ADAPTIVE CALIBRATION OF COORDINATE MEASURING MACHINE USING ARTIFACT

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Abstract - The calibration of the coordinate measuring machines is performed based on the mathematical model of those machine. The feature of the artifact is measured by CMM, the kinematic parameters are determined by comparing the estimated coordinates and the calibrated coordinates. However, it is assumed that the CMM is rigid and stable in any orientations and locations. Actually the CMM is not rigid and not stable. It is proposed that the model equation, the kinematic parameters and the estimators are replaced with the neural network. The calibration method using the neural network is called the adaptive calibration. The neural network studied the relationship between the inputs and the coordinates successfully. In this article, the example of the articulated arm coordinate measuring machine is shown.

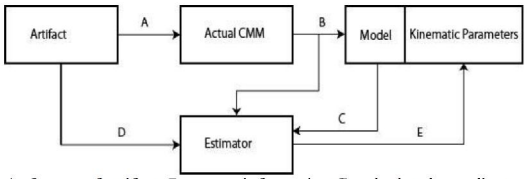
Keywords - Calibration, Kinematic Calibration, Adaptive calibration, Neural Network, Artifact, Coordinate Measuring Machine, Kinematic Parameters

I. INTRODUCTION

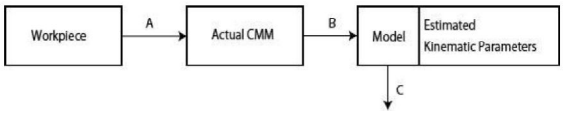
The research of the calibration and test method of the coordinate measuring machines are focused on the Cartesian type coordinate measuring machines [1]-[6].After that, because the accuracy of the articulated arm coordinate measuring machines are improved and are widely used in the manufacturing site, the calibration method and test method of the articulated arm coordinate measuring machines are studied [7]-[10]. At last, because the parallel mechanism is known to be with high positioning accuracy and high rigidity, the coordinate measuring machine based on the parallel mechanism was developed, which is called the parallel coordinate measuring machine. The Cartesian coordinate measuring machines has the Cartesian coordinate system as nature. However the articulated arm coordinate measuring machine is not based on the Cartesian coordinate system, so the geometric errors of the articulate arm coordinate system are more complicated than those of the Cartesian coordinate system. The parallel coordinate system is much complicated and it is not based on the natural coordinate system. So the geometric errors of the parallel coordinate measuring machine are more complicated than those of the Cartesian and the articulated arm coordinate measuring machine.

In this article, the calibration process using the artifact is discussed about the general coordinate measuring machines. The kinematic models are shown and it is explained how to determine the kinematic parameters.

In order to improve the accuracy of the coordinate measuring machine, the model equation of the coordinate measuring machine gets much more complicated. So it is proposed that the model equation, the kinematic parameters and the estimator of the kinematic parameters are replaced with the neural network estimator of kinematic parameters in this article.



A: feature of artifact, B: sensor information C: calculated coordinates
D: calibrated coordinates E: estimated kinematic parameters
(a) Diagram of estimation of kinematic parameters using artefact



A: feature of workpiece B:sensor information C: calculated coordinates
(b) Diagram of measurement using estimated kinematic parameters

Fig. 1 Usual calibration and measurement

II. USUAL CALIBRATION AND MEASUREMENT

The calibration process of the coordinate measuring machines is shown in Fig.1(a). The actual CMM measures the coordinates of the feature of the artifact and the sensor information is detected by the actual CMM. The coordinates are temporally calculated using the model of the coordinate measuring machine and the estimated kinematic parameters. In the estimator, the temporally calculated coordinates are compared with the calibrated coordinates and the kinematic parameters are estimated. This estimated kinematic parameters are used with the model of the coordinate measuring machine as shown in Fig.1 (b).

The measurement process is shown in Fig.1(b). The coordinate measuring machines are used to measure the coordinates of the workpiece. In measurement process, the actual CMM measures the coordinates of the feature of the workpiece and the sensor information is detected by the actual CMM. The coordinates are calculated using the model of the

coordinate measuring machine and the estimated kinematic parameters.

It is necessary that the model and the kinematic parameters are clearly separated and defined in the measurement system based on the usual calibration using the artifact as shown in Fig.1.

The examples show how the models and kinematic parameters of the Cartesian coordinate measuring machine, the articulate arm coordinate measuring machine, and the parallel coordinate measuring machine are defined.

