Proceeding of the 2004 American Control Conference
Boston, Massachusetts June 30 - July 2, 2004

Kinematic Calibration on a Parallel Kinematic Machine Tool of the Stewart Platform by Circular Tests

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***Abstract*— This paper presents a methodology to calibrate kinematic parameters on a Hexapod-type parallel kinematic machine tool of the Stewart platform. Unlike in the case of conventional serial kinematic feed drives, on parallel kinematic feed drives the tool position and orientation can be only indirectly estimated from angular position of servo motors. Therefore, for high-accuracy motion control of parallel kinematic feed drives, it is the most critical issue to calibrate kinematic parameters such as the reference length of struts and the location of base joints. This paper demonstrates a calibration method based on circular tests to measure the machine's contouring accuracy in a circular operation. To optimize the positioning accuracy of a parallel kinematic feed drive over the entire workspace, it is important to evaluate the machine's global positioning error in circular tests by using the specialized jig plate. The effectiveness of the calibration is experimentally validated on a commercial parallel kinematic machining center.**

I. INTRODUCTION

Most of machine tools in today's market are driven by feed drives that are aligned serially. For example, a 5-axis machining center typically has three linear axes aligned orthogonal to each other, and two rotary axes aligned parallel to linear axes. As a counterpart to such a mechanism, which is referred to as a serial kinematic machine in this paper, parallel kinematic feed drives have recently attracted increasing attention for application in a machine tool due to their potentials in high-speed and high-accuracy 6-DOF (degrees of freedom) positioning. The moving mass in parallel kinematic feed drives can be smaller since they do not need guideways, which is a clear advantage for high-speed and high-acceleration positioning. Unlike in the case of serial kinematic mechanism, a kinematic error in each axis does not impose an accumulating effect on the machine's positioning accuracy, which is a potential advantage for high-accuracy motion control [1].

In the 60's, Gough [2] and Stewart [3] first presented the application of a parallel mechanism to tire testing and to actuated flight simulation. The first prototype of commercial parallel kinematic machine tools, called "Hexapod," has been introduced to public in 1994 by Ingersoll and Giddings & Lewis. A comprehensive review on the development of parallel kinematics for machine tools can be found in [1].

Although more than ten years have been passed since the first parallel kinematic machine tool was introduced, they are not widely accepted in today's industry. Despite many conceptual advantages of parallel kinematic feed drives, there are critical and inherent issues with their application in a machine tool [4]. One such issue is the stiffness; in a parallel kinematic machine tool, a spindle unit is supported and driven by struts only. It typically exhibits lower stiffness against an external force, compared to conventional feed drives with a guideway that introduces higher friction.

Another critical issue is the difficulty to optimize its positioning accuracy. Unlike in the case of conventional serial kinematic feed drives, on parallel kinematic feed drives the tool position and orientation can be only indirectly estimated from angular position of servo motors. Therefore, for their high-accuracy motion control, it is in practice the most critical issue to calibrate various kinematic parameters such as the reference length of struts and the location of base joints. The calibration strategies found in the literature can be roughly categorized into two [5]: 1) by somehow directly measuring the motion of machine components (e.g. Zhuang and Liu [6]), and 2) by measuring the motion of spindle tip, from which kinematic parameters are indirectly identified. As the latter approach, for example, Weck and Staimer [4] used a redundant leg, and Soons [5] used a laser interferometer to measure the position of the tool tip.

On conventional serial kinematic machine tools, due to the simplicity of setup and the easiness of measurement, the circular test by using the DBB (Double Ball Bar) device [7] has been widely accepted by machine tool manufacturers as a standard tool to measure the machine's contouring accuracy. The circular test is accepted as an ISO standard [8]. It can be extended for the calibration of parallel kinematic machine tools [9]. In our previous works, we presented a calibration methodology based on circular tests performed under the condition where the elastic deformation of struts due to the platform weight is minimized [10]. We verified on a commercial parallel kinematic machine that the circularity error was reduced to as small as 7 μm by the calibration, when the spindle is near the center of the workspace [11].

