International Journal of the Physical Sciences Vol. 6(21), pp. 4999-5004, 30 September, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS11.984
ISSN 1992 - 1950 ©2011 Academic Journals

Full Length Research Paper

Kinematic calibration of a parallel robot using coordinate measuring machine

Dayong Yu

School of Aeronautics and Astronautics, Zhejiang University, Hangzhou 310027, China. E-mail: wy_ydy@yahoo.com.cn. Tel: +86-571-87952100. Fax: +86-571-87951391.

Accepted 29 July, 2011

In the applications of parallel robots, kinematic calibration is required to eliminate the errors resulting from the manufacturing and assembly. In this paper, a new method for calibrating a parallel robot is proposed. An error model for kinematic calibration is constructed using differential geometry method. All leg length information and pose error are obtained based on measurement results coordinate measuring machine. A nonlinear least squares procedure is employed to determine the kinematic parameters. The parameters of the measurement error in the leg sensors are considered during kinematic modeling and parameter identification program. Experimental results presented demonstrate that the root mean square pose error can be improved at 80% with the 48 identified parameters.

Comment [微软中国1]: Revised

Key words: Parallel robot, error modeling, kinematic calibration, parameter identification, nonlinear least squares.

INTRODUCTION

Parallel robots such as a Stewart platform (Stewart, 1965) have some advantages of high rigidity, high velocity, and high load-carrying capacity over serial robots. These robots have found a variety of application in flight and vehicle simulators, high precision machining centers, and so on. However, they have some disadvantages of relatively small workspace and difficult forward kinematics problems.

It is well known that excellent pose performance of parallel robots may be achieved based on an accurate kinematic model. However, parameters of the model inevitably deviate from its normal values due to manufacturing and assembly error. A direct consequence is to reduce the accuracy of parallel robots, since their control strategy heavily relies on a precise description of the kinematic model. So there has always been a demand for parameter identification and kinematic calibration to improve the ability of parallel robots in order to reach consistently and accurately a specified pose. This process provides better estimate of the parameters of the kinematic model to be used for analysis and motion control of parallel robots. Although, it is possible to determine the parameters in theirs kinematic model, the resulting model will still contain some inaccuracies arising from joint and link clearances, steady state errors in joint positions, inaccurate knowledge of the kinematic parameters, and payload carried by parallel robots. One way to tackle this problem is to identify parameters in the kinematic model, and then consider them in kinematic error compensation, especially when it is impossible to use absolute end pose measurements for pose feedback. As a result, a considerable amount of research has been devoted to the kinematic parameter identification and calibration of parallel robots. For example, Zhuang et al. (1991) proposed a method to calibrate a 42 parameter model of a Stewart platform. Their idea was to acquire special measurement sets which allow decomposing linear sub-models based on Stewart platforms of the error model. Linear sub-models offer the advantage that identification of the kinematic parameters becomes straight forward, no initial guess is needed and the optimum is global. This method of holding one leg at constant legs was further improved by Daney (2003) who combined it with an idea of Khalil and Murareci (1997) to keep the direction of the leg fixed during data acquisition. A method that is currently widely accepted is the double ball bar system. With this system, three position data can be collected for each measurement and pose can be computed simultaneously using three-point method. Wampler et al. (1995) developed a slightly different type of calibration based on implicit loops. By applying five additional passive sensors on one leg, the forward kinematics can be computed so that closed form loop equations can be formed for the remaining five legs, and the calibration algorithm uses this additional data to solve for the kinematic parameters. This is not different from having an independent measure of the manipulator pose. A method to use redundant sensors on passive joints to calibrate parallel manipulators was proposed by Zhuang and Liu (1996). Redundant sensor data is obtained from as few as three additional sensors. To solve the forward kinematics, the authors implement a numerical method that solves for all joint variables, both passive and active. This allows the formation of measurement residual for the passive measured joints, thus a costs function that is minimized. By imposing appropriate physical constraints on the passive joints, the kinematic parameters of parallel manipulators can be identified only with the measurement data obtained from the actuators. Khalil and Besnard (1999) reported that locking universal and/or spherical joints, with some locking mechanisms, could calibrate Stewart platform autonomously. The locking mechanisms must be very stiff in order to prevent the joint and the link from bending deformation.

