A Calibration Method for Parallel Mechanism Type Machine Tools by Response Surface Methodology

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Abstract:
This study proposes a calibration method for parallel mechanisms by using Response Surface Methodology. The measurement of the postures and positions of parallel mechanisms is so difficult that the effective and easy feasible calibration method has not yet been established. This study proposes a method that can estimate exact input-output relation of a parallel mechanism from only fewer measurement data of its postures and positions. The estimated input-output relation can reveal effect of various errors involved in the parallel mechanism, and can introduce appropriate compensation values, which achieves high-precision positioning.The study describes the calibration method for parallel mechanisms by using RSM and demonstrate the calibration of a Stewart Platform which a spatial six-degree of freedom mechanism by numerical simulation.

Keywords: Parallel Mechanism, Machine Tool, Calibration, Response Surface Method, Stewart platform

1. Introduction

Parallel mechanisms can arrange actuators near the base so that their movement parts may be lightweight. Furthermore, the output part is supported and moved by plural link-chains that are respectively connected to the base, each of which is driven by an individual actuator. These features provide them salient advantage in high-power, high-accuracy and high-rigidity. Thus, a lot of studies have tried to adopt parallel mechanisms to multiaxial machine tools. However, the rigidities of current ordinary parallel mechanisms are not sufficient for machine tools. Additionally, the volume ratio of the workspace to the mechanism body is very small and the accuracy of the positioning of the output part is not always enough for machine tools.

Previously, we have developed a hybrid type parallel mechanism consisting of a spatial parallel mechanism and a planar mechanism, which can obtain a large workspace by combining the motions of both the mechanisms[1-2]. In addition, the spatial parallel mechanism devises the cross-section shape of the coupler links to suppress the deformation, and the planar mechanism uses a precision XY table, thereby, resulting in the high rigidity. However, the positioning accuracy is not always sufficiently. As the movement parts of the spatial parallel mechanism have no guide face, the positioning accuracy can be ensured by only the control system. Thus, the calibration of the input-output relations is strongly required in order to achieve exact positioning. Although the calibration needs the measurements of several poses of the parallel mechanism, it is fairly difficult to measure the poses of the spatial parallel mechanism. Especially the spatial attitudes of the output links cannot be obtained by ordinary simple methods. Furthermore, although the parallel mechanisms can take various pose, it is also difficult to predict the appropriate poses to be measured for the calibration. However, in order to apply parallel mechanisms to machine tools, they need highly accuracy positioning. Thus, a lot of calibration methods [3-13] have been studied.

Oiwa[3] installed a translatory passively retractable link to a parallel mechanism and obtained the difference between the ideal and measured displacements of the translatory link at an arbitrary pose of a parallel mechanism to estimate the mechanism parameters. Ota[4] measured a tool tip position with DBB (Double-Ball-Bar) and estimated mechanism parameters from a forward kinematics of a parallel mechanism and a convergence calculation by Newton-Raphson method. However these methods do not examine the poses to be measured for the calibration. The adoption of the measurement poses is essential for effective calibration because the input-output relation of a parallel mechanism has strongly non-linearity. Takeda[5] propose the calibration method using Fourier series. However the method carefully decides the measurement movement. Thus the method is not always efficient because the number of experiment may be large. Because the measurement of the poses of a parallel mechanism is fairly difficult, it is preferred to calibrate by a few useful measured poses.

Therefore, the present study proposes a calibration method that needs only a few poses to be measured for parallel mechanisms. The proposed calibration method compensates the input-output relations over the whole workspace by using Response Surface Method (RSM)[14-19] that is applied to various fields. RSM is a statistical method that makes it possible to estimate the response of a system from effective factors, which are selected by "the design of experimental" so that the number of investigated conditions may be smaller. The present method efficiently generates a response surface for errors of the positions and postures of the output-link of a parallel mechanism, which we call here a estimated-error-surface(EES). Moreover, calibration values for the output-link can be calculated with numerical computation by using the estimated-error-surface.

In what follows, this paper denotes a specific method to calibrate parallel mechanisms for multiaxial machine tools and demonstrates its availability by numerical simulations of the calibration for a Stewart Platform that is the representative spatial six-degree of freedom mechanism.

