XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6–11, 2009, Lisbon, Portugal

SELF-CALIBRATION OF 2D PLANAR COORDINATE MEASURING MACHINE

Ryoshu Furutani [1]

[1] Tokyo Denki University (School of Engineering), Tokyo, Japan, ryo@cck.dendai.ac.jp

Abstract – It is described how to calibrate the kinematic parameters of a parallel CMMs, in this paper. The artefact which consists of spheres is selected as physical constraints for self-calibration. The kinematic calibration of the parallel CMM is performed using the artefact of two spheres. The parallel CMM can measure a sphere in a lot of different orientations so that a lot of sensor information can be got at the identical location. If the number of sensor information is larger than that of whole parameters, e.g. the kinematic parameters and the orientation and location of stylus, the whole parameters can be self-calibrated without any information of artefacts. Two type of parallel CMMs are considered. The model equation of CMMs and the allocation of spheres are discussed. Finally, best allocations of spheres are proved.

Keywords : Parallel CMM, Self-Calibration, Kinematic Parameters

1. INTRODUCTION

The Coordinate Measuring Machines are widely used for measuring the machine parts. There are some types of CMMs. The first one is the Cartesian CMM. The Cartesian CMM consists of three rams, which corresponds to x-, y- and z-axis. The other type of CMM is the articulating arm. It has more than three movable joints and has more than three degree of freedom in movement. Therefore it can measure same points in a lot of different orientations. This type of CMM is also commercially available. The last one is a parallel type CMM. In this type of CMM the probing system is supported by the parallel mechanism. This type of CMM can also measure same points in a lot of different orientations.

The articulating arm CMM is calibrated using the sphere as the artefact[1]. In the calibration, the centers of spheres are measured in some different orientations, so the number of location of spheres is reduced in the calibration of that less than in calibration of the Cartesian CMM.

In limited condition, the parallel type of CMM can be calibrated by measuring a few centers of spheres in a lot of orientations[2].

In this article, the planar parallel type of CMM is calibrated using two spheres. In one method, the center locations of two spheres are calibrated. In the other method, the center locations of spheres are not known. The results of both methods are compared. It is shown shat the later method has possibility to calibrate the planar CMM.

2. PRINCIPLE

The Cartesian CMM, the articulating arm CMM and the parallel CMM are calibrated by determining the actual values of the kinematic parameters. The articulating arm CMM and the parallel CMM have more degree of freedom than positioning of those in movement. As a result, these CMM can measure the same points in different orientations. When the position of stylus is constrained by the position of the artefact, some joints of these types CMM can be movable using redundant freedom in movement. This point is so different from the Cartesian type CMM, because the Cartesian type CMM has just three degree of freedom in movement.

Therefore, when a point is measured, only one information is taken in the case of the Cartesian type CMM. Meanwhile, a lot of information is taken in the case of the articulating arm CMM and the parallel CMM.

In this article, the artefact, consist of some centers of spheres.

The number of spheres, measurements of each sphere and dispositions of the physical constraints are n_s, n_m and n_d , respectively. The number of the parameters of CMM is n_p . The number of parameters of transformation from coordinate system of physical constraints to world coordinate system is n_t .

When centers of spheres are calibrated in n_c dimensions, the number of equations is $n_c n_s n_m n_d$. The number of parameters is $n_p + n_d n_t$. The parameters could be estimated in the case of

$$n_c n_s n_m n_d \geq n_p + n_d n_t \tag{1}$$

The situation in (1) corresponds the calibration using calibrated artefacts.

Meanwhile, when the centers of spheres are not calibrated, the coordinates of centers of spheres is regarded as zero. Then the number of parameters of transformation from coordinate system of physical constraints to world coordinate system is $n_c n_s$. The parameters could be estimated in the case of

$$n_c n_s n_m n_d \geq n_p + n_d n_c n_s \quad (2)$$

2. MODEL OF 2D PLANAR PALRALLEL CMM

The models of 2D planar parallel CMM are shown in Fig.1 and Fig.2.

In Fig.1, three linear stages are fixed on world coordinate system. The end-effecter is connected with three linear stages with each rigid connecting rod. When the end-effecter moves to some position and rotates around a point of end-effecter, three linear stages moves and their movements are measured. 2D Planar parallel CMM in Fig.1 has 14 kinematic parameters and three parameters of coordinate transformation.

In Fig.2, three fixed points in world coordinate system and the end-effecter is connected with the extract and contract arms. When the end-effecter moves to some position and rotates around a point of end-effecter, three arms extract or contract. Then the lengths extracted or contracted are measured. 2D Planar parallel CMM in Fig.2 has 11 kinematic parameters and three parameters of coordinate transformation.