A. Cartesian Coordinate Measuring Machine

The example of the Cartesian coordinate measuring machine is shown in Fig.2 [6]. In this case, the squareness errors between machine axes and the scale errors of axes are calibrated as the kinematic parameters. XYZ coordinate system is the coordinate system of CMM, i.e. three axes aren't orthogonal and their unit length are not identical because of scale errors and the squareness errors. These two coordinate systems have relationship expressed by Eq. (1). Where $\mathbf{T}$ is matrix that components are basis of XYZ coordinate system, it describes squareness error. These angle parameters, θx , θy , θz , αx , αy and αz , are defined in Fig.2. The squareness errorsare calculated by inner product of $\mathbf{T}$'s each column. $\mathbf{K}$ is the diagonal matrix of which components are scale error of each axis, it describes scale error.

$$\hat{\mathbf{x}} = \mathbf{xTK} \tag{1}$$

$$\mathbf{T} = \begin{pmatrix} Cos\theta x & Cos\alpha y Sin\theta y & -Sin\alpha z Sin\theta z \\ -Sin\alpha x Sin\theta x & Cos\theta y & Cos\alpha z Sin\theta z \\ Cos\alpha x Sin\theta x & -Sin\alpha y Sin\theta y & Cos\theta z \end{pmatrix} \tag{2}$$

$$\mathbf{K} = \begin{pmatrix} kx & 0 & 0 \\ 0 & ky & 0 \\ 0 & 0 & kz \end{pmatrix} \tag{3}$$

These equations and parameters are the model and the kinematic parameters as shown in Fig.1. The estimator is described as Eq.(4).

$$f_i = \sqrt{\left(\hat{\mathbf{x}}_j - \hat{\mathbf{x}}_k\right)\cdot\left(\hat{\mathbf{x}}_j - \hat{\mathbf{x}}_k\right)} - L_{j,k} \tag{4}$$

,where $\hat{\mathbf{x}}$ is defined in Eq. (5)

$$\hat{\mathbf{x}} = \mathbf{x}\left(\mathbf{TK}\right)^{-1} \tag{5}$$

L_{jk} is the calibrated length of the artifact.

B. Articulated arm Coordinate Measuring Machine

The model equation of the articulated arm coordinate measuring machine with 6 rotational joints are shown as Eq.(6).

$$^{i-1}A_i = \begin{pmatrix} \cos\theta_i & -\sin\theta_i \cos\alpha_i & \sin\theta_i \sin\alpha_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_i & -\cos\theta_i \sin\alpha_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{6}$$

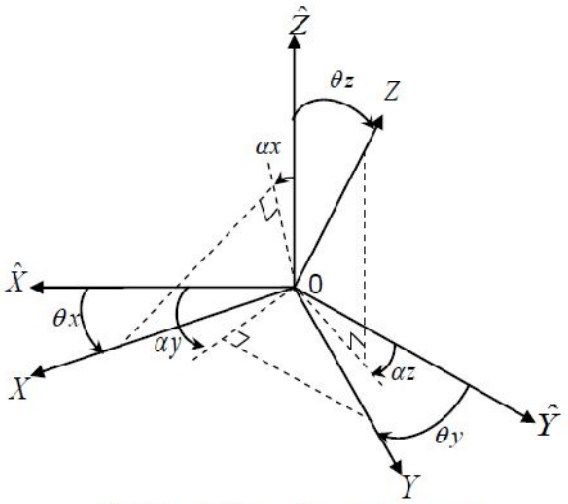


Fig. 2Schematic diagram of two coordinate system

Location and attitude of end of the articulated arm coordinate measuring machine is described in Eq. (7).

$$T = {}^0A_1\,{}^1A_2\,{}^2A_3\,{}^3A_4\,{}^4A_5\,{}^5A_6 \tag{7}$$

The kinematic parameters are described as $(\theta_i, d_i, a_i, \alpha_i)$.It is assumed that the arms of the articulated arm coordinate measuring machine are not deformed. In order to improve the accuracy of the articulated arm coordinate measuring machine, the measuring posture of that is taken into consideration. The arm of the articulated coordinate measuring machine is assumed as cantilever, and each arm has weight and has the deformation by the weight itself as shown in Fig.3 [10].

