XVII IMEKO World Congress
Metrology in the 3rd Millennium
June 22–27, 2003, Dubrovnik, Croatia

CALIBRATION OF A CMM USING A LASER TRACKING SYSTEM

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Abstract – A new calibration approach of a coordinate measuring machine (CMM) using a laser tracking system is proposed. According to the conventional approach of the laser tracking system, trilateration principle is mainly adapted. Therefore one retroreflector and four laser trackers are required. Though this approach is capable of attaining high accuracy measurement, measuring volume is likely to become smaller due to physical limitations for middle size CMM. Consequentially, we need new approach, which uses the least laser trackers in numbers. In this paper, effective calibration strategy to estimate 21 kinematic parameters of CMM's axes is described. Additionally to confirm the validity of the proposed approach, the parameters estimation using a ball plate was conducted in parallel. The estimation results by the laser tracker and the ball plate showed good agreement.

Key words:CMM, Laser Tracking System, Calibration

1. INTRODUCTION

Many calibration methods of a CMM have been introduced so far. Some of them make use of a laser interferometer when precise calibration is required [1], and the others geometrical gages for simple calibration [2]-[3]. Geometrical gages such as a step gage and a ball plate have been widely used and accepted as practical standards. Those gages are effective in some cases, however, are not always appropriate to estimate 21 kinematic parameters of a CMM. Because the gages cannot be placed on the effective measurement positions or orientations due to physical limitations, or probing errors are inevitable. On the other hand, the laser tracker consists of a laser interferometer and a tracking system; therefore the displacement of a target retroreflector, which is fixed on the CMM's ram, can be measured. Taking advantage of these merits, we designed the measurement strategy to estimate 21 parameters.

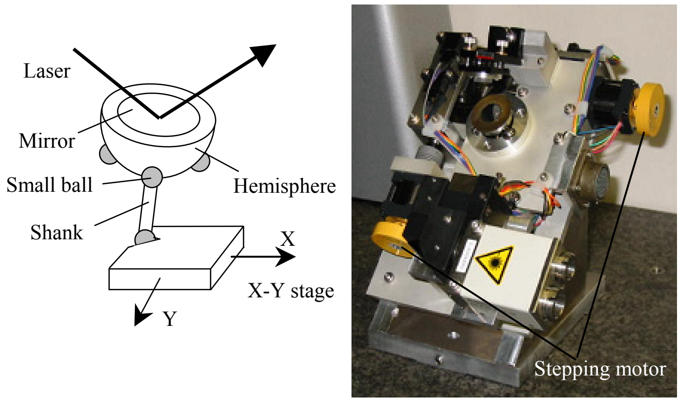


Fig1. Schematic of the tracking mirror based on the hemisphere

This strategy does not need to determine the coordinate of the retroreflector. Only the displacement in one direction must be measured. Therefore to confirm the validity of the measurement strategy, we used a laser tracker as a laser interferometer. As a result, the 21 kinematic parameters were estimated and the result showed good agreement with the estimation using a ball plate.

2. LASER TRACKER

The laser tracker we developed can chase a moving retroreflector that is attached to the ram (z axis) of a CMM. The tracking mechanism as shown in Fig.1, employs a hemispherical tracking mirror that rotates in two directions. Three small balls support the hemispherical mirror and the end of a shank is connected to the X-Y stage, which is driven by two stepping-motors. The advantage of this design is that the laser tracker is free from misalignment of rotation axes. With this mechanism, the center of the hemisphere does not moved when the hemisphere rotates to any orientations. This system realized the uncertainty of 0.3 μm within a measuring volume of $120\times120\times120\ \mathrm{mm}^3$ [4].

In this study, the CMM to be calibrated has the measurement uncertainty of 1.4+3L/1000 μm, so that the laser tracker is precise sufficiently for the calibration work.

3. OUTLINE OF CMM CALIBRATION

3.1 Error model

Considering the error vector of each measurement point as a result of parameters influence, the error vector is the vector summation of the 21 kinematical parameters.

Let us define a straightness parameter of i axis in i-j plane as t_{ij}, a rotational parameter of i axis with respect to j axis as r_{ij}, and a squareness parameter between i and j axes as w_{ij} $(i,j = x,y,z)$. Using these parameters, three-dimensional error vector e is expressed as equation (1), where p is 3×12 matrix and consists of offsets for each element of vector r. Offsets mean the lengths from corresponding axis to the probe tip. CMM calibration can be conducted by estimating each t and r that minimizes the error e, therefore the appropriate measurement strategy that enables the separation of parameters is necessary.

$$e = \begin{pmatrix} e_x \\ e_y \\ e_z \end{pmatrix} = t + p \times r \qquad t = \begin{pmatrix} t_{xx}+t_{yx}+t_{zx} \\ t_{xy}+t_{yy}+t_{zy} \\ t_{xz}+t_{yz}+t_{zz} \end{pmatrix} \in R^3 \tag{1}$$

$$r = \left(r_{xx}\, r_{xy} \;\cdot\;\cdot\; r_{yz}\;\; r_{zz}\;\; w_{xy} \cdots w_{yz}\right)^T \in R^{12}$$

3.2. Measurement strategy

In the laser tracking system, the laser beam from the tracker to the retroreflector is used to measure change in length between the two. The CMM readings of the retroreflector position is written as p_i (x_i,y_i,z_i). At the start position the index i equals 0, i.e. p_0 (x_0,y_0,z_0). The CMM readings p_i contains e. We define the distance $p_0\,p_i$ measured by the laser tracker as l_i, and measured by the CMM as L_i respectively; the difference ΔL_i between L_i and l_i is expressed as equation (2).

