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KINEMATICAL CALIBRATION OF ARTICULATED CMM USING MULTIPLE SIMPLE ARTIFACTS

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Abstract – Articulated Coordinate Measuring Machines(CMMs) are widely used to measure a large scale and/or complicated workpiece, as it is very flexible. The kinematical calibration of the articulated CMM is usually performed using some 3D artifacts. However, 3D artifact is too large and difficult to be handled. So, we tried to use a simple artifact several times and to get the equivalent calibration result to 3D artifact. In this paper, the principle of using multiple simple artifacts is presented. The kinematical calibration using some typical simple artifacts and/or the combination of those are simulated. In this simulation, the calibration, which was performed with the ball bar in four different locations and orientations, was equivalent to the calibration with 3D artifact. Finally, the experiment of calibration with the ball bar is performed.

Keywords: kinematical calibration, artifact, articulated CMM.

1. INTRODUCTION

Articulated Coordinate Measuring Machines(CMMs) are widely used to measure a large scale and/or complicated workpiece, as it is very flexible. The kinematical calibration of the articulated CMM is usually performed using some 3D artifacts. However 3D artifacts are normally very large, because they should cover the measuring volume. As the kinematical calibration had better be executed on site, the artifact should be smaller and lighter in consideration on frequently handling it. So we considered using a simple artifact instead of 3D artifact. The simple artifact could cover narrower measuring volume than 3D artifact. Therefore the calibration result with the simple artifact was worse than that with 3D artifact. In order to improve the calibration result, we used a simple artifact in several different locations and orientations. This situation that the simple artifact is used in several different locations and orientations is called the multiple simple artifact. The calibration result with the multiple simple artifact is equivalent to that with 3D artifact in simulation and experiment.

2. MODEL OF ARTICULATED CMM

6R type articulated CMM is a target CMM in this paper, shown in Fig. 1. The model of the articulated CMM is described in DH-notation[1]. Therefore the number of kinematical parameters of the articulated CMM is 21 excluding the redundancy. However, the coordinates of the stylus tip are described in the coordinate system of CMM and the coordinates of the artifacts are described in the coordinate system of the artifact itself. The coordinate system of CMM is generally different from that of the artifact. As a result, the coordinates system of CMM should be transformed to that of the artifact. The additional six parameters, three parameters for translation and three for rotation, should be calibrated as well as the kinematical parameters.

Fig.1 Articulated CMM

3. SIMPLE ARTIFACTS

As the CMM is a measuring machine to measure a discrete point in 3D space, a point is most adequate artifact to the CMM. So the spheres are adopted as the artifact and the center of spheres are reference points. Table 1 shows the simple artifacts in this paper. The artifact (c) consists of three spheres and the freedom of coordinate system is zero. Therefore the kinematical parameters of CMM could be calibrated in the artifact coordinate system including mirror

image coordinate system. But the kinematical parameters of CMM could be calibrated with the artifact (b) excluding the freedom of the rotation around the line connecting two spheres. In the artifact (d), the artifact coordinate system could be fixed on the artifact.

The artifact (a),(b),(c) were used as a simple artifact in simulation. The artifact (d), which has nine spheres, was used as 3D artifact. The artifact (d) is not a simple artifact but a normal artifact like the ball plate, the hole plate and so on . It was used to be compared with the simple artifacts and the multiple simple artifacts.

Table 1 simple artifacts and the freedom of coordinate system of CMM

id	number of sphere(s)	freedom of coordinate system
a	1	3 (orientations)
b	2	1 (orientation)
c	3	0
d	4 or more	0

4. SIMULATION USING A SIMPLE ARTIFACT AND MULTIPLE ARTIFACT

4.1 Condition of Simulation

The measuring volume is 400x400x400. The simple artifacts are shown in Fig.2. The spheres of artifact (b) and (c) are located at the lattice. The pitch of lattice is 200. The coordinates calculated from the model of CMM and the calibrated kinematical parameters are compared with the true coordinates of a point in estimating the calibration result. However this CMM has six rotary axes and each axis has 324000 steps around. It is impossible to measure all points, $(324000)^6$ points. So the calibration result was estimated at the lattices in Fig.2.