The DBB test has, however, an inherent problem in its nature to perform the kinematic calibration based on it. In a DBB test, one can only measure the distance between two balls. In other words, it only measures a relative position error on a local coordinate system defined with respect to the fixed ball location. To improve the machine's positioning accuracy over the entire workspace, the calibration must evaluate the machine's positioning error on the global coordinates defined with respect to the table. This paper demonstrates a calibration method by performing

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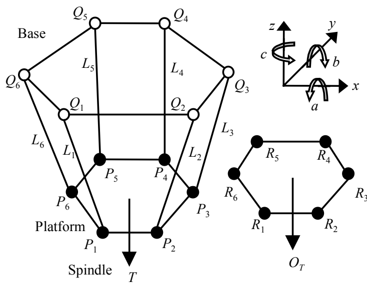


Fig. 1. Stewart platform

TABLE I
MAJOR SPECIFICATIONS OF PM-600

Workspace, mm	ϕ600 (XY) $\times$400 (Z) (420 $\times$ 420 $\times$ 400)
Tilting angle, deg	$\pm$25
Maximum rapid traverse speed, m/min	100
Maximum acceleration, m/s^2	14.7
Spindle speed, min^{-1}	12,000/30,000
Spindle power, kW	6

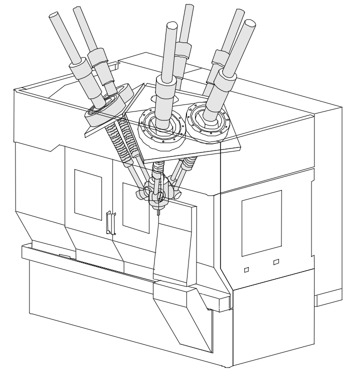


Fig. 2. A Hexapod-type parallel mechanism machine tool, COSMO CENTER PM-600 by Okuma Corp.

circular tests on a specialized jig plate to evaluate the machine's global positioning error. The effectiveness of the proposed calibration method is experimentally validated on a commercial parallel kinematic machining center.

The remainder of this paper is organized as follows. The following chapter briefly reviews a mechanism of a "Hexapod" type parallel kinematic machine tool of the Stewart platform, and then outlines the calibration strategy. In Chapter III, the issues in the conventional calibration strategy based on circular tests are discussed, and then a jig plate to evaluate the machine's global positioning error in circular tests is presented. Chapter IV presents the experimental validation of the proposed calibration method.

II. A PARALLEL KINEMATIC MACHINE TOOL AND ITS KINEMATIC CALIBRATION

A. A Parallel Kinematic Machine Tool of the Stewart Platform

This paper considers the kinematic calibration on a parallel kinematic feed drive of the Stewart platform depicted in Figure 1. It has six telescoping struts, each of which is connected to a base plate by a 2-DOF joint. The other end of a strut is connected by a 3-DOF joint to a platform plate, where a spindle is installed.

Figure 2 shows a schematic view of COSMO CENTER PM-600 developed by Okuma Corp., a commercial Hexapod-type parallel kinematic machining center of the Stewart platform, which is used as an experimental machine throughout our study. Table I shows its major specifications. Each strut is driven by a built-in servo motor via a ball screw. The "length" of each strut is indirectly measured by a rotary encoder installed in a motor. In this paper, six joints on the platform plate are referred to as platform joints, while those on the base plate are referred to as base joints.

B. Inverse and Forward Kinematics of the Stewart Platform

In Fig. 1, $\boldsymbol{T} = [X, Y, Z, A, B, C]$ represents the position and the orientation of the spindle tip (tool tip). When $\boldsymbol{T}$ is given, the problem to calculate the length of each strut, $\boldsymbol{L} = [L_1, \cdots, L_6]$, is called the inverse kinematic problem. It is denoted as:

$$\boldsymbol{L} = \mathcal{F}(\boldsymbol{T}) \tag{1}$$

where $\mathcal{F}$ represents the inverse kinematic function of the Stewart platform. Note that $\mathcal{F}$ is a function of the location of platform joints, $\boldsymbol{P}_j \in \mathbb{R}^3$ $(j = 1 \sim 6)$, and the location of base joints, $\boldsymbol{Q}_j \in \mathbb{R}^3$ $(j = 1 \sim 6)$. The inverse kinematic problem for the Stewart platform can be algebraically solved [11]. When the command position and orientation of the spindle tip is given, the command "length" of each strut, i.e. the command to each servo motor, is given by solving the inverse kinematic problem.

