Calibration of Three Dimensional Mechanism
- Novel Calibration Method for 3DOF Parallel Mechanism -

K. Takamasu, I. Murui, O. Sato, G. Olea and R. Furutani*
Department of Precision Engineering, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, JAPAN
Phone: +81-3-5841-6472, Fax: +81-3-5841-8556, E-mail: takamasu@pe.u-tokyo.ac.jp
* Department of Precision Engineering, Tokyo Denki University
2-2 Kandanishiki-cho Chiyoda-ku, Tokyo, 101-8457, JAPAN
E-mail: ryo@cck.dendai.ac.jp

Abstract
Many types of three dimensional mechanisms (3D-mechanism) are used in modern industry. Specially, in automation technology, product engineering and robotics, 3D-mechanisms play the key roles of complicated manipulation, 3D positioning and 3D measurement. Usually, the repeatability of 3D-mechanism is tested and evaluated. However, when we use 3D-mechanism in wide purposes and in wide conditions, the absolute calibration is the key technique to control the mechanism precisely. In this article, we analyze theoretically the method of the absolute calibration for 3D-mechanisms, such as a Cartesian mechanism, an articulated mechanism and a parallel mechanism. After theoretical analysis, we introduce a novel 3DOF parallel mechanism for a coordinate measuring machine (CMM) and a micro milling machine and a novel calibration method for these parallel mechanisms.
Keywords: Calibration, Three Dimensional Mechanism, Coordinate Measuring Machine, Parallel Mechanism

1. Introduction
In automation technology, product engineering and robotics, 3D-mechanisms play the key roles of complicated manipulation, 3D positioning and 3D measurement. Usually, the repeatability of 3D-mechanism is tested and evaluated. However, when we use 3D-mechanism in wide purposes and in wide conditions, the absolute calibration is the key technique to control the mechanism precisely. In this article, we analyze theoretically the method of the absolute calibration for 3D-mechanisms, such as a Cartesian mechanism, an articulated mechanism and a parallel mechanism. Then, we proposed a novel parallel mechanism using magnetic spherical joints and a novel calibration method for the mechanism.

2. Geometric Calibration
There are two types of calibrations, geometric calibration and non-geometric calibration, and in the geometric calibration, there are also two types of calibrations, kinematic (size) calibration and form-deviation calibration of three dimensional position and orientation for three dimensional mechanisms (3D-mechanisms) (Table 1). The kinematic (size) calibration calibrates the parameters describe the forward kinematic functions of three dimensional positioning and orientation, when we can assume every guide (linear guide and/or rotational guide) of 3D-mechanism is perfect and has no deformation by force and/or thermal effect. And, the form-deviation calibration calibrates the errors and deformations of each linear and/or rotational guide, frames and elements of 3D-mechanism.

A typical coordinate measuring machine (CMM) using Cartesian coordinate system is very stable and has only three kinematic parameters, three angles between X, Y and Z axes for kinematic calibration (see fig. 1). Therefore, the form-deviation calibration is done for 6DOF of three guide way errors (scale error, two straightness, pitching, yawing, rolling errors) of X, Y and Z axes ($6 \times 3 = 18$) and total 21 parameters ($3 + 18 = 21$) are calibrated. Fig. 2 shows a calibration method using a ball plate or a hole plate for 21 geometric parameters (3 kinematic parameters and 18 form-deviation parameters) of a Cartesian type CMM [1][2].

An articulated type robot with 6DOF (fig. 3) has 27 kinematic parameters [3], and 3DOF parallel mechanism (fig. 4) has 39 kinematic parameters. The number of kinematic parameters for articulated and parallel mechanism is larger than that of Cartesian mechanism. Therefore, a special artifact and/or a large precise measurement system is necessary for kinematic calibrations of these complicated 3D-mechanisms, such as articulated and parallel mechanisms. Moreover, the form-deviation calibrations of the complicated 3D-mechanisms are very hard tasks [4]. In this article, we propose a novel calibration method of kinematic calibration for 3DOF parallel mechanism.