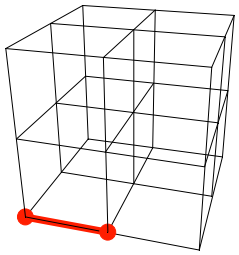
Table 2 Multiple Simple Artifacts

id	No. of (a)	No. of (b)	No. of (c)	No.of (d)	No.of Spheres
A		1			2
B			1		3
C	3		1		6
D		4			8
E	6		1		9
F				1	9
G	3			1	12

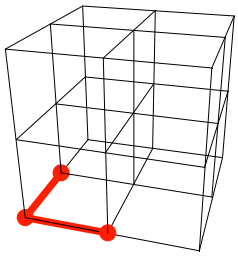
4.2 Multiple Simple Artifacts

The multiple simple artifacts are shown in Table 2. The artifact (A),(B) and (F) are the simple artifacts and are simulated to be compared with the multiple simple artifacts. The artifact (C),(D),(E) and (G) are the multiple simple artifacts. The kinematical parameters could not be calibrated with only the artifact (a).

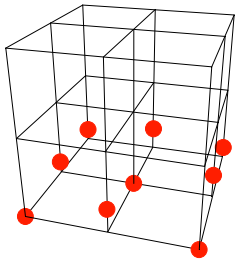
The artifacts (C),(D),(E) and (G) are shown in Fig.3.



a) Artifact (b)

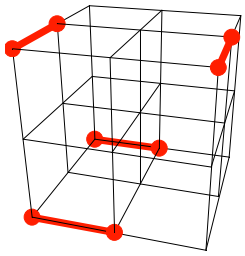


b) Artifact (c)

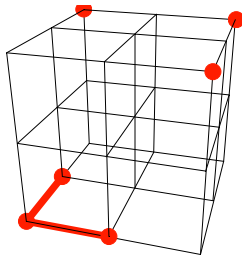


c) Artifact (d)

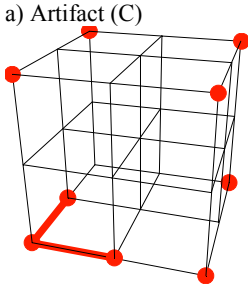
Fig.2 Simple artifacts are located in a measuring volume(400x400x400). The spheres in the artifact (b) and (c) are located at the lattice. The pitch of lattice is 200. The artifact (d) is not a simple artifact. It was used to be compared with a simple artifact.



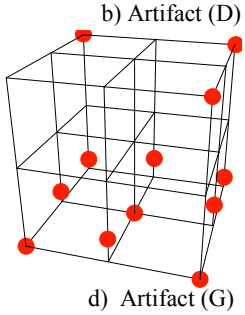
a) Artifact (C)



b) Artifact (D)



c) Artifact (E)



d) Artifact (G)

Fig.3 Multiple simple artifacts

4.3 Procedure

The calibration procedure was simulated in following way.

(1) An artifact was put in the measuring volume.
(2) The central points of all spheres in the artifact were measured several times in different postures of the articulated CMM.
(3) The kinematical parameters and the parameters of coordinate system were simultaneously calculated by Least Squares Method[2].

4.4 Uncertainty

The coordinates of stylus tip of CMM is expressed as (1).

$$\mathbf{x} = \mathbf{f}(\mathbf{p}, \boldsymbol{\theta}, \mathbf{r}) \qquad (1)$$

In (1), $\mathbf{x}$ is the coordinates of stylus tip of CMM, $\mathbf{p}$ is kinematical parameters, $\boldsymbol{\theta}$ is output from the rotary encoder at each joint and $\mathbf{r}$ is the parameters for coordinate transformation. Here, the uncertainty of CMM, u_x is calculated according to (2).

$$u_x^2 = \left(\frac{\partial \mathbf{f}}{\partial \mathbf{p}}\right)^2 u_p^2 + \left(\frac{\partial \mathbf{f}}{\partial \boldsymbol{\theta}}\right)^2 u_\theta^2 + \left(\frac{\partial \mathbf{f}}{\partial \mathbf{r}}\right)^2 u_r^2 \qquad (2)$$