The problem to calculate $\boldsymbol{T}$ for the given $\boldsymbol{L}$ is referred to as the forward kinematic problem:

$$\boldsymbol{T} = \mathcal{F}^{-1}(\boldsymbol{L}) \tag{2}$$

The forward kinematic problem of the Stewart platform cannot be algebraically solved. In this paper, we employ the Newton-Raphson method to numerically solve it.

C. Kinematic Parameters to Be Calibrated

There are more than 200 potential error sources in the parallel mechanism shown in Figure 1 [1]. Since it is not possible to identify all of them, this paper only considers the calibration of the following kinematic parameters:

1) An error in the reference length of each strut: $\Delta L_i \in \mathbb{R}$ $(i = 1 \sim 6)$
2) An error in the location of each base joint: $\Delta Q_i \in \mathbb{R}^3$ $(i = 1 \sim 6)$

These total 24 parameters are contained in the inverse kinematic function of the Stewart platform, and thus directly affect the machine's positioning accuracies. It should be noted that an error in the location of each platform joint, $\Delta P_i \in \mathbb{R}^3$ $(i = 1 \sim 6)$, is also contained in the inverse kinematic function. In our previous study [11], it was experimentally shown that the sensitivity of the parameters, $\Delta P_i \in \mathbb{R}^3$ $(i = 1 \sim 6)$, on the machine's positioning error in a circular test was not as large as that of the parameters shown above. In this paper, we do not consider the calibration of ΔP_i; the location of platform joints are actually measured by using a coordinate measuring machine (CMM).

D. Kinematic Calibration Based on Circular Tests

A circular test is conducted by using a DBB device shown in Figure 3. One ball (B), referred to as *the fixed ball* in this paper, is fixed on the table, while the other ball (A), called *the moving ball*, is attached to the spindle. The distance between the two balls is measured by an optical encoder installed in the bar as the machine moves along a circular path [7].

For the given reference radius of the circular path, $\hat{R}_i \in \mathbb{R}$ $(i = 1 \sim N)$, the actual length of the bar, $R_i \in \mathbb{R}$, is given as a function of the kinematic parameters, i.e.:

$$R_i = f(\hat{R}_i, K) \tag{3}$$

where $K \in \mathbb{R}^M$ is a vector containing all the kinematic parameters to be tuned (M represents the number of kinematic parameters to be calibrated). f is a function that describes the forward kinematics of the Stewart platform. The objective of the kinematic calibration is to solve Eq. (3) for K from R_i $(i = 1 \sim N)$. Since kinematic errors can be assumed sufficiently small with respect to their nominal values in practice, we can linearize Eq. (3) for K and stack N data measured at different spindle locations and orientations to have:

$$\Delta R = A \cdot \Delta K \tag{4}$$

where $\Delta R = \{R_i\}_{i=1,\cdots,N} \in \mathbb{R}^{N\times 1}$ represents the measured positioning error in the radial direction at the i-th position. $\Delta K = \{\Delta k_j\}_{j=1,\cdots,M} \in \mathbb{R}^{M\times 1}$ represents the kinematic error vector to be calibrated. $A = \{\frac{\partial f_i}{\partial k_j}\}_{i=1,\cdots,N,\ j=1,\cdots,M} \in \mathbb{R}^{N\times M}$ represents the sensitivity matrix. Since the forward kinematics denoted by function f is implicit, the matrix A can be computed only numerically. By simply using the least square fitting (LSF), the optimal ΔK^* that minimizes the calibration error $\|\Delta R - A\Delta K\|_2$ is given by:

$$\Delta K^* = (A^T A)^{-1} A^T \Delta R \tag{5}$$

The practical validity of such a simple LSF-based calibration was experimentally verified by many previous works [4][9][11].