2. Calibration Method by Response Surface Methodology

This section exhibits a calibration method for parallel mechanism type machine tools by RSM. RSM, which is a statistical technique applied in various fields such as quality engineering, can clarify the relationship between responses and factors in a certain system. In this paper, we try to perform a calibration of parallel mechanism type machine tools with RSM by clarifying the relationship between desired poses and actually achieved ones.

2.1 Factor and Response

In order to use RSM, factors and responses in an objective system must be defined. In the calibration of parallel mechanisms, it is necessary to know the output errors caused by dimension errors, backlash, and so on, with respect to the desired poses. Thus, the desired pose (the positions and postures of a mechanism) is defined as the factors, and the output errors that reveal differences between the desired poses and the achieved ones are defined as the responses.

2.2 Estimated-Error-Surface

RSM needs to obtain the relation between factors and responses. Thus, the study reveals the relation between the poses of the mechanism and the output errors. This study uses a multivariable quadratic equation as the approximate mode to reveals these relations. The obtained relation is called as the Estimated Error Surface (ESS), which is corresponding to "Response Surface" as above described. In order to obtain Estimated Error Surface, the number of the measuring points of the output errors must be larger than the term number of the multivariable quadratic equation. The increase in the number of the measuring points not only improves the accuracy of the approximate model, but also remarkably increases labor and time. Thus, the study selects the measurement points of the output errors of parallel mechanisms by "the design of experiments", which are here performed by using D-optimal designs.[19] The D-optimal designs determine the combination of the measuring points so as to minimize the dispersion of each coefficient of the approximate model. The used D-optimal designs utilized Genetic Algorithm to obtain the optimum combination.

The obtained EES shows the changes of the output errors over the workspace and will reveal appropriate compensation values for the calibration

2.3 Calculation of Compensation Values

The proposed calibration method compensates the outputs of parallel mechanisms as follows. Firstly, the desired pose of a parallel mechanism "$\boldsymbol{P}$" is given. The inputs for respective driving links are determined by the inverse kinematics. However, the achieved pose will have output errors. The EES can estimate such output errors $EES[\boldsymbol{P}]$. Thus, the proposed method determines $\boldsymbol{P}'$ that satisfies the following equation;

$$\boldsymbol{P} = \boldsymbol{P}' + EES[\boldsymbol{P}'] \qquad (2.1)$$

By using $\boldsymbol{P}'$ as the operated values instead of $\boldsymbol{P}$ and calculating the inverse kinematics, the compensated input values that achieve the desired pose $\boldsymbol{P}$ is obtained. $\boldsymbol{P}'$ is easily determined by Newton-Raphson method.

3. Simulation and Results

The measurement of the spatial pose of a parallel mechanism is difficult and the identification of their dimension errors that cause the output error is near impossible. Thus, this paper verifies the proposed method by numerical simulations and considers the accuracy of the obtained calibration. Because the accuracy of the calibration depends on the accuracy of the EES, it is strongly required that the EES will be sufficiently accuracy.

This study evaluates the accuracy of the proposed method using a mean and a maximum difference between the obtained results and a true value which is determined by a numerical simulation, and verifies its usefulness.

3.1 Object Mechanism

This paper calibrated a Stewart Platform[20] mechanism (STWP), which is the representative spatial 6-degree of freedom (dof) parallel mechanism shown in Fig3.1. The base and the output-link of the STWP are coupled 6 link chains. Each link-chain has a input link near the base and couples the base with a 3-dof spherical joint and the output-link with a 2-dof universal joint. This mechanism can perform multiaxial processing by positioning a tool that is fixed on a

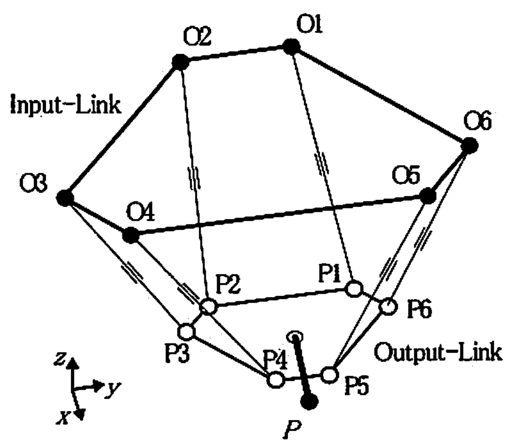


Fig3.1 Object mechanism

Table3.1 Movable range

Workspace[mm]	400×400×400 (-200<x<200, -200<y<200, 0<z<400)
Tilting angle (β,α) [deg]	±25
Base radius[mm]	800
Output Link radius[mm]	200