It is the goal of this paper to determine the kinematic parameters experimentally for a parallel robot used in spacecraft docking simulator. The kinematic parameters of this mechanism are considered during modeling and identification stages. A well-known parameters estimation technique is employed to determine the parameters. The measurement technique applied is the coordinate measurement machine with an accuracy of ±0.070 mm, and a coordinate repeatability of ±0.050 mm. The results presented in this paper differ from previously published results in the sense that they contain the parameters of the displacement sensor and are based on a highly accurate measurement system. With the identified parameters, it is founded that the Root Mean Square pose error improves by at least 80% when compared to the Root Mean Square based on the normal parameters provide by the constructor.

KINEMATIC MODEL OF THE PARALLEL ROBOT

Here describes the parallel robot and its kinematics model. The robot consists of two rigid bodies, the base and the mobile platform, connected by 6 legs. The leg linear actuator provides 6 degree of freedom for the platform pose relative to the base, corresponding to position *P* and rotation matrix *R*. A pose *X*=[*P*, *R*] is associated to 6 length variations l_i measured by internal leg sensors, *i*=1, …, 6.

Each leg is attached to the base by a hook joint and to the platform by a hook joint; so, 23 parameters are required to model each leg. But as shown in Masory (1997), the principal source of error in positioning is due to limited knowledge of the joint centers and to the fact that part of the length is not given by the sensors. We thus use a simpler model with attachment point's a_i in the mobile frame, b_i in the reference frame, and offset lengths $l_{0,i}$. This gives 7 parameters per leg, therefore 42 overall, denoted by *ρ*.

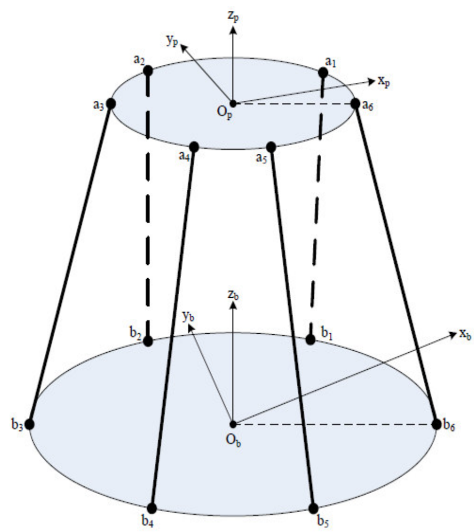

Figure 1. Schematic representation of the parallel robot.

Inverse kinematics

The inverse kinematics problem of the parallel robot deals with calculating the leg lengths when the pose is given and the kinematics parameters are known. In effect, it is a mapping from global pose to local leg transducer readings. The inverse kinematics of a parallel robot is simple, yielding a nonlinear closed form solution.

The vector chain in Figure 1 can be expressed as:

$$l_i = Ra_i + P - b_i \quad (1)$$

The length of leg *i* can then be determined by taking the magnitude of Equation 1:

$$\lambda_i = \| l_i \| = \| Ra_i + P - b_i \| \quad (2)$$

And the leg length sensor reading can be obtained by:

$$s_i = \lambda_i - l_{0,i} \quad (3)$$

Forward kinematics

For the parallel robots, the forward kinematics is difficult to compute since it consists in solving (Equation 1) for *P* and *R* given l_i and *ρ*. Define the vector function to describe the difference between the estimated sensor reading (s_i) and the actual sensor reading ($\hat{s}_i$).

$$f = \begin{bmatrix} f_1 \\ \vdots \\ f_6 \end{bmatrix} = \begin{bmatrix} s_1^2 - \hat{s}_1^2 \\ \vdots \\ s_6^2 - \hat{s}_6^2 \end{bmatrix} \quad (4)$$

The Newton-Raphson algorithm can be stated as (Patel and Ehmann, 2000):

Measure $\hat{s}$ and select an initial guess for the pose X
Compute s based on X_0
Form f