As $\mathbf{r}$ is the parameters to transform the coordinate system of CMM to that of the artifact, $\mathbf{r}$ is not used any more in measuring after calibration. Therefore, (3) is derived neglecting the last term in (2).

$$u_x^2 = \left(\frac{\partial \mathbf{f}}{\partial \mathbf{p}}\right)^2 u_p^2 + \left(\frac{\partial \mathbf{f}}{\partial \boldsymbol{\theta}}\right)^2 u_\theta^2 \qquad (3)$$

u_p is the uncertainty of the calibration of kinematical parameters, u_θ is the uncertainty of the rotary encoders at each joints. u_p could be calculated from the variance-covariance matrix in LSM.

4.5 Simulation Result

The maximal uncertainty in a measuring volume is shown in Table 3. Table 3 showed that the artifact (C),(D),(E),(F) and (G) were better than the artifact (A) and (B). So, the artifact (C) was selected to apply the actual experiment, because it consists of only the same artifacts and measuring spheres are not more than others.

5. EXPERIMENT

5.1 Setup of Artifact and measurement

The actual artifact is shown in Fig.4. Two spheres are fixed on the basement. The distance between two spheres were measured by the more accurate Cartesian type CMM (Falcio Apex 707:MITUTOYO) and its distance is 401.3232mm. The basement of the artifact can be tilted.

The artifact (C) was set up by that the artifact in Fig.4 were put in a measuring volume in four different locations and orientations. The calibration was performed according to the calibration procedure in simulation. At first, every spheres was measured in five different postures of CMM at four locations and orientations of the artifacts. Totally 40 (=5x2x4) points were measured.

5.2 Calibration

The number of kinematical parameters is 21. The number of parameters for coordinate transformation is 20(=5x4) according to Table 1. Totally 41 parameters should be calculated by Least Squares Method. As the coordinates has three values like x,y and z, 40 points means 120 data. Therefore the number of data,120, is larger than the number of parameters, 41, and these parameters can be estimated in principle.

Fig.4 Simple artifact with two spheres. The distance between two spheres is about 400mm. The basement of the spheres can be tilted.

Table 3 Simulation Result

id	Max.of Uncertainty
A	0.496
B	0.072
C	0.034
D	0.030
E	0.029
F	0.034
G	0.029

5.3 Result

The maximal uncertainty was 0.068mm in experiment. It was worse than simulation result. However, the uncertainty was smaller than error of length of the artifact measured by the originally calibrated articulated CMM. Therefore the calibration procedure works well. The difference between simulation and experiment could occur with the stylus's contacting spheres.

6. CONCLUSION

The simple artifacts like 1-sphre, 2-spheres and 3-spheres are selected as the artifact to calibrate the Articulated Coordinate Measuring Machine. The calibration using these simple artifacts is not better than the calibration using a normal ball-plate.

The multiple simple artifact was proposed as the combination of the simple artifacts. Some multiple simple artifacts are simulated to investigate whether the parameters of CMM are calibrated using the multiple simple artifacts. As a result, the multiple simple artifact which consists of four 2-spheres artifacts is best artifact.

According to simulation result, 2-spheres artifact was manufactured. The CMM was calibrated using 2-spheres artifact.

7. FUTURE WORK

In experiment, the actual artifact was used. Only the distance between two spheres were measured by more accurate CMM. If the distance between two spheres is measured incorrectly, the value of parameters related with the length will be also incorrect. But the ratios the value parameters related with the length and the distance between two spheres are correct at any time.

Therefore, the following calibration procedure is considered.

(1) setup the artifact in measuring volume.
(2) Measure the spheres of artifacts
(3) The parameters are calculated from measured data, when the distance between two spheres is equal to one.
(4) After calibration, the distance between two spheres will be measured in most accurate method, e.g. a laser interferometer.

In this method, more accurate calibration will be achieved.

REFERENCES

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