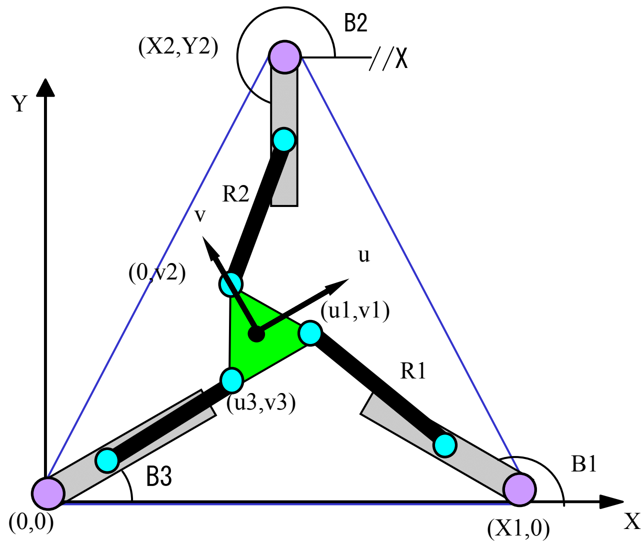

Fig.1. Model of 2D Planar CMM with linear stages

3. ARTEFACTS AND PARAMETERS

In this paper, the artefact consists of two spheres. The number of disposition of the artefact is one.

3.1. Parameters of CMM with linear stages and calibrated artefact

The kinematic parameters in CMM with linear stages consist of the coordinates and directional angle of linear stages, the coordinates of fixed points connected with rods and the length of rods. The number of kinematic parameters is 14. In each measurement of sphere, the angle of the end-effecter is added as the parameter of coordinate transformation. So, the number of parameters of coordinate transformation is $2 + n_m n_d n_s = 2 + 2n_m$. The number of

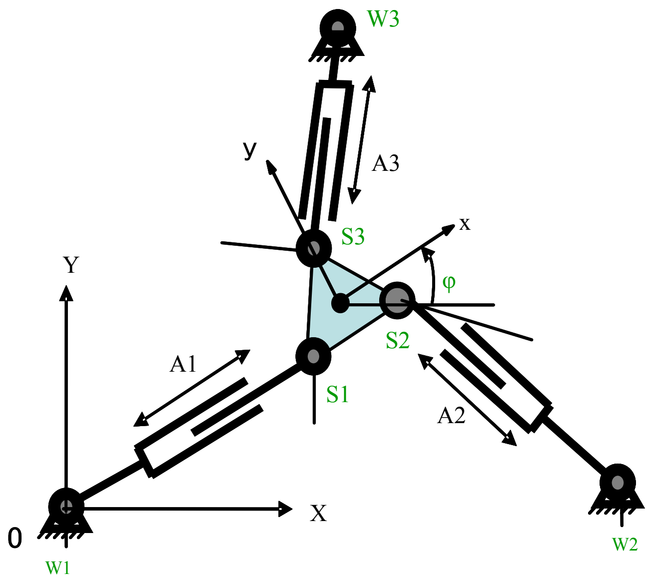

Fig.2. Model of 2D planar CMM with extract and contract arms

equations is $n_c n_s n_m n_d = 4n_m$. From (1), $4n_m \geq 16 + 2n_m$. At each sphere, 8 times measurements are necessary to calibrate the kinematic and coordinate parameters.

3.2. Parameters of CMM with linear stages and not calibrated artefact

In this situation, the number of equation and kinematic parameters is identical to the case of 3.1.

However, the number of parameters of coordinate transformation is different. In this case, the position of the sphere is not calibrated, then the coordinates of the center of spheres are regarded as (0,0). Therefore, the number of parameters of coordinate transform is $n_c n_s n_d + n_m n_d n_s = 4 + 2n_m$. From (2), $4n_m \geq 18 + 2n_m$. At each sphere, 9 times measurements are necessary to calibrate the kinematic and coordinate parameters.

3.3. Parameters of CMM with extract and contract arms and calibrated artefact

The kinematic parameters in CMM with extract and contract arms consist of the coordinates of the fixed points of the basement, the coordinates of fixed points connected with arms and the initial length of arms. The number of kinematic parameters is 11. In each measurement of sphere, the angle of the end-effecter is added as the parameter of coordinate transformation. So, the number of parameters of coordinate transformation is $2 + n_m n_d n_s = 2 + 2n_m$. The number of equations is $n_c n_s n_m n_d = 4n_m$. From (1), $4n_m \geq 13 + 2n_m$. At each sphere, 7 times measurements are necessary to calibrate the kinematic and coordinate parameters.