III. Kinematic Calibration to Evaluate Global Positioning Error

A. Issues in the Conventional Circular Test Procedure

On conventional serial mechanism machine tools, a circular test is typically conducted by the following procedure [7]:

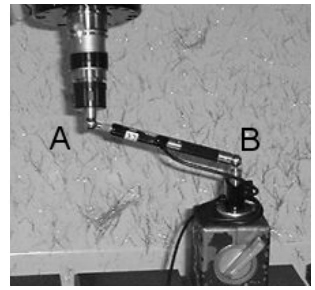


Fig. 3. A DBB device.

Standard Circular Test Procedure:

1) Locate the spindle at the given center position and orientation. Set the fixed ball on the table under the spindle.
2) Move the spindle by the given measurement radius, and then attach the moving ball to the spindle. Set the bar between the fixed ball and the moving ball.
3) Start the measurement; move the spindle along a circular path.
4) Calculate the center of the measured trajectory and then re-compute the contouring error (the deviation from the reference circle) by using this "optimal" center.

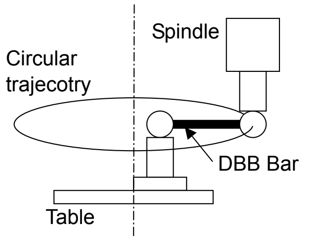
In 4), the center of the measured trajectory can be computed by solving the following problem by using e.g. the Newton method:

$$\min_{x_0,y_0,r_0} \sum_{i=1}^{N} \left(\sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} - r_0 \right)^2 \tag{6}$$

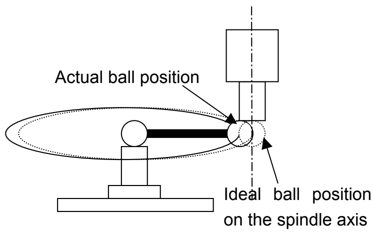
where (x_i, y_i) $(i = 1 \sim N)$ is the measured trajectory of the spindle position on X-Y plane. The re-computation of the error profile by using the optimized center (this re-computation is hereafter referred to as *the center compensation*) is commonly done when a circular test is performed on a conventional serial mechanism machine tool [7]. This compensation is needed to cancel setup errors such as a) position shift of the fixed ball from the reference circle center, and b) position shift of the moving ball from the spindle center (see Figure 4).

Such setup errors appear as the center deviation on an error trajectory. By applying the center compensation, such setup errors can be ignored. For the kinematic calibration on a parallel kinematic machine tool, however, it is crucial to evaluate the center deviation for the following reason:

1. *The center deviation shows the machine's global positioning error.* In a circular test, one can only measure a relative positioning error with respect to the location of the fixed ball. In order to evaluate the machine's global positioning error, the location of the fixed ball must be defined on the global coordinates. Notice that it is not the case in the procedure above, since the fixed ball is located based on the spindle location.
2. *The conventional procedure limits the number of parameters to be calibrated.* For example, suppose that all the



(a) a shift of the fixed ball from the reference circle center



(b) a shift of the moving ball from the spindle center

Fig. 4. Major setup errors in a circular test

base joints are shifted to the same direction by the same distance. In the conventional procedure, such an error does not appear at all on an error trajectory. It is easy to see that at least six parameters must be prescribed in order to make the matrix A in Eq. (4) nonsingular (See [10]).

3. *The conventional calibration cannot define the machine's coordinates with respect to the table.* In the conventional calibration, the coordinates are defined with respect to the parameters fixed in 2.

B. Jig Plate for Circular Tests

To address issues discussed in the previous section, we propose to perform a circular test on a specialized jig plate to locate the fixed ball. Figure 5 shows an outlook of the jig plate. It has nine taper bores on its top surface. Two ball holders of different height are available such that a circular test can be performed at different Z height levels (Figure 5 shows the longer ball holder). The ball holders have a 7/24 taper at its bottom, and can be inserted to the bore by the face and taper contact (i.e. the dual contact like the "Big Plus" spindle system) by tightening screws. This jig plate allows us to locate the fixed ball in the global coordinates defined with respect to the table.

