자가 보정을 이용한 삼차원 측정기의 계통오차 계산

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Self-calibration in 3-dimensional for CMM calibration

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1. Introduction

The metrological concept of self-calibration has its base on the succinct geometrical rule that measurement results of a same artifact should be congruent regardless of its position and orientation within a measuring machine. The congruency between multiple views of measurements of an artifact allows discriminating between the machine error and the artifact error, permitting calibration to be performed without being affected by the imprecision of the artifact. Self-calibration is particularly useful when one attempts to test high precision machines or measuring instruments for which no certified artifacts are available because of practical reasons such as fabrication cost and technical difficulty.

The well-known reversal principles for testing mechanical squares and spindles are examples of 1-D self-calibration [1]. Recently, the idea of self-calibration was successfully applied to the motion accuracy testing of 2-D stages[2,3]. Out-of-plane motions errors of a precision surface profile measuring machine were shown to be also handled, which may be referred to as $2^1/_2$-D self-calibration [4]. To our knowledge, no attempt has been made to achieve 3-D self-calibration yet. The algorithm proposed in this paper aims to provide a complete solution for 3-D self-calibration, which is particularly useful for testing coordinate measuring machines.

2. 3-D algorithm of self-calibration

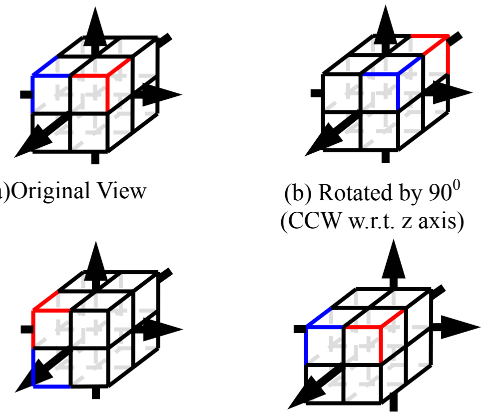
The self-calibration algorithm described hereafter seeks to determine the machine errors for the discrete grid points designated on the artifact. Then inter- and extrapolation of the discrete errors leads to the construction of a full 3-D error map over the entire operation range of the machine under test. Accordingly, the volumetric machine error of a CMM is described by use of the error function of $\mathbf{G}_{i,j,k}$, with subscripts i, j, and k indicating the location of (x_i, y_j, z_k). Similarly, the error function of the artifact is denoted as $\mathbf{A}_{i,j,k}$. The artifact is assumed to provide a 3-D set of grid points equally spaced with an interval of Δ. The subscripts i, j, and k are the integer numbers ranging from $-(N-1)/2$ to $(N-1)/2$, respectively. The origin of (x_i, y_j, z_k) is located at the centre site of the grid points by selecting N to be an odd number.

The measured deviation for mark (i, j, k) from its nominal position in the CMM machine coordinate system is a superposition of three major contributions:

$$\mathbf{V}_{i,j,k} = \mathbf{G}_{i,j,k} + \mathbf{A}_{i,j,k} + \mathbf{E}_{i,j,k} \qquad (1)$$

The last term $\mathbf{E}_{i,j,k}$ represents the misalignment error of the artifact with respect to the xyz-coordinates system of the CMM.

3-D self-calibration is based on the geometrical congruence of the four multiple measurement results with different views as illustrated in Figure 1; (a) View 1 is the initial view, (b) View 2 is for the artifact rotated counterclockwise 90^0 about the z axis, (c) View 3 is for the artifact rotated counterclockwise 90^0 about the x axis, and finally (d) View 4 is for the artifact translated along the +x axis direction by one sample site interval of Δ.



(a)Original View

(b) Rotated by 90^0 (CCW w.r.t. z axis)

(c) Rotated by 90^0 (CCW w.r.t. x axis)

(d) Shift +Δ (along x axis)

Figure 1: Four artifact views for self-calibration.