If X^TX<tolerance$_1$, exit with X as the solution
Compute the partial derivative matrix $J = \partial f / \partial X$ such that $J_{i,j} = \partial f_i / \partial X_j$

Solve for the update δX from $J\delta X=-f$
If $\delta X^T \delta X$<tolerance$_2$, exit with X as the solution
update X by $X=X+\delta X$ and go to step 2

In steps one, an initial pose vector X must be guessed. This is usually taken as the last pose of the mobile platform. In step two, the estimated length can be computed with the inverse kinematics (Equation 2). Step three and four are straightforward, with f formed through (Equation 4) and tolerance$_1$ being the allowed error in the pose calculation. The partial derivatives required in step five can be computed. Step six involves a 6 by 6 matrix inversion to calculate δX, and then in step seven, the norm of δX is tested to see if the update is significant. If the update is considered significant, then the algorithm repeats from step two with the update pose vector.

Error model

There is a method by Ropponen and Arai (1995) available to develop an error model of a parallel robot that provides the framework to include the complete errors of the geometrical features for specifying the pose error. By differentiating both sides of Equation 1, one can obtain:

$$\begin{bmatrix} \delta x \\ \delta y \\ \delta z \\ \delta \alpha \\ \delta \beta \\ \delta \gamma \end{bmatrix} = \begin{bmatrix} u_1^T & (Ra_1 \times u_1)^T \\ \vdots & \vdots \\ u_6^T & (Ra_6 \times u_6)^T \end{bmatrix} \left\{ \begin{bmatrix} \delta\lambda_1 \\ \vdots \\ \delta\lambda_6 \end{bmatrix} - \begin{bmatrix} \left(u_1^T R \quad -u_1^T\right) & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \left(u_6^T R \quad -u_6^T\right) \end{bmatrix} \begin{bmatrix} \delta a_{1x} \\ \delta a_{1y} \\ \delta a_{1z} \\ \vdots \\ \delta b_{6x} \\ \delta b_{6y} \\ \delta b_{6z} \end{bmatrix} \right\} \quad 5$$

Where $[\delta x\ \delta y\ \delta z\ \delta\alpha\ \delta\beta\ \delta\gamma]^T$ describes pose error of the parallel robot, u_i is the unit vector of the ith leg, two attachment point errors described by vector δa_i and δb_i are introduced to the parallel robot. On the other hand, $\delta\lambda_i$ is a length error in the leg.

The computation of the pose errors in Equation 5 involves three sections: the first one is the inverse Jacobian matrix, J^{-1}, the second one is the leg length errors, $\delta\lambda$, and the third one is the positional errors of the attachment points, $J_s\delta s$. Thus, Equation 1 can be rewritten as:

$$\delta p = J^{-1}(\delta\lambda - J_s \delta s) \quad (6)$$

The complete errors of the geometrical features in Equation 6, which are identified as leg length and position errors of the joints, have to be identified in order to improve the pose accuracy of the parallel robot. It is well known that the initial setup length of the leg is specified by the designer. As a result, an error in assembly will produce a constant error, $l_{0,i}$, in the leg lengths. On the other hand, each leg contains a sensor and a measuring error in the sensor produces an error in the leg length. This paper makes the assumptions that the value of $\delta\lambda$ is the error produced in both the assembly and the sensor. Thus, one can obtain:

$$(l_{0,i} + \tau_i l_i)^2 = \|Ra_i + P - b_i\| \quad (7)$$

Due to the length measuring error, $\tau_i l_i$, in the ith sensor, one assume that the ith leg length with error equal to $l_{0,i} + \tau_i l_i$.