Table 1 Classification of Calibration Parameters

classification		parameters
geometric calibration	kinematic (size) calibration	size dimensions, positions, angular dimensions ...
	form-deviation calibration	scale, straightness, pitching, yawing, rolling ...
non-geometric calibration		deformation, clearance, dynamic effect ...

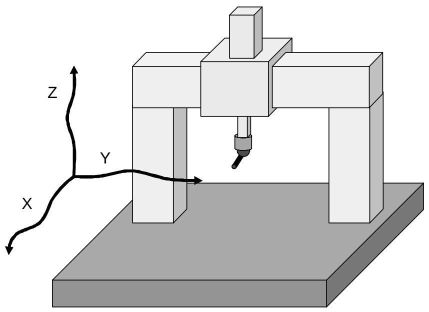


Fig.1 Conventional CMM by Cartesian Coordinate System has 3 Kinematic Parameters and 18 Form-Deviation Parameters

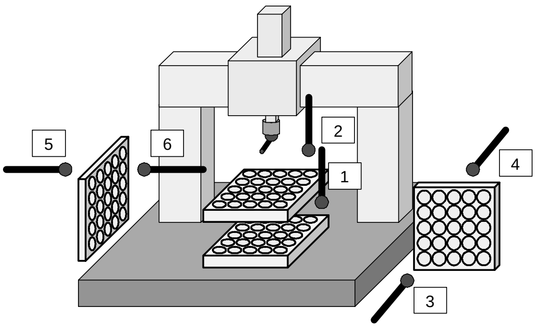


Fig.2 Kinematic and Form-Deviation Calibration Using Ball Plate or Hole Plate

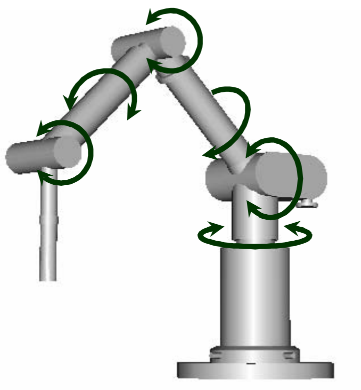


Fig.3 6DOF Articulated Type Robot has 27 Kinematic Parameters

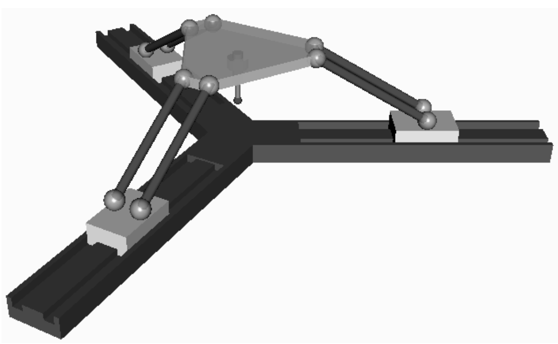


Fig.4 3DOF Parallel Mechanism has 39 Kinematic Parameters

3. Prototype of 3DOF Parallel CMM

Traditional CMMs and machine tools are based on a serial mechanism. However, the drawbacks of the serial mechanisms are their weakness against external force and accumulation of errors. Therefore, we develop a novel type of CMM and a milling machine based on a 3DOF parallel mechanism where the base unit and the end-effecter, i.e. a probing system or a milling tool, are connected by six links. The advantages of the mechanism are its robustness against external force and error accumulation.

However, we found the difficulties of development of parallel mechanism on the accuracy of spherical joints and the method of the absolute calibration. Consequently, we proposed the novel spherical joints and the novel calibration method for 3DOF parallel mechanism and we made experiments for evaluating effects of the novel calibration method.

Table 2 shows the specifications of the prototype of 3DOF parallel CMM, Coordinate Measuring Machine using parallel mechanism and fig. 5 displays the photograph of it. Fig. 6 shows 3DOF parallel milling machine based on the same parallel mechanism [5]. These mechanisms consist of three linear actuators, three linear scales, six connecting links, an end-effecter and twelve spherical joints. All heavy components, the linear actuators and the linear scales, are fixed on the base unit, and the end-effecter can move only X, Y and Z directions and does not rotate. This mechanism has 39 kinematic parameters, so it is very hard task to calibrate the all kinematic parameters precisely.