For each view, the measurement data sets are expressed as:

View 1:
$$\begin{aligned} V_{1,x,i,j,k} &= G_{x,i,j,k} + A_{x,i,j,k} + E_{1,x,i,j,k} \\ V_{1,y,i,j,k} &= G_{y,i,j,k} + A_{y,i,j,k} + E_{1,y,i,j,k} \\ V_{1,z,i,j,k} &= G_{z,i,j,k} + A_{z,i,j,k} + E_{1,z,i,j,k} \end{aligned} \qquad (2)$$

View 2:
$$\begin{aligned} V_{2,x,i,j,k} &= G_{x,-j,i,k} - A_{y,i,j,k} + E_{2,x,i,j,k} \\ V_{2,y,i,j,k} &= G_{y,-j,i,k} + A_{x,i,j,k} + E_{2,y,i,j,k} \\ V_{2,z,i,j,k} &= G_{z,-j,i,k} + A_{z,i,j,k} + E_{2,z,i,j,k} \end{aligned} \qquad (3)$$

View 3:
$$\begin{aligned} V_{3,x,i,j,k} &= G_{x,i,-k,j} + A_{x,i,j,k} + E_{3,x,i,j,k} \\ V_{3,y,i,j,k} &= G_{y,i,-k,j} - A_{z,i,j,k} + E_{3,y,i,j,k} \\ V_{3,z,i,j,k} &= G_{z,i,-k,j} + A_{y,i,j,k} + E_{3,z,i,j,k} \end{aligned} \qquad (4)$$

where $-\frac{N-1}{2} \le i, j, k \le \frac{N-1}{2}$, and

View 4:
$$\begin{aligned} V_{4,x,i,j,k} &= G_{x,i+1,j,k} + A_{x,i,j,k} + E_{4,x,i,j,k} \\ V_{4,y,i,j,k} &= G_{y,i+1,j,k} + A_{y,i,j,k} + E_{4,y,i,j,k} \\ V_{4,z,i,j,k} &= G_{z,i+1,j,k} + A_{z,i,j,k} + E_{4,z,i,j,k} \end{aligned} \qquad (5)$$

where $-\frac{N-1}{2} \le i \le \frac{N-1}{2} - 1, \quad -\frac{N-1}{2} \le j, k \le \frac{N-1}{2} - 1$

The first subscripts 1, 2, 3, and 4 represent the view order, and note that the subscripts (i, j, k) indicating the grid position within the artifact remains unchanged for all the views.

The first step of the self-calibration procedure is to determine the alignment error $\mathbf{E}_{i,j,k}$ in View 1, View 2 and View 3. Since there is no translation and rotation of $\mathbf{G}_{i,j,k}$ and $\mathbf{A}_{i,j,k}$, it is possible to calculate the rigid-body misalignment components of the mounting error as explained in detail in [5].

After elimination the mounting error in View 1 (and similar in View 2 and View 3), the measurement data are be rearranged as:

$$U_{1,x,i,j,k} = V_{1,x,i,j,k} - E_{1,x,i,j,k} = G_{x,i,j,k} + A_{x,i,j,k}$$
$$U_{1,y,i,j,k} = V_{1,y,i,j,k} - E_{1,y,i,j,k} = G_{y,i,j,k} + A_{y,i,j,k} \quad (6)$$
$$U_{1,z,i,j,k} = V_{1,z,i,j,k} - E_{1,z,i,j,k} = G_{z,i,j,k} + A_{z,i,j,k}$$

Then subtracting View 1 to View 2 enables the removal of the artifact error term such as:

$$G_{x,i,j,k} - G_{y,-j,i,k} = U_{1,x,i,j,k} - U_{2,y,i,j,k}$$
$$\text{(View1)–(View2)} \quad G_{y,i,j,k} + G_{x,-j,i,k} = U_{1,y,i,j,k} + U_{2,x,i,j,k} \quad (7)$$
$$G_{z,i,j,k} - G_{z,-j,i,k} = U_{1,z,i,j,k} - U_{2,z,i,j,k}$$

In a similar way between View 1 and View 3:

$$G_{x,i,j,k} - G_{x,i,-k,j} = U_{1,x,i,j,k} - U_{3,x,i,j,k}$$
$$\text{(View1)–(View3)} \quad G_{y,i,j,k} - G_{z,i,-k,j} = U_{1,y,i,j,k} - U_{3,z,i,j,k} \quad (8)$$
$$G_{z,i,j,k} + G_{y,i,-k,j} = U_{1,z,i,j,k} + U_{3,y,i,j,k}$$