ESTIMATION OF KINEMATIC PARAMETERS

Since the measurement system has a very high accuracy, it is assumed that the errors in the parallel robot pose are due to the inaccuracy geometrical parameters in the kinematic model described by Khalil and Besnard (1999). Nonlinear Least Squares is chosen to estimated the actual values of the model parameters. It is based on minimizing the error between the pose data measured and the pose data calculated from the kinematic model. The generalized relationship between the kinematic parameters and the pose of the parallel robot is given by the forward kinematics as:

$$p = f(L_0, \Gamma, A, B) = f(\psi) \quad (8)$$

Where p=[x y z α β γ]^T, L_0= [$l_{0,1}\ l_{0,2} \ldots l_{0,6}$]^T, Γ= [$\tau_1\ \tau_2\ \tau_3\tau_4\ \tau_5\ \tau_6$]^T, A= [$a_{1x}\ a_{1y}\ a_{1z} \ldots a_{6x}\ a_{6y}\ a_{6z}$]^T, B= [$b_{1x}\ b_{1y}\ b1z \ldots b_{6x}\ b_{6y}\ b_{6z}$]^T. Note that the aim of calibration method is to calculate the actual values of the 36 coordinates of point's a_i and b_i, the 6 offsets of the legs and 6 errors of the sensors.

Comment [微软中国2]: Error parameters are defined.

Based on the nonlinear kinematics model $f(\psi)$ of the parallel robot expressed with Equation 8, the kinematic parameters are estimated by minimizing the summed square of the error vector associated with n number of measurement.

$$E = \sum_{i=1}^{n} [p_i - f(\psi)]^T [p_i - f(\psi)] \quad (9)$$

Where p_i is the ith measured pose. This is basically a nonlinear least squares optimization problem that can be solved using either the interior-reflective Newton algorithm or Levenburg-Marquardt algorithm.

In this study, Levenburg-Marquardt algorithm is implemented for the nonlinear least square estimation of the kinematic parameters. The solution is obtained by providing the analytical forms of the cost function and of the gradient matrix of the cost function with respect to the identification parameters.

EXPERIMENTAL RESULTS AND DISCUSSION

The important elements of the experimental setup depicted in Figure 2, are the coordinate measuring

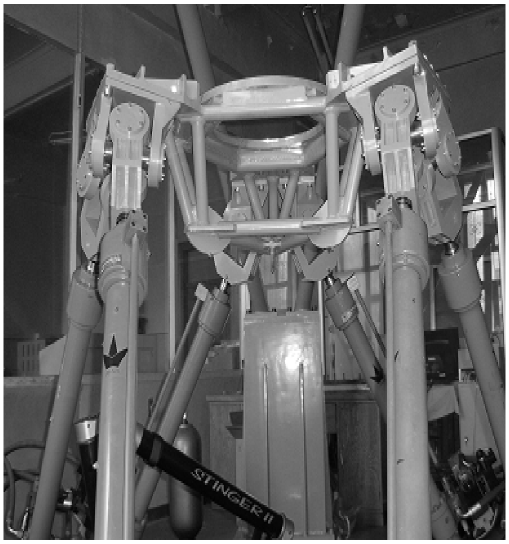

Figure 2. Experimental setup.

machine, tooling balls and the parallel robots. After the coordinate measuring machine has been calibrated to measure the parallel robot pose with respect to the reference frame, the parallel robot is commanded to 120 different well-spaced poses within the robot workspace, which have been determined to cover the range of motion of all the legs. Note that at least 8 measurements are needed to estimate the 48 parameters. The greater number of measurement would contribute to the convergence of the algorithm and reduce the effect of measurement noise. A good initial guess helps a least square estimation algorithm to converge quickly without experiencing any numerical singularities. Therefore, the nominal values of the parameters are taken as the initial values for the parameters while implementing nonlinear least square algorithm.

The estimated technique mentioned above has been implemented using a program prepared in MatLab. The developed program can perform the calibration procedure considering any combination of the parameters used in the kinematic model. The parameters identified from estimated technique with and without the sensor errors are given in Table 1. The RMS pose errors with the nominal parameters and with the 48, and the 42 estimated parameters determined separately from the estimated technique are provided in Tables 2 and 3, respectively. The pose errors of the parallel robot with the nominal parameters, the 42, the 48 estimated parameters are depicted in the first, second and the third columns of Figure 3, respectively.

Table 1. Values of the nominal parameters and the estimated parameters (Unit: m).

Comment [微软中国3]: Unit is appended.