When the insertion and the separation of ball holders were repeated for ten times at each location, the repeatability error in the ball location was 1.0 μm at average for the shorter holder, and was 3.2 μm at average for the longer holder (measured by using a CMM). The errors are sufficiently small for a circular test.

C. Calibration Procedure using the Jig Plate

First, set up the jig plate on the table. Note that the calibration will ideally define the machine's origin at the location of the center hole. We chose 15 center locations for the circular test as shown in Table II. Similarly as in our previous work [10], these locations are chosen such that they cover as much a portion of the machine's entire workspace as possible. At each location, either of the ball holders is installed on the jig plate and conduct the circular test in the same manner presented in Section III-A. Note that the center location in each test (the command position to the machine) is given by the actual location of the fixed ball measured in priori by a CMM. Alsot note that the center compensation is not needed. Raw error trajectories must be used in the calibration (Eq. (5)).

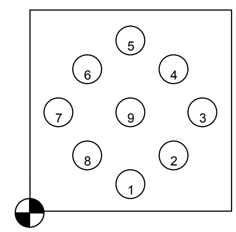
It should be noted that the spindle tip location at the center of each circular test and the fixed ball location do not necessarily coincide, unlike in the case of the conventional procedure presented in Section III-A. This positioning error appears as the center deviation in an error trajectory. Furthermore, note that the calibration will define the machine coordinates with respect to the location of fixed balls. Therefore, for example, by locating the jig plate parallel to a T-groove on the machine table, the flatness or the straightness of the machine's motion with respect to the table will be secured by the calibration.

Fig. 5. The jig plate and the ball holder for circular tests

TABLE II

CENTER LOCATIONS AND ORIENTATION IN CIRCULAR TESTS

Name	Center $*1$	Z $*2$	A (deg)	B (deg)
a	9	1	0	0
b	4	1	10	-10
c	6	1	10	10
d	8	1	-10	10
e	2	1	-10	-10
f	9	2	0	0
g	3	2	0	-15
h	5	2	15	0
i	7	2	0	15
j	1	2	-15	0
k	9	3	0	0
l	4	3	10	-10
m	6	3	10	10
n	8	3	-10	10
o	2	3	-10	-10



$*1$: indicates the location of the fixed ball on the jig (shown in the figure above) in each DBB test.

$*2$: indicates the location of the platform in the z-direction. 1(lowest) – 3(highest).

IV. EXPERIMENTAL VALIDATION

The proposed calibration scheme was experimentally tested on a commercial parallel kinematics machine tool shown in Section II-A to compare with the conventional calibration method. The conventional calibration scheme based on *the Standard Circular Test Procedure* given in Section III-A is referred to as *Conv-A* hereafter, while the proposed calibration scheme using the jig plate shown in Section III-C is referred to as *Proposed*.

In *the Standard Circular Test Procedure*, it is possible (although quite time-consuming in practice) to measure a position shift of the fixed ball and the moving ball by using a micrometer, and then to compensate it on the measured error trajectory. Notice that even if setup errors are completely eliminated, the issues (1)$\sim$(3) presented in Section III-A are not addressed, since the machine's global positioning error at the center is still not evaluated. This scheme (the calibration without using the jig plate, but with the compensation of setup errors) is referred to as *Conv-B*, and is also compared with the proposed scheme.

The kinematic parameters were calibrated by using three methods, *Conv-A*, *Conv-B*, and *Proposed*. Then, in each case, the machine's contouring accuracy was again measured by circular tests on the jig plate at total eight different positions. Table III compares (a) the center deviation, (b) the mean radial error (i.e. the mean of the deviation from the reference circle), and (c) the circularity error (i.e. the difference between the maximum and minimum errors from the reference circle). "Default" indicates the case where original values (design values) of kinematic parameters were used without any calibration. "Position" corresponds to the center location shown in Table II. As examples, error trajectories measured in the locations *d* and *k* are shown in Figure 6(a)(b), respectively. In all circular tests, the feedrate was 1,000 mm/min and the reference radius was 150 mm.