View 1 and View 4:

$$G_{x,i+1,j,k} - G_{x,i,j,k} = V_{4,x,i,j,k} - U_{1,x,i,j,k} - E_{4,x,i,j,k}$$
$$G_{y,i+1,j,k} - G_{y,i,j,k} = V_{4,y,i,j,k} - U_{1,y,i,j,k} - E_{4,y,i,j,k} \quad (9)$$
$$G_{z,i+1,j,k} - G_{z,i,j,k} = V_{4,z,i,j,k} - U_{1,z,i,j,k} - E_{4,z,i,j,k}$$

By an algebraic manipulation procedure, one can determine the error components of the machine error. Due to the space limitation of this paper, detailed derivation is omitted here as is well described in [5].

3. Experiments and discussions

To validate the proposed algorithm by experiment, a 3-D rectangular type artifact was built up with a 5x5x5 array of precision steel balls of 9 mm in diameter as shown in Figure 2. The balls were glued on five holding plates made of aluminum with a separation distance of 65 mm. The center location of each ball was determined through least squares fitting of five data points obtained from its surface. The artifact was surrounded by three outer plates, each of which has Kelvin kinematic seats underneath. In contact with a base plate with mating kinematic seats, the artifact was capable of maintaining high positioning reproducibility for the four views required for 3-D self-calibration.

Figure 2: 3-D artifact and its kinematic mounting base.

The performance of self-calibration is ultimately limited by the measurement repeatability of the ball centers of the CMM under calibration. The measurement repeatability is usually influenced by many factors, of which the most dominating one is the environmental temperature. Any temperature variation affects both the machine and the artifact. Figure 3 shows a statistical result of calibration repeatability that was obtained with respect to all the grid points of the artifact through three separate self-calibrations of a same machine. The maximum value of repeatability turned out to be 17.0 μm.

Figure 4 shows the result of self-calibration in which the systematic positioning error of the CMM is presented in the form of 3-D map. The maximum deviation was measured 17.0 μm within a calibration volume of 260 mm side.

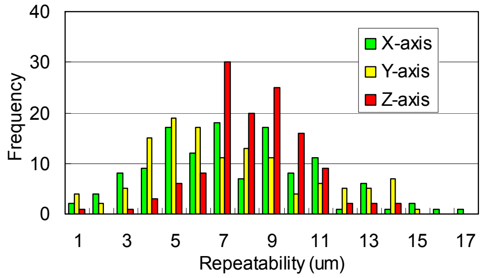


Figure 3: Statistical result of calibration repeatability.

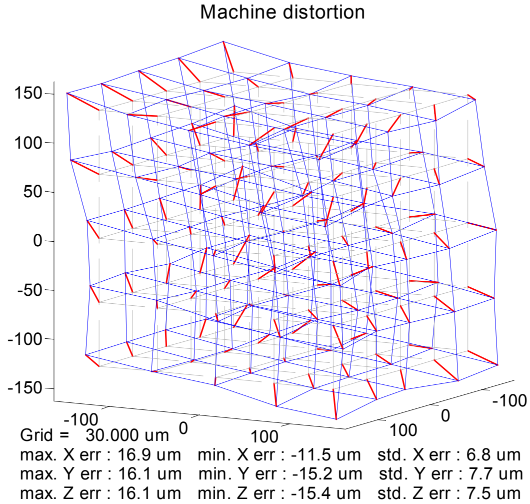


Figure 4: The reconstructed 3-D error map.

The proposed algorithm also allows reconstructing the 3-D error map of actual ball placements on the 3-D artifact, which tuned out to be much larger than the machine error. The result reveals that the calibration repeatability is in the same level of the measurement repeatability of the CMM itself, proving the validity of the proposed 3-D self-calibration algorithm.

4. Conclusions

We proposed a complete algorithm of 3-D self-calibration by extending the existing 2-D algorithm. The extended algorithm then allows obtaining a full 3-D map of systematic positioning errors that are necessary for the complete analysis of the volumetric errors of CMMs. Experimental results show that our algorithm provides accurate calibration results, and the practical limit of the calibration accuracy is determined by the measurement repeatability of the CMM under calibration itself.

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