3.4. Parameters of CMM with extract and contract arms and not calibrated artefact

In this situation, the number of equation and kinematic parameters is identical to the case of 3.3. The number of parameters of coordinate transformation is identical to 3.2.

Therefore, from (2), $4n_m \geq 15 + 2n_m$. At each sphere, 8 times measurements are necessary to calibrate the kinematic and coordinate parameters.

4. SIMULATIONS

4.1. Procedure

At first, the kinematic parameters are determined. The sphere is settled at nine calibrated locations in measuring area. Then, the coordinates of 9 spheres are measured in some different orientations of CMM and probe.

At second, two spheres are extracted as the artefacts from nine spheres. So, ${}_9C_2(=36)$ artefacts are generated. The sensor data of selected spheres are also extracted for calibration measurement. These data are called as calibration data. The other data are used for estimation of calibration result. These data are called as reference data.

At third, the kinematic parameters and coordinate parameters are estimated by least-squared method using the calibration data. The locations of all spheres are calculated using the estimated kinematic parameters and sensor data. The difference between the calculated location of spheres and calibrated location of those shows how the kinematic parameters are calibrated.

4.2. Condition

In this paper, there are three fixed points in basement. They are expressed as (0,0),(15,0) and (7.5,13) in world coordinate system. There are three points in the end-effecter. They are expressed as (-1.5, $\sqrt{3}/2$),(1.5, $\sqrt{3}/2$) and (0, $\sqrt{3}$) in the end-effecter coordinate system. The probing point is (0,0) in the end-effecter coordinate system.

CMM in Fig.1 has three rod length, (7,7,7) as the additional parameters and three directional angles of linear stages, (30,150,-90), to x-axis in world coordinate system.

4.3. Estimation of kinematic parameters with calibrated artefacts

In this case, as the position of the spheres in the artefact is calibrated, the kinematic parameters are calibrated based on the calibrated coordinates, $\mathbf{a}_i$, which are calibrated in the artefact coordinate system.

When the matrix transforming the artefact coordinate system to world coordinate system is $\mathbf{T}_{AW}$, the rotational matrix around probing point is $\mathbf{R}(\varphi_{i,j})$ and the coordinates of the joints of the end-effecter is $\mathbf{u}_k$, the coordinates of the joints of the end-effecter, $\mathbf{U}_{i,j,k}$, is expressed as (3) in world coordinate system. The j means j-th measurement result.

$$\mathbf{U}_{i,j,k} = \mathbf{R}(\varphi_{i,j})\mathbf{u}_k + \mathbf{T}_{AW}\mathbf{a}_i \tag{3}$$

In the case of CMM with linear stages, when the fixed point of the linear stages is $\mathbf{x}_k$, the directional angle of linear stages is θ_k and the sensor information is $s_{i,j,k}$. The points on stages, $\mathbf{X}_{j,j,k}$, is expressed as (4) in the world coordinate system.

$$\mathbf{X}_{i,j,k} = \mathbf{x}_k + \mathbf{R}(\theta_k)\begin{pmatrix} s_{i,j,k} \\ 0 \\ 1 \end{pmatrix} \tag{4}$$

$$\left|\mathbf{U}_{i,j,k} - \mathbf{X}_{i,j,k}\right| = L_k \tag{5}$$

From (5), the kinematic parameters could be estimated using least-squared method.

In the case of CMM with extract and contract arms, the distance between joints is $s_{i,j,k} + \ell_k$, ℓ_k is the offset of sensor.

$$\left|\mathbf{U}_{i,j,k} - \mathbf{x}_k\right| = s_{i,j,k} + \ell_k \tag{6}$$

From (6), the kinematic parameters could be estimated using least-squared method.

4.4. Estimation of kinematic parameters with not calibrated artefacts

In this case, as the position of the spheres in the artefact is not calibrated, the calibrated coordinates of sphere is regarded as $\mathbf{0}$ in the artefact coordinate system, and the vector transforming the artefact coordinate system to world coordinate system is $\mathbf{V}_i$.

From (3), the coordinates of the joints of the end-effecter, $\mathbf{U}_{i,j,k}$ is expressed as (3)'.

$$\mathbf{U}_{i,j,k} = \mathbf{R}(\varphi_{i,j})\mathbf{u}_k + \mathbf{V}_i \tag{3'}$$

The other equations are similar to those in 4.3. The kinematic parameters could be also estimated using least-squared method.