The end-effecter, connecting links and carriers are connected by the spherical joints using steel balls and magnets shown by fig. 7. This magnetic spherical joint consists of a magnet and a triangle hole and holds the steel ball at three points on its spherical surface kinematicaly. The advantage of the magnetic spherical joint is high repeatability because of no gap between the housing and the ball. Using this joint gives the high repeatability of the position of the end-effecter when we separate all connecting links and end-effecter from the base plate and reset up them when each position of the carriers are not changed (see fig. 8). This means we can choose deferent way of calibration for each component. Therefore, we propose the novel kinemtic calibration method for 3DOF parallel mechanism using the magnetic spherical joints [6].

Table 2 Specifications of Parallel CMM

size	$400 \times 400 \times 250$ mm
measuring range	$170 \times 170 \times 110$ mm
resolution	1 μm
repeatability	2 μm
set/reset accuracy	3 μm

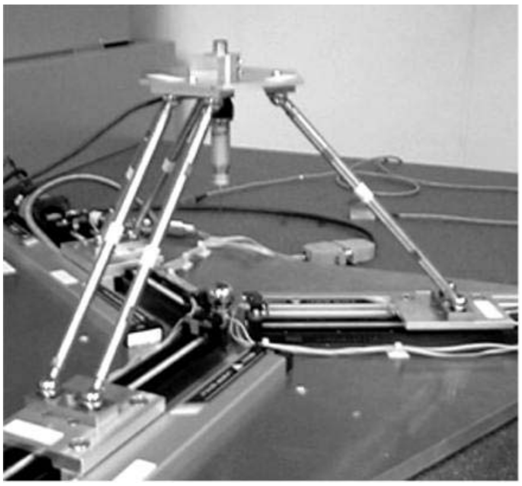


Fig.5 Prototype of Parallel CMM

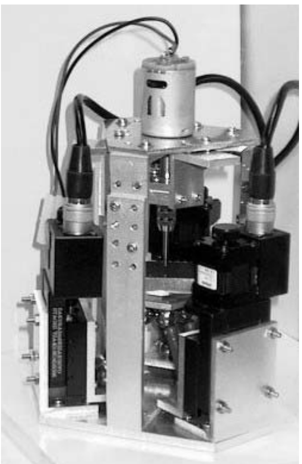
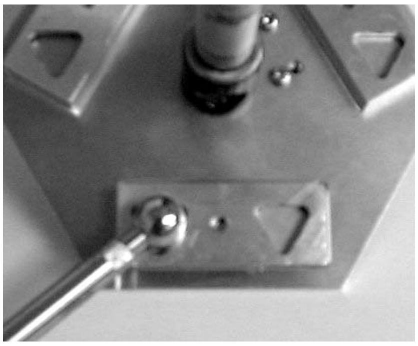
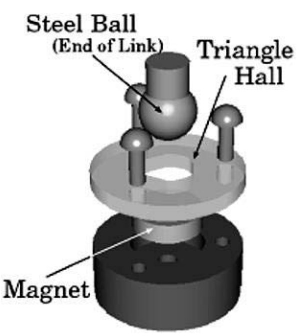