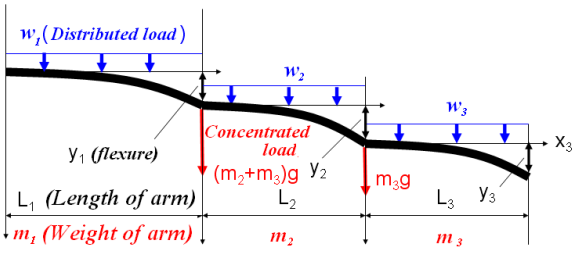


Fig. 3Model of deformation of arm as cantilever

The deformation of the arm is introduced into the kinematic parameters as the deviation of those.

C. Parallel Coordinate Measuring Machine

As the parallel mechanism is complicated, 2D planar coordinate measuring machine as shown in Fig.4 is considered as the example of the parallel coordinate measuring machine.

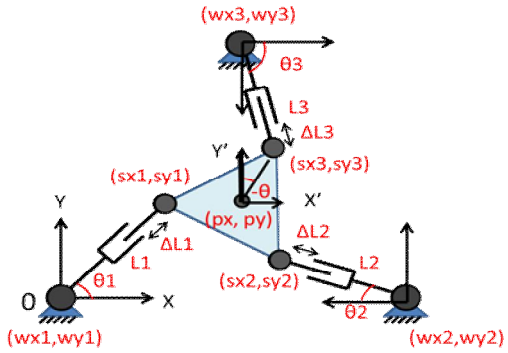


Fig. 4Model of 2D planar coordinate measuring machine

The model equations are built based on the kinematics of the parallel mechanism. The equation is shown as Eq. (8)

$$\sqrt{(wxi - uxi)^2 + (wyi - uyi)^2} = Li + \Delta Li \qquad (8)$$

where uxi and uyi are the coordinates of the vertex of triangle stage represented in the world coordinate system.

In this coordinate measuring machine, the sensor information is the length deviation □Li and the kinematic parameters are the base coordinates (wxi,wyi), the vertex of the platform (sxi, syi) and stylus coordinates (px,py).

The estimator is described as Eq.(8).
It is assumed that the joints of the parallel coordinate measuring machine is not deformed. However, it is proved that the triangle is always stressed by three arms from the structure of the movement. So the deformation of the triangle and joints should be taken into consideration [16].

III. ADAPTIVE CALIBRATION AND MEASUREMENT

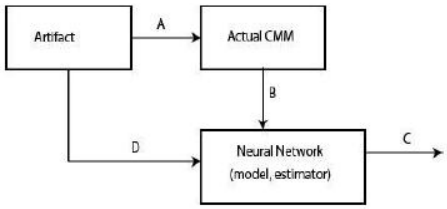
As the behaviour of the coordinate measuring machine is complicated, it is difficult to express the model of the coordinate measuring machine as the physical model and mathematical equation.

The Cartesian coordinate measuring machine and the articulated arm coordinate measuring machine could be expressed as some equations divided into some regions, e.g. spline functions.

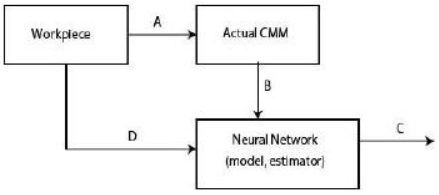
However, in the parallel coordinate measuring machine as shown in Fig. 4, the triangle stage and the arms are not rigid and the deformation of those should be considered.

In the calibration, the model equations, the kinematic parameters and the estimators as shown in Fig.1(a) are replaced with the neural network as shown in Fig.5(a). The calibration method using the neural network is feasible and flexible. So it is called the adaptive calibration.
The neural network studies the relationship between the sensor information and the calibrated coordinates of the artifact. The neural network could express some equations divided into some regions in the case of the Cartesian coordinate measuring machines and the articulated arm coordinate machines. In the case of the parallel coordinate machines, the neural network could express the equation including the deformation of the stage and the arms.

In measurement, the model equation and the kinematic parameters as shown in Fig.1(b) are also replace with the neural network as shown in Fig.5(b). In Fig.5, the neural network studies in the adaptive calibration and it does not study in the measurement.



A: feature of artifact, B: sensor information C: calculated coordinates
D: calibrated coordinates
(a) Kinematic parameters are estimated adaptively using artifact.



A: feature of workpiece B:sensor information C: calculated coordinates
(b) Coordinates are calculated using adaptively estimated kinematic parameters.