Table3.2 Parameters of mechanism error

Parameters	Error obtained		
	x [mm]	y [mm]	z [mm]
O1	0	-0.1	-0.1
O2	0	0.1	-0.1
O3	0.1	0	0
O4	0	0	0
O5	0	0	0.1
O6	-0.1	0.1	0
P1	0	-0.1	0
P2	0	0	0
P3	-0.1	0.1	0
P4	0	0	-0.1
P5	0	0	0
P6	0	0.1	0.1
Spindle Length	0 [mm]		

Table3.3 Definition range (Estimation range)

Factor	Displacement	
	Largest	Smallest
x[mm]	50	-50
y[mm]	50	-50
z[mm]	100	0
β[deg]	10	-10
α[deg]	10	-10

center of the output link in its normal direction. Generally the processing by a rotating tool does not require the positioning in the tool rotational direction, thus the mechanism needs only 5 dof for spatial processing. The study, therefore, calibrates the pose of the output link of the STWP about the positions in 3 orthogonal axial directions and the gradients about 2 orthogonal axial directions. Details of the mechanism are as shown in Table3.1, by referring to the COSMOCENTER PM-600[21-22] which is the STWP type machine tools developed by OKUMA. Inc.[23] In this study the position of the STWP is revealed by the position of the output point P (x,y,z), which is the position of the tool tip as shown in Fig. 3.1. In addition, the posture of the STWP is expressed with z-y-x Eulerian angle method. The tilting angle of the output link is revealed by (β,α). α and β denotes the rotational angles about x and y axes respectively. Here, the initial pose of the STWP is the case when the lengths of the input links are all equal and the height of the output link z is 500mm.

The study assumes the joints on the input and the output links have positional errors in 3 axial directions (x,y,z) as show in Fig.3.1, which will induce the output errors. The number of the joints on the input and the output links are 6 respectively and each joint has 3 error parameters, thus the study takes error conditions of 36 ($6\times2\times3$) patterns into consideration. In this simulation, the position errors are given to each joint within the range of -0.1mm to +0.1mm randomly. The quantities of the position errors of each joint are assumed as shown in Table 3. 2.

Note that the proposed method directly calibrates the positions of the tool tip without identifying the position errors of the joints, etc. The present calibration does not need to consider the amounts of errors involved at any parts of an objective mechanism.

3. 2 Conditions for Simulation

The calibration for the STWP uses a quadratic equation for the approximate model of the EES as follows;

$$f(x,y,z,\beta,\alpha)=1+x+y+z+\beta+\alpha+ x^2+xy+xz+x\beta+x\alpha+ y^2+yz+y\beta+y\alpha+z^2+ z\beta+z\alpha+\beta^2+\beta\alpha+\alpha^2 \quad (3.1)$$

where (x,y,z) and (β,α) are the positions and attitudes of the output link as above described. $f(x,y,z,\beta,\alpha)$ reveals the output error induced at a certain position and attitude. As the above equation involves 5 variables, its term number is 21 with including constant term. The present calibration, therefore, requires the measuring points of equal to or more than 21. In this simulation, the calibration is performed with 42-measuring points, which is the twice of the term number.

Here, the range of the EES is defined as 100mm in x-axis, 100mm in y-axis and 100mm in z-axis around the center of the orthogonal coordinate system shown in Fig.3.1., and the ranges of the rotational angles about y axis (β) and x (α) axis are both defined to be -10 to 10 degrees. The definition range of each factor is shown in Table3.3. The EES is calculated within these ranges.

3.3 Calibration

The effective measuring points to obtain the EES were determined by D-optimal designs. The results are shown in Fig3.2; the determined measuring points mainly exist near the boundary of the range of the EES.