Fig.6 Prototype of Micro Milling Machine

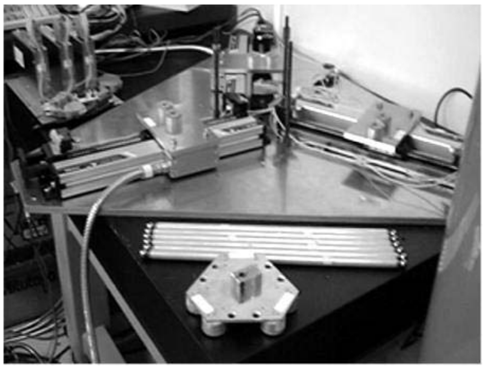


(a) Photograph of Magnetic Spherical Joint

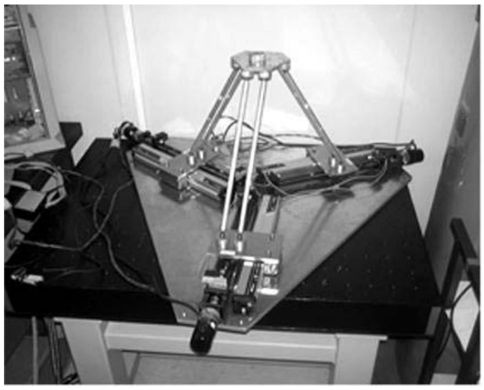


(b) Construction of Magnetic Spherical Joint

Fig.7 Magnetic spherical joint



(a) Separate All Components



(b) Setting up Them Again

Fig.8 Separate All Components and Setting up Them Again

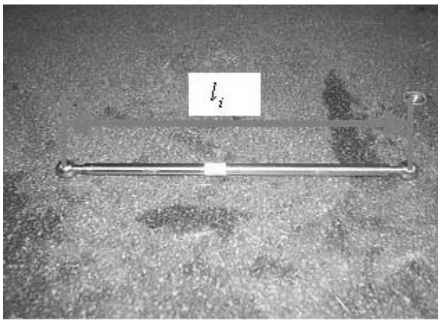
4. Parameter Identification and Calibration of 3DOF Parallel CMM

Table 3 indicates the 39 kinematic parameters for the model of the parallel CMM. When we make a parallel CMM of large size, some parameters can still be identified directly with high accuracy using conventional measuring instruments. Because of using the magnetic spherical joints, we assure that each value of parameters measured by other way does not change after setting up. Therefore, we measured 32 parameters of the end-effecter, connection rods and carriers by the conventional CMM (see fig. 9).

In the other hand, the parameters of linear actuators and linear scales change their values by separating/resetting. And it becomes hard to measure their values directly when the parallel CMM gets larger or regardless of the size of the parallel CMM. Fig. 10 shows the model of the base plate, the arranged position of each actuator, θ_1, θ_2, ϕ, r, and the initial origin of each scale, q_1, q_2, q_3. And those of the base plate are calculated using the result of measuring by the conventional CMM and the signal from each linear scale. We put a steel ball on the end-effecter. Then we move the end-effecter at 64 points in the workspace and measured the centre of the ball by the conventional CMM (see fig. 11). All kinematic parameters and the initial origin of each scales are identified with high accuracy. The result of our experiment, the maximum positioning error after calibration reduced from 500 μm to 7 μm (see fig. 12).

Table 3 List of Kinematic Parameters

part	parameters	symbols	no.
links (6)	lengths	$l_1, l_2, l_3, l_4, l_5, l_6$	6
carriers (11)	heights	$h_{12}, h_{21}, h_{22}, h_{31}, h_{32}$	5
	widths	d_1, d_2, d_3	3
	angles	$\alpha_1, \alpha_2, \alpha_3$	3
end-effecter (15)	positions	$g_1, g_2, g_3, g_4, g_5, g_6$	6
	angles	$\beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \gamma_3, \gamma_4, \gamma_5, \gamma_6$	9
base plate (7)	angles	θ_1, θ_2, ϕ	3
	height	r	1
	carrier offsets	q_1, q_2, q_2	3
total			39



(a) 6 links (6 Parameters)

(c) Carrier (15 Parameters)

(a) End-Effecter (15 Parameters)

Fig.9 32 Parameters for Connection Links, Carrier and End-effecter are Measured by Conventional CMM