Table III(c) indicates that the circularity error under the calibration *Proposed* was slightly worse than that under the conventional calibration at many locations. In Table III(a), however, the center deviation was significantly reduced by the calibration *Proposed* at most locations (mean: 8.6 μm, maximum: 17.8 μm), compared with the calibration *Conv-A* (mean: 47.9 μm, maximum: 81.9 μm) and *Conv-B* (mean: 43.1 μm, maximum: 64.6 μm). These results clearly validates the discussion in Section III-A. That is, since the calibrations *Conv-A* and *Conv-B* cannot evaluate the machine's global positioning error, they cannot guarantee the global positioning accuracy at each center, although a relative positioning error can be reduced.

To further investigate the machine's global positioning accuracy, the flatness error [7] with respect to the table's top surface and the parallelity error [7] with respect to one of T grooves on the table were measured. The flatness error was measured as follows: at total eight points in the range of $X = -260 \sim 260$mm, $Y = -260 \sim 260$mm, the spindle is located at the same Z height level and then the actual distance between the spindle tip and the table surface is measured by using a micrometer at each point. Figure 7(a) summarizes the flatness error (the Z height level at the point $(X, Y) = (260, 260)$mm is considered at the reference level) for each calibration method. Similarly, the parallelity error was measured as follows: the spindle is moved to the +X direction along one of T grooves on the table, and the actual distance from the spindle tip and the groove is continuously measured by using a micrometer. Figure 7(b) summarizes the parallelity error for each calibration. The conventional calibration methods, *Conv-A* and *Conv-B*, resulted in a large flatness error, 186 and 194 μm (in the range X380$\times$Y380mm), respectively. The parallelity error was also large, 78 and 71 μm (in the range X380mm), respectively. By applying the calibration *Proposed*, the flatness error and the parallelity error were drastically reduced to 20 and 19 μm, respectively. These results also validate the importance of evaluating the machine's global positioning error in the calibration by using the jig plate.

At last, it should be noted that it is possible to compensate the machine's global positioning error after the conventional calibrations based on post-calibration measurements. For example, one can simply "rotate" the parameters of base joint position, Q_i $(i_1, \cdots, 6)$ such that the flatness error and the parallelity error are minimized. It does not, however, always guarantee the optimal positioning accuracy over the

TABLE III

COMPARISON OF CALIBRATION RESULTS

(a) Center deviation (unit: μm)

Position	Default	Conv-A	Conv-B	Proposed
a	0.0	0.0	0.0	0.0
d	72.1	13.6	25.3	**12.9**
f	91.9	26.2	26.8	**1.9**
h	212.0	51.6	20.9	**15.0**
j	26.5	**9.4**	54.0	17.8
k	96.7	81.9	52.1	**3.1**
l	158.7	72.0	64.6	**4.9**
n	65.1	80.7	58.4	**4.7**

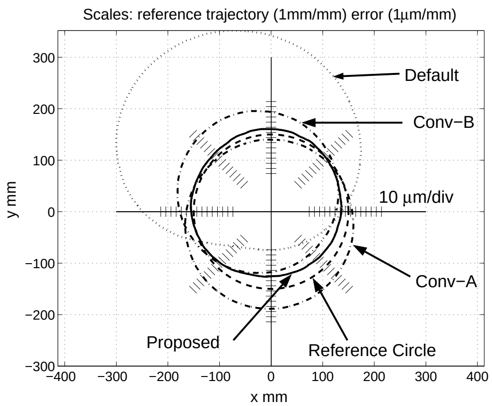
(b) Mean radial error (unit: μm)

