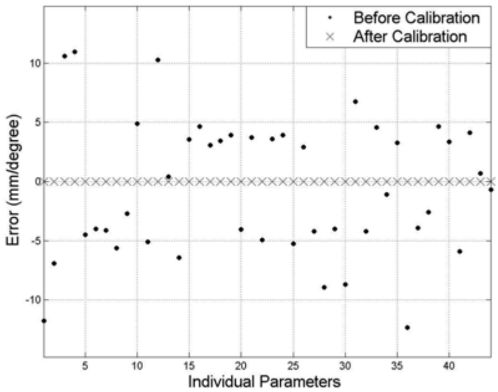

Fig. 7 Errors in individual parameters (Nominal Set 2)

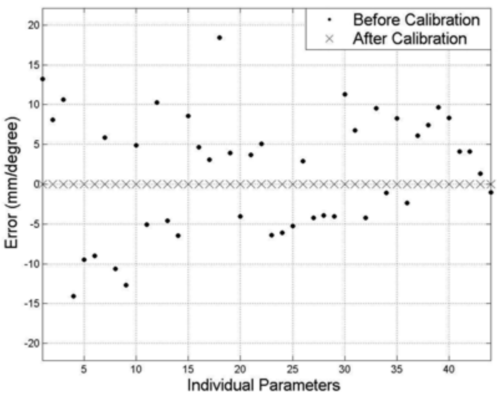

Fig. 8 Errors in individual parameters (Nominal Set 3)

To study the noise effects, random Gaussian noise was added to the exact measurements including the articular variables, the rotary sensor measurements and the angles measured by inclinometer. Noise in angular variables is expressed in degrees while that in linear variables is expressed in mm. Errors before and after calibration in kinematic parameters for the 6 chains of the platform are compared in figures 9 – 12. Table 3 shows average errors in position and orientation for 50 random postures. From results, it is evident that calibration, with the proposed device, is effective even with noisy measurements.

Table 3 Effects of measurement noise

	Initial Error	Measurement noise			
		0.001 deg 0.001 mm	0.001 deg 0.005 mm	0.005 deg 0.001 mm	0.005 deg 0.005 mm
Position	1.3440	0.0018	0.0198	0.0425	0.0488
Orientation	0.3450	0.0003	0.0006	0.0009	0.0019

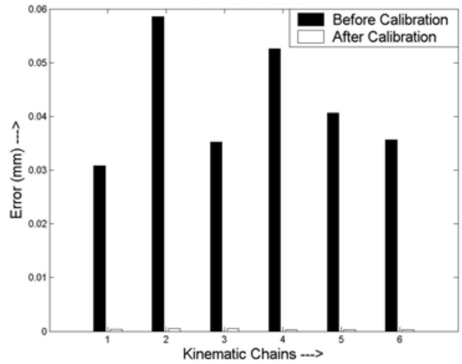

Fig. 9 Errors in kinematic chains with measurement noise (0.001 degree, 0.001 mm)

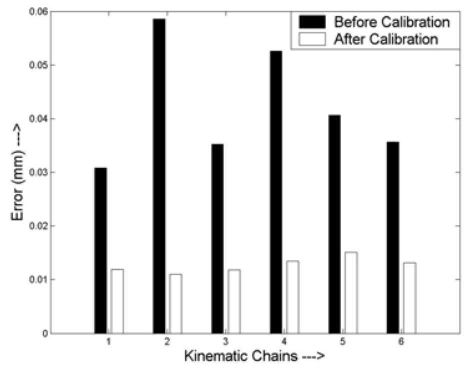

Fig. 10 Errors in kinematic chains with measurement noise (0.001 degree, 0.005 mm)

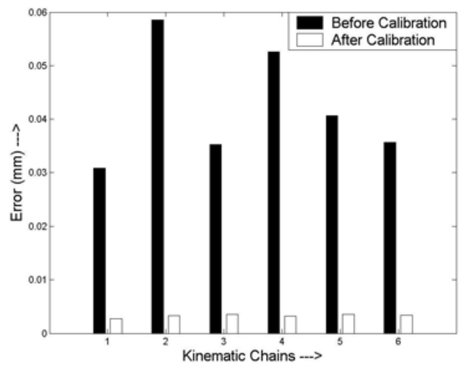

Fig. 11 Errors in kinematic chains with measurement noise (0.005 degree, 0.001 mm)

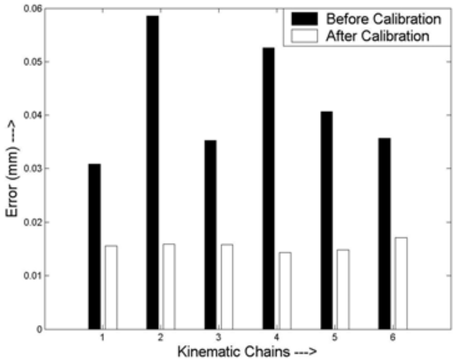

Fig. 12 Errors in kinematic chains with measurement noise (0.005 degree, 0.005 mm)

5. CONCLUSIONS

Kinematic calibration of Gough-Stewart platform using a new measurement device is presented. The device measures components of posture using an inclinometer, a rotary sensor and an LVDT. Two additional kinematic parameters are introduced to model error sources of the measurement device. Computer simulations reveal that all kinematic parameters can be identified with the partial pose measurements provided by the device. Results show that the identification is robust against the initial errors and the measurement noise.

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