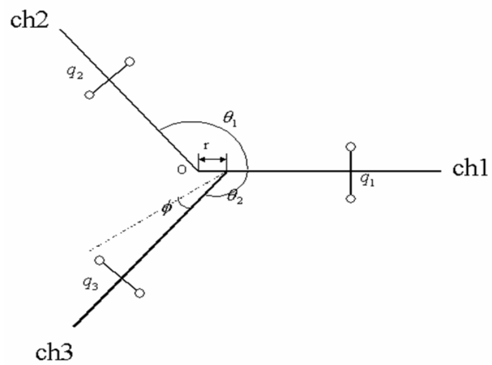


Fig.10 7 Parameters of Base Plate

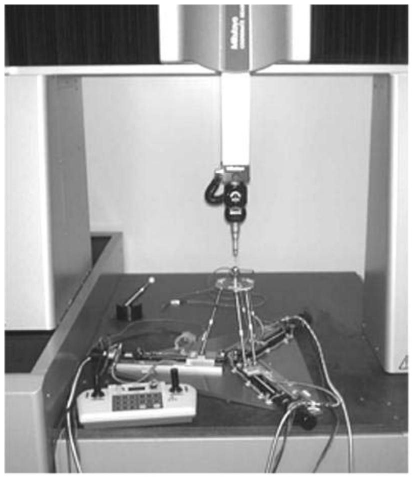
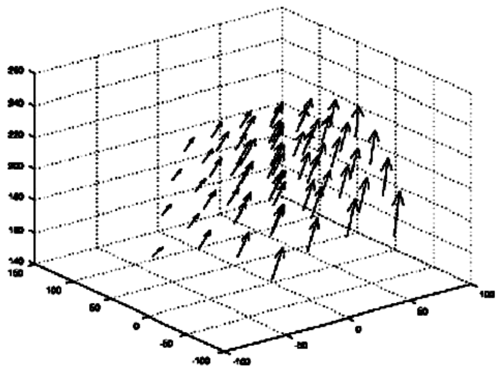
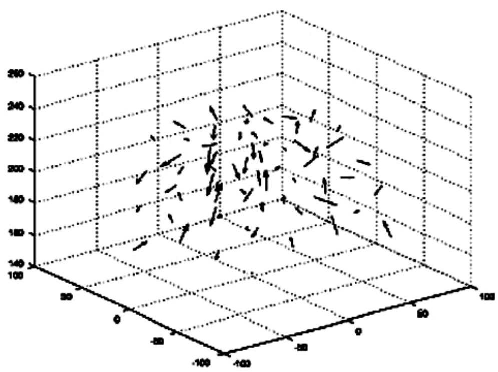


Fig.11 Calibration by Conventional CMM



(a) Before Calibration: Magnifying Power 50



(b) After Calibration: Magnifying Power 3000

Fig.12 Maximum Positional Errors Reduce From 500 μm to 7 μm

5. Conclusion

In this article, the prototype of 3DOF parallel CMM is introduced. Using the magnetic spherical joints, this prototype has the high repeatability of the position of the end-effecter when we separate all connecting rods and end-effecter from the base plate and reset up them. Then we suggested calibrate each component of parallel CMM by each method.

We classified the kinematic parameters of each component depending on the way of parameter identification, and decided each method to calibrate each component. We calibrated the parameters of the end-effecter, the connecting rods and the carriers by measuring directly with the conventional CMM, and the parameters of the base plate by the least squares method. We calibrated our prototype of parallel CMM. The result of our experiment, the maximum positioning error after calibration reduced to 7 μm.

References

[1] M. Abbe, K. Takamasu, S. Ozono: Reliability of Parametric Error on Calibration of CMM, IMEKO-XVI World Congress, 2000, pp. 180-184

[2] Schwenke, H. et al., Assessment of uncertainties in dimensional metrology by Monte Carlo simulation: Proposal of a modular and visual software, Ann. CIRP, Vol. 49/1, 2000, p. 395

[3] R. Furutani, K. Shimojima, K. Takamasu, Parameter Calibration of Articulated CMM, euspen 2002, 2002, pp. 605-608

[4] Merlet, J.-P., Parallel Robots, Kluwer academic publishers, 2000.

[5] O. Sato, M. Hiraki, K. Takamasu, The Calibration of Parallel-CMM: Parallel-Coordinate Measuring Machine, euspen 2002, 2002, pp. 573-576

[6] O. Sato, M. Hiraki, K. Takamasu and S. Ozono: Calibration of 2-DOF parallel mechanism, Initiatives of precision engineering at the beginning of a millennium, Kluwer academic publishers, 2001, pp. 734-738.