Fig. 5 Adaptive calibration and measurement

IV. SIMULATION

In computer simulation, the adaptive calibration is tested about the articulated arm coordinate measuring machine. The articulated arm coordinate measuring machine has 6 rotary axes. The relationship between the neighbouring axes are expressed by DH-notation as similar to [8]-[9].

A. Direct Estimation

The coordinates of stylus are calculated using the model equation, the ideal kinematic parameters and 6 set of angles of the rotary axes. When the neural network studied a lot of the relationship between the coordinates of stylus and the angles, the neural network could not successfully study.
At this simulation, the 6 angle inputs equivalent to the rotary axes, the three hidden layers with 100 nodes and 3 coordinates equivalent to the coordinates of stylus are used.100 000 sets of the relationship between the input and the coordinates.

B. KINEMATIC MODEL

The relationship between the rotary axes and the coordinates is expressed the model equation using DH notation. The kinematic parameters vary in the orientation and the location of the arms. The neural network studies the relationship between the angles of the rotary axes and the kinematic parameters.
In this case, the neural network could successfully study the kinematic parameters.

CONCLUSION

In order to express the complicated model of the coordinate measuring machine, the adaptive calibration is proposed. The adaptive calibration is that the model equation, the kinematic parameters and the estimators are replaced with the neural network.
In simulation of the articulated arm coordinate measuring machine, some constructions of neural network are tested.
At this moment, the direct estimation of the relationship between the angles of the rotary axes and the coordinates of stylus is difficult. It might be necessary to be large scale neural network to express these direct relationship. In the combination of kinematic model equation and the kinematic parameters, the neural network studied the relationship between the angles of the rotary axes and the coordinates.

REFERENCES

[1] H.Schewenke, W.Knapp, H. Haitjema, A.Weckenmann, R. Schmitt, F. Delbressine, Geometric error measurement and compensation of machines – an update, CIRP Annals-Manufacturing Technology, 57, 2008, pp.660-675

[2] T.Ohnishi, S.Takase and K.Takamasu, Study of Improvement mechods of CMM (Coordinate Measuring Machine) in Workshop Environment – Correction of Squareness Error-, Journal of JSPE, 73(7), 2007, pp.818-822

[3] J.S.Agaplou and H.Du, Asuring the Day to –Day Accuracy of Coordinate Measuring Machines – A Comparison of Tools and Procedures, Journal of Manufacturing Process, 9(2),2007,pp.109-120

[4] E.Curran and P.Phelan, Quick check error verification of coordinate measuring machines, Journal of Materials Processing Technology, Vol. 5648, 2004, pp.1207-1212

[5] B.Bringmann and A. Kung, A measuring artefact for true 3D Machine Testing and Calibration, CIRP Annals-Manufacturing Technology, 54(1), 2005, pp.471-474

[6] Y.Asano, R.Furutani and M.Ozaki, Verification of Interim Check Method of CMM, International Journal of Automation and Technology, 5(2), 2011, Au5-2-4609S

[7] J. Santolaria, J.A. Yague, R.Jimenez and J.J. Aguilar, Calibration-based thermal error model for articulated arm coordinate measuring machines, Journal of the international societies for Precision Engineering and Nanotechnology, 33, 2009, pp.476-485

[8] K.Takamasu, R.Furutani, K.Shimojima and S.Ozono, Artifact calibration of coordinate measuring machine, Journal of JSPE, 69(6), 2003, pp.851-855

[9] K.Shimojima, R.Furutani, S.Ozono, M.Hiraki and K.Araki, The estimation method of uncertainty of coordinate measuring machine(1st Report), Journal of JSPE, 70(9), 2004, pp.841-845

[10] H.Hamana, M.Tominaga, M.Ozaki and R.Furutani, Calibration of Articulated Arm Coordinate Measuring Machine Considering Measuring Posture, International Journal of Automation and Technology, 5(2), 2011, Au5-2-4610

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

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

[13] 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, 2004, pp.1158-1165

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

[15] R.Furutani and M.Ozaki,Uncertainty of Calibration of 2D Planar Coordinate Measuring Machine, Measurement,45, 2012, pp.427-430

[16] R.Furutani and M.Ozaki, Calibration and Verification of Small Parallel Coordinate Measuring Machine, Proceedings of 7th International Metrology Conference (CAFMET 2018), 2018.

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