Position	Default	Conv-A	Conv-B	Proposed
a	+58.4	+9.0	+3.6	**+1.3**
d	+64.6	+13.6	+5.1	**+3.2**
f	+60.1	+9.1	**+0.8**	-3.4
h	+57.8	+9.3	+1.8	**-0.4**
j	+67.8	+10.0	**+1.7**	-2.0
k	+58.1	+5.9	**+1.6**	+3.9
l	+45.1	+6.4	**+2.4**	+4.0
n	+64.9	+6.5	**+0.6**	5.4

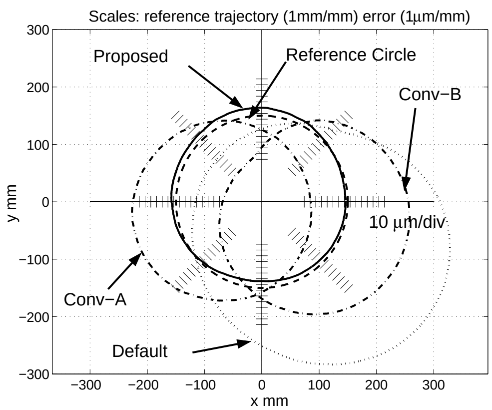
(c) Circularity error (unit: μm)

Position	Default	Conv-A	Conv-B	Proposed
a	25.1	4.9	4.5	**3.9**
d	18.8	**4.1**	5.6	5.2
f	24.8	**5.2**	9.5	7.3
h	61.6	**7.2**	10.6	12.3
j	17.2	**7.6**	12.9	12.9
k	25.4	**4.6**	17.6	5.7
l	43.6	6.6	**6.5**	6.7
n	14.9	**5.3**	26.8	5.7

$*$ Bold numbers indicate the best result at each position.

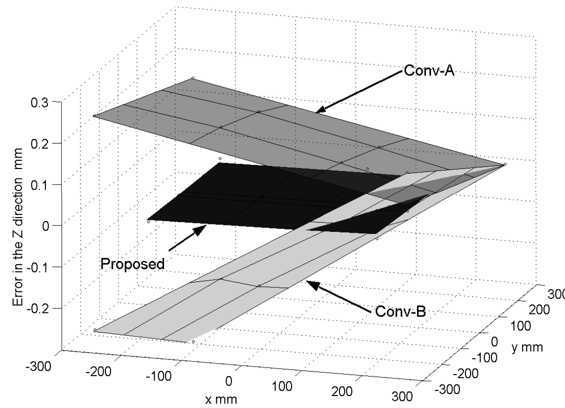


(a) At the position d (in Table II)

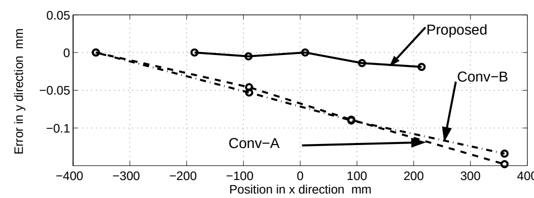


(b) At the position k (in Table II)

Fig. 6. Comparison of contouring error trajectories



(a) Flatness error with respect to the table



(b) Parallelity error with respect to the table

Fig. 7. Comparison of parallelity and straightness errors

entire workspace, in addition that it requires considerable amount of additional works.

V. Conclusion

For high-accuracy motion control of parallel kinematic feed drives, the most critical issue in practice is the calibration of kinematic parameters. This paper presented a practical calibration methodology of kinematic parameters on a Hexapod-type parallel kinematic machine tool. The proposed calibration method identifies total 23 kinematic parameters based on the machine's contouring error in circular tests conducted with total 15 different locations and orientations. By performing circular tests on the specialized jig plate, the machine's global positioning error can be evaluated to some extent. The effectiveness of evaluating the center deviation in circular tests for the kinematic calibration was experimentally validated on a commercial parallel kinematic machining center. In particular, the flatness error and the parallelity error, which are indices of the machine's global positioning error over a large portion of the workspace, were drastically improved by applying the proposed calibration method.

Acknowledgement

This work was in part supported by the JSPS Grants-in-Aid for Scientific Research (#15560094).

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