4.5. Results

Fig.3 shows the example of result, in which the planar CMM with extract and contract arms is kinematically calibrated with the calibrated artefacts. From Fig.3, it is proved that when the artefact is settled at whiter area,

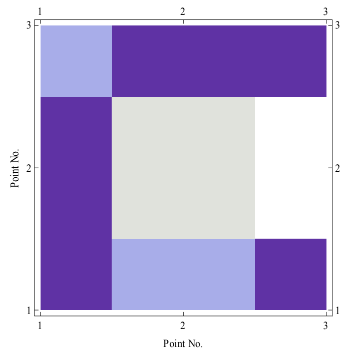

Fig.3 calibration result with two sphere artefact

CMM is successfully calibrated.

5. POSITION OF ARTEFACT

In 4., it is proved that 2D parallel CMM is kinematically calibrated. In order to investigate which location is better for self-calibration, two locations of the artefact are selected from Fig.4.

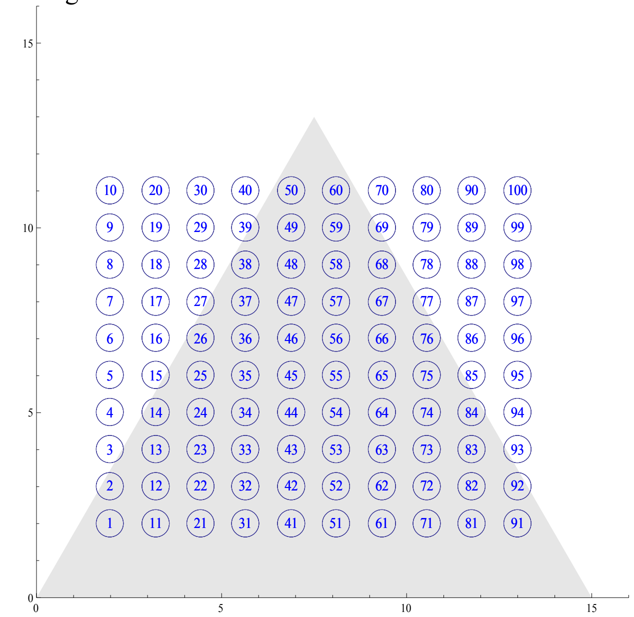

Fig.4 candidates of sphere artefact

Fig.5 shows which combinations of two spheres work as the artefact, s.g., the kinematic parameters of 2D parallel CMM is calibrated successfully. When two locations are selected in upper-right area, the kinematic parameters are not calibrated.

In order to avoid that two locations are near, the candidates of locations are divided into two groups as shown in Fig.6.