ψ	Nominal values	Without sensor errors	With sensor errors
a_{1x}	0.1669	0.1752	0.1802
a_{1y}	-0.5447	-0.5365	-0.5362
a_{1z}	0.1300	0.1330	0.1350
b_{1x}	1.8419	1.6639	1.8464
b_{1y}	-0.7842	-0.7941	-0.7889
b_{1z}	0.9083	0.9328	0.9092
$l_{0,1}$	1.8625	1.7066	1.8525
r_1	1	-	1.0001
a_{2x}	0.1669	0.1736	0.1645
a_{2y}	0.1598	0.1513	0.1543
a_{2z}	0.5367	0.5319	0.5285
b_{2x}	1.8419	1.6331	1.8350
b_{2y}	-0.3945	-0.4049	-0.3972
b_{2z}	1.1333	1.1375	1.1308
$l_{0,2}$	1.8625	1.6749	1.8594
r_2	1	-	0.9995
a_{3x}	0.1669	0.1675	0.1639
a_{3y}	0.3849	0.3803	0.3777
a_{3z}	0.4067	0.4127	0.4127
b_{3x}	1.8419	1.6278	1.8244
b_{3y}	1.1787	1.1933	1.1787
b_{3z}	0.2250	0.2346	0.2384
$l_{0,3}$	1.8625	1.6801	1.8515
r_3	1	-	1.0003
a_{4x}	0.1669	0.1801	0.1732
a_{4y}	0.3849	0.3864	0.3836
a_{4z}	-0.4067	-0.3988	-0.4005
b_{4x}	1.8419	1.7071	1.8418
b_{4y}	1.1787	1.2272	1.1835
b_{4z}	-0.2250	-0.2045	-0.2148
$l_{0,4}$	1.8625	1.7554	1.8625
r_4	1	-	0.9997
a_{5x}	0.1669	0.1518	0.1697
a_{5y}	0.1598	0.1619	0.1533
a_{5z}	-0.5367	-0.5259	-0.5279
b_{5x}	1.8419	1.7108	1.8408
b_{5y}	-0.3945	-0.4302	-0.3970
b_{5z}	-1.1333	-1.1658	-1.1282
$l_{0,5}$	1.8625	1.7866	1.8606
r_5	1	-	0.9998
a_{6x}	0.1669	0.1526	0.1664
a_{6y}	-0.5447	-0.5366	-0.5399
a_{6z}	-0.1300	-0.1194	-0.1274
b_{6x}	1.8419	1.6732	1.8370
b_{6y}	-0.7842	-0.7903	-0.7822
b_{6z}	-0.9083	-0.9305	-0.9062
$l_{0,6}$	1.8625	1.7391	1.8576
r_6	1	-	1.0004

Table 2. RMS of pose error with 48 parameters (Unit: m and degree).

Comment [微软中国4]: Unit is appended.

Parameters	RMS_p	$\sum RMS_p$	RMS_o	$\sum RMS_o$
	0.4444		0.1061	
Normal parameters	1.5349	4.1913	0.2254	0.6065
	2.2120		0.2750	
	0.1718		0.0159	
Estimated parameters	0.2226	0.5343	0.0498	0.1161
	0.1399		0.0504	
	61.34		85.01	
Improvement %	85.50	87.25	77.90	80.86
	93.68		81.67	

Table 3. RMS of pose error with 42 parameters (Unit: m and degree).

Comment [微软中国5]: Unit is appended.

Parameters	RMS_p	$\sum RMS_p$	RMS_o	$\sum RMS_o$
	0.4444		0.1061	
Normal parameters	1.5349	4.1913	0.2254	0.6065
	2.2120		0.2750	
	0.2023		0.0211	
Estimated parameters	0.2658	0.6306	0.0585	0.1439
	0.1625		0.0643	
	54.48		80.11	
Improvement %	82.68	84.95	74.05	76.27
	92.65		76.62	