The position and posture errors of the tool tip at the determined measuring points were calculated by the numerical simulations instead of the experiments. The coefficients of the approximate model that expresses the EES are calculated using a least squares method with the simulated output errors at the measuring points.

The evaluation was carried out by comparing the output errors by the obtained EES with the calculated values by the numerical simulations. The comparison was performed

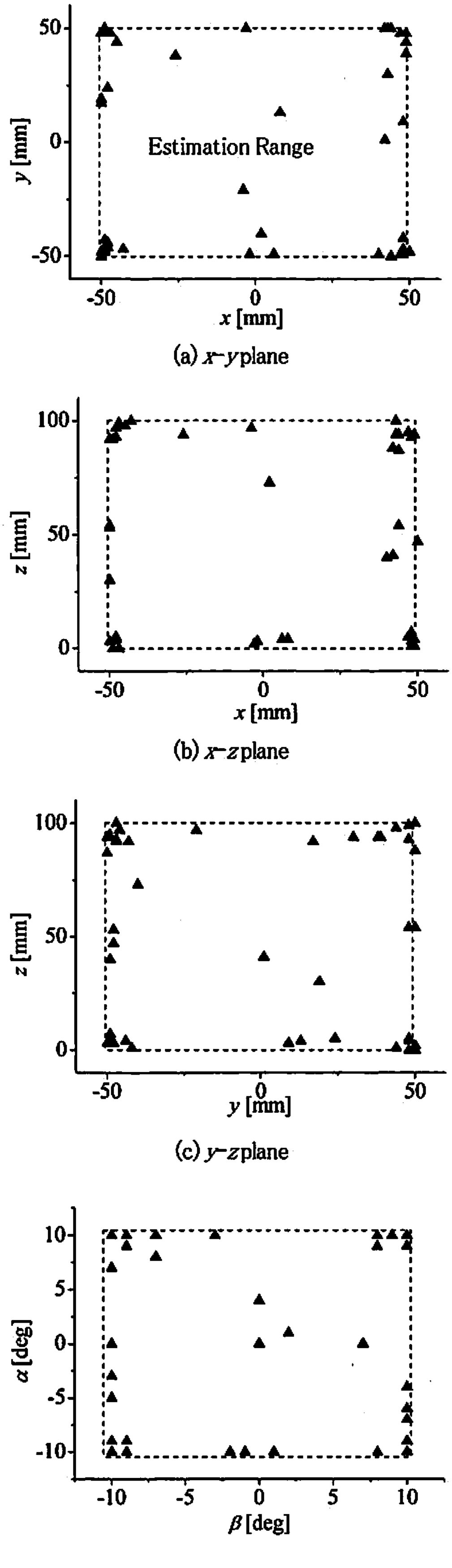


Fig3.2 Optimal Design by D–optimal designs

at each position and posture that equally divide the ranges of the factors (x, y, z, β, α) by each level shown in Table3.4.

Table3.5 shows the mean and the maximum differences between the true value of the output error and the obtained values with the EES. The mean differences about the tool position are 2μm or less about all factors, and about the factors x and y, the mean differences are only 1μm or less. The maximum differences are 8μm or less about all factors, and as long as about factors x, y, the maximum vales are 2μm or less. Thus the determined EES estimates the output errors well over the investigated work space range. The accuracy of the estimation about factor z is relatively less to the other factors. The reason why is considered that the