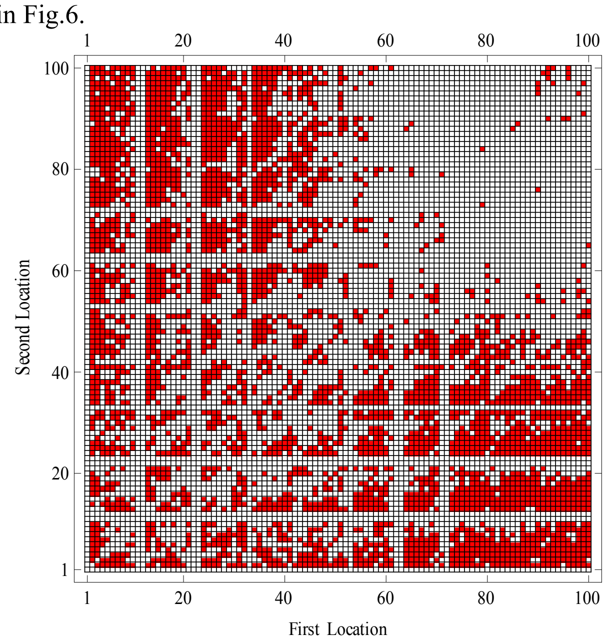

Fig.5 Result of kinematic calibration

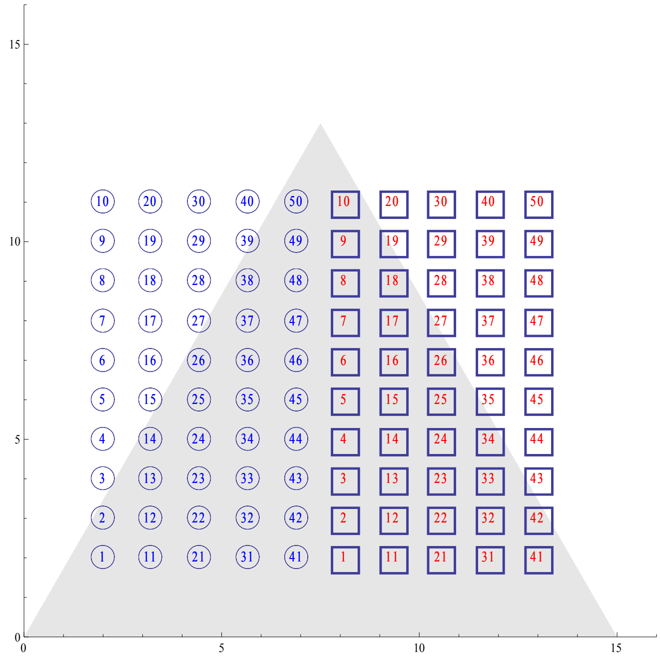

Fig.6 Candidates of sphere artefact

Fig.7 shows which combination of two spheres work as the artefact as shown in Fig.5.

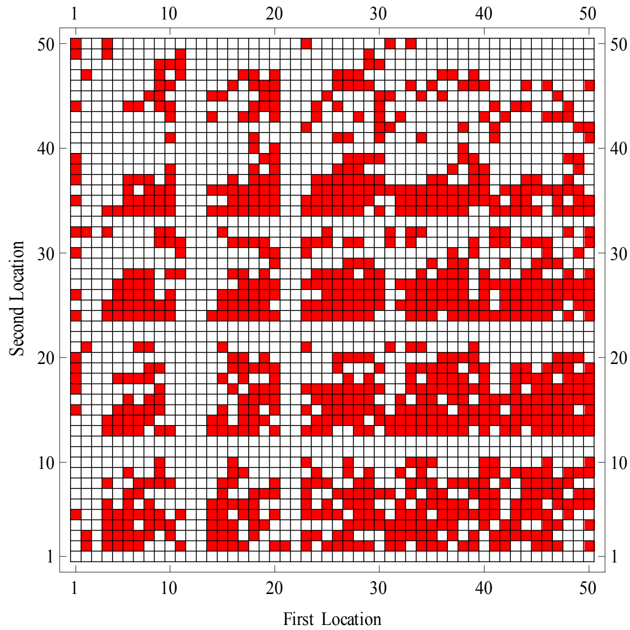

Fig.7 Result of kinematic calibration

6. CONCLUSIONS

2D parallel CMMs are considered. The model of 2D parallel CMM, the artefact and calibration process are discussed.

In 2D parallel CMM, especially, two types of CMMs are handled. One is CMM with linear stages and the other is CMM with extract and contract arms. In both cases, the calibrated artefact and not calibrated artefact are formalized.

In the combination of two types of parallel CMMs and two types of artefacts, the kinematic calibration process is simulated.

It is proved from a series of simulation how dependent the allocations of spheres are on the CMM types and the artefacts.

REFERENCES

[1] R. Furutani, K. Shimojima and K. Takamasu, “Parameter Calibration for Non-Cartesian CMM”, VDI Berichte, 8th ISMQC, pp.317-326, Erlangen, Germany, Sept. 2004

[2] R. Furutani, “Self-Calibration of 2D Parallel CMM”, 7th Coordinate Measuring Technique, pp.75-80, Bielsko-Biela, Poland, Apr. 2006

[3] Zhuang,H.:Self-Calibration of Parallel Mechanisms with a Case Study on Stewart Platforms,IEEE Trans. Robotics and Automation, 13(3),pp.387-397,1997

[4] K.Takamasu, K. Sato, O. Chanin, S. Shimojima and R. Furutani, “Artefact Calibration of Coordinate Measuring Machine(2nd Report)-Self Calibration of Redundant Coordinate Measuring Machine-“, Journal of JSPE,70(5), pp.711-715,2004,in Japanese

[5] O. Sato, K. Shimojima, R. Furutani and K.Takamasu, “Artefact calibration of parallel mechanism, kinematic calibration with a priori knowledge”, Measurement Science and Technology, 15,pp.1158-1165, 2004

[6] K. Takamasu, R. Furutani, K. Shimojima and O. Sato,”Artefact Calibration of Coordinate Measuring Machine-Kinematic Calibration-“,Journal of JSPE, 69(6), pp.851-855, 2003, in Japanese

[7] R. Furutani, K. Shimojima and K. Takamasu,”Kinematical calibration of Articulated CMM using multiple Simple Artifacts”, IMEKO World Congress XVII,CD-ROM, Dubrobnik, Croatia, June 2003

[8] Y.J. Chiu and M.H. Perng,”Self-calibration of a general hexpod manipulator using cylinder constraints”, Machine Tools and Manufacture, 43,pp.1051-1066, 2003