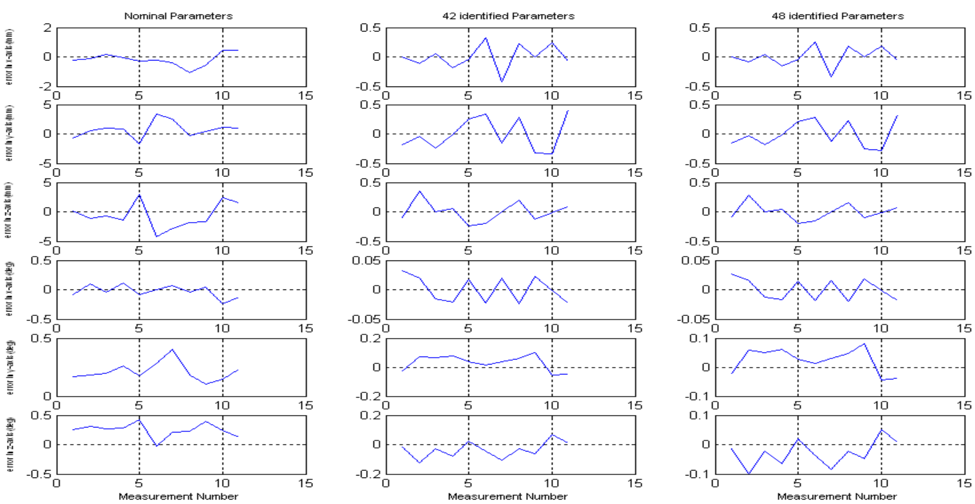

Figure 3. The errors in the 11 poses with the nominal, the 42 and the 48 identified parameters.

By calibration based on 42-parameter model, an accuracy improvement of a factor 6.6 for the parallel robot could be gained on the summation of RMS of position whereas by calibration based on 48-parameter model the predication of the position of the parallel robot improved by a factor of 7.8 for the summation of RMS.

The presented identification procedure can be utilized for the class of six-branch parallel manipulators. The developed calibration program can be used for any manipulators of this class after proving routines that calculate poses of the branch ends expressed in the base reference frame and derivatives of the branch ends' poses with respect to the calibration parameters, and also after providing leg displacement data for a sufficient set of mobile platform poses.

Conclusions

New calibration results based on coordinate measurement technique and a more complete kinematic model including sensor errors of a parallel robot. As a result the parallel robot's pose accuracy is improved. The experiment has obtained the expectant aim and verified that, it is feasible to improve pose accuracy of the parallel robot by presenting the calibration method and identification program in practice. Based on the same set 120 measurement poses the parameters of 42-parameter model and 48-parameter model were identified.

REFERENCES

Stewart D (1965). A platform with six degree of freedom. Proc. Inst. Mech. Eng., 180(1): 371-386.

Zhuang HQ, Roth Z (1991). A method for kinematic calibration of Stewart platforms. Proc. ASME Annu. Winter Meet., Atlanta, GA, 29: 43-48.

Daney D (2003). Kinematic calibration of the Gough platform. Robotica. 21(4): 677-690.

Khalil W, Murareci D (1997). Autonomous calibration of parallel robots. Proc. 5th Symp. Robot Control, 2: 405-410.

Wampler CW, Hollerbach JM, Arai T (1995). An implicit loop method for kinematic calibration and its application to closed-chain mechanisms. IEEE Trans. Robot. Automat., 11(5): 710-724.

Zhuang HQ, Liu L (1996). Self-calibration of a class of parallel manipulators. Proc. IEEE Int. Conf. Robot. Automat., 2: 994-999.

Khalil W, Besnard S (1999). Self calibration of Stewart-Gough parallel robots without extra sensors. IEEE Trans. Robot. Automat., 15(6): 1116-1121.

Masory O, Wang J, Zhuang HQ (1997). Kinematic modeling and calibration of a Stewart platform. Adv. Robot., 11(5): 519-539.

Patel AJ, Ehmann KF (2000). Calibration of a hexapod machine tool using a redundant leg. Int. J. Mach. Tools Manuf., 40: 489-512.

Ropponen T, Arai T (1995). Accuracy analysis of a modified Stewart platform manipulator. Proc. IEEE Intern. Conf. Robotics Automat., 1: 521-525.