Table3.4 Level of factor

Factor	Level of Factor
x	20
y	20
z	20
β	5
α	5

Table3.5 Evaluation of accuracy of EES

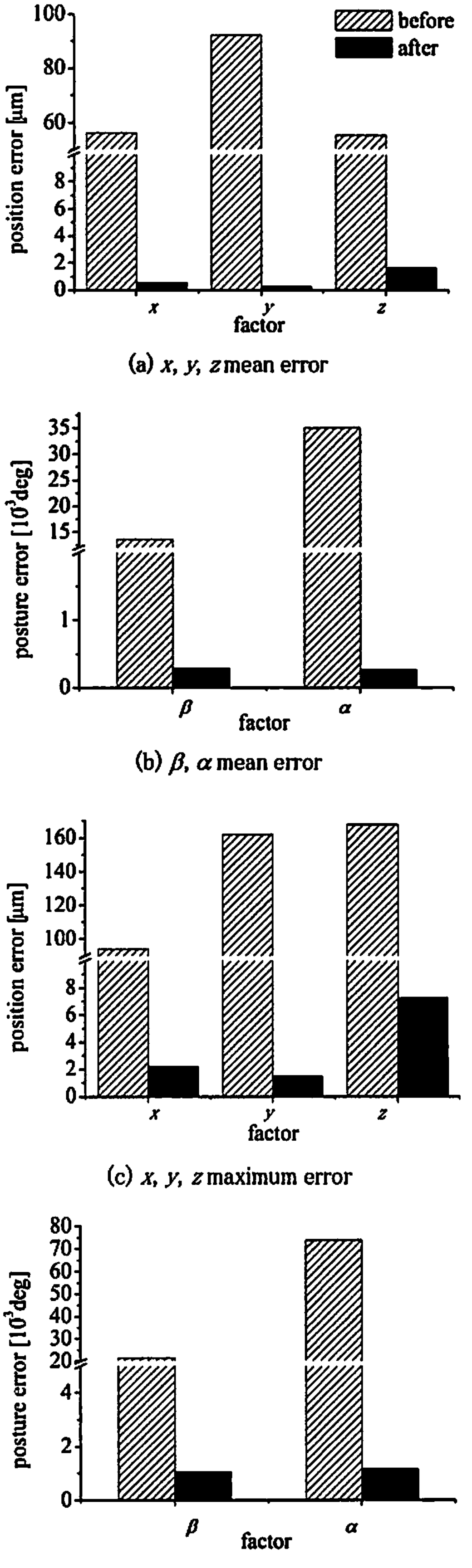
Factor	Mean error	Maximum error
x [μm]	0.542	2.188
y [μm]	0.249	1.485
z [μm]	1.634	7.236
β [deg]	0.000	0.001
α [deg]	0.000	0.001

Table3.6 Output–point error before the calibration

Factor	Mean error	Maximum error
x [μm]	56.113	94.036
y [μm]	92.084	161.684
z [μm]	55.245	167.706
β [deg]	0.014	0.021
α [deg]	0.035	0.074

Table3.7 Evaluation of accuracy after the calibration

Factor	Mean error	Maximum error
x [μm]	0.542	2.200
y [μm]	0.249	1.463
z [μm]	1.632	7.269
β [deg]	0.000	0.001
α [deg]	0.000	0.001



(a) x, y, z mean error

(b) β, α mean error

(c) x, y, z maximum error

(d) β, α maximum error

Fig3.3 Results of the calibration

variation of the factor z has stronger nonlinearity than the other factors. Furthermore, the mean and the maximum differences between the true and the estimated values with the EES about the tool posture are all within 0.001 degrees or less. Thus, the determined EES well estimates the output errors totally.

Using the obtained EES, the calibration of the STWP was carried out. At the same points that evaluate the accuracy of the EES, the calibrations were performed as described in 2.3. From the results, the differences between the desired positions and the compensated ones by the proposed calibration were calculated. Table 3.6, 3.7 and Fig. 3.3 shows the variations of the output error before and after the calibrations. As known from the results, the accuracy is dramatically improved. Since the proposed method conducts the compensation values from the EES, the accuracy of the calibration almost agrees with the EES as known from the comparison of Table 3.5 and 3.7.

From the above results, the study has verified that the proposed method can effectively calibrate the output errors of the STWP with high accuracy from only a few data.

4. Conclusion

The calibration method for parallel type mechanisms as machine tools by using the Response Surface Methodology is proposed. The method can calibrate the output errors of parallel mechanisms by fewer measurements of their poses by design of experiments. Generally, the measurement of the spatial pose of the mechanism is so difficult that the proposed method is hoped to be practicable. Furthermore, the method does not need to identify the error existing in any parts of mechanisms, and directly clarifies their output error.

This study performed numerical simulations of the calibration about the Stewart Platform mechanism by the proposed method. As a result, the present method can reduce the output errors of the tool position and posture by less than and equal to 2μm and 0.001 degrees respectively. Thus, the method makes it possible to calibrate the output errors of parallel mechanisms with high accuracy only from fewer measured data.

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