The difference ΔL_i can be linearized as equation (3). As it is clearly noticed from equation (1), equation (3) contains the 21 ser path and on those lines the length measurements at kinematic parameters. To estimate these parameters, it is necessary to design a set of 21 independent measurements in the measuring volume. Therefore we selected the measuring lines as shown in Fig.2. In these figures, the solid lines show every 30 mm interval were conducted. About 300 points are measured in total.

$$\Delta L_i = \sqrt{(x_i - u_0)^2 + (y_i - v_0)^2 + (z_i - w_0)^2} - l_i \tag{2}$$

$$\Delta L_i = L_i - l_i \approx \frac{(x_i - x_0)}{l_i}\cdot e_x + \frac{(y_i - y_0)}{l_i}\cdot e_y + \frac{(z_i - z_0)}{l_i}\cdot e_z \tag{3}$$

3.3. Kinematic parameters estimation

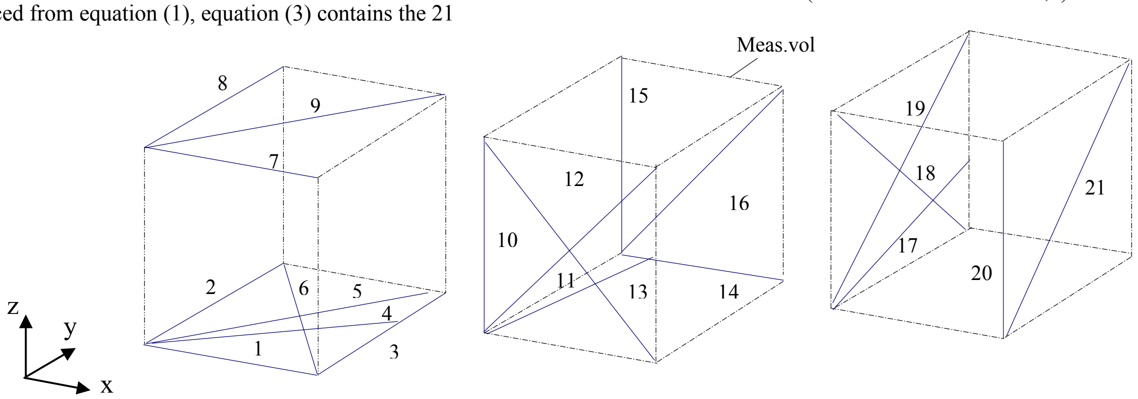
Each of the 21 kinematic parameters in equation (1) is a function of the spatial position. For example, the straightness parameter t_{xx} is expressed by a polynomial as shown in equation (4), where B_x is composed by n basis functions such as Legendre function (in this experiment n was defined as six) and α is its coefficient. In the same way the other parameters are expressed by polynomials or constants. Jacobi matrix, which is used for the parameters estimation, is expressed as A in equation (5). In this equation m means the number of measurement. Applying the linear least square method to the Jacobi matrix A, a set of Legendre function coefficients of the 21 parameters, totally 129 coefficients, are calculated simultaneously.

In this study, non-linear least square method was applied where equation (2) was used, and the solution of linear least square fit for equation (3) was used as the initial values of repetitive calculations.

$$t_{xx} = \alpha_1 B_1(x) + \alpha_2 B_2(x) + \cdots \alpha_n B_n(x) = \alpha_{txx} \times B_x \tag{4}$$

$$\alpha_{txx} = (\alpha_1 \alpha_2 \cdots \alpha_n)^T \in R^n \qquad B_x = \left(B(x)_1 B(x)_2 \cdots B(x)_n\right) \in R^{1\times n}$$

$$A = \begin{pmatrix} \frac{\partial \Delta L_1}{\partial \alpha_{txx}} & \frac{\partial \Delta L_1}{\partial \alpha_{txy}} & \cdot\;\cdot & \frac{\partial \Delta L_1}{\partial \alpha_{wyz}} \\ \frac{\partial \Delta L_2}{\partial \alpha_{txx}} & \frac{\partial \Delta L_2}{\partial \alpha_{txy}} & \cdot\;\cdot & \cdot \\ \cdot & \cdot & \cdot\;\cdot & \cdot \\ \cdot & \cdot & \cdot\;\cdot & \cdot \\ \frac{\partial \Delta L_m}{\partial \alpha_{txx}} & \cdot & \cdot\;\cdot & \frac{\partial \Delta L_m}{\partial \alpha_{wyz}} \end{pmatrix} \tag{5}$$



(a) Parallel with XY plane (b) Parallel with XZ plane (c) Parallel with YZ plane

Fig.2 Measurement strategy for detecting 21 sets of kinematic parameters

Table 1 Rough condition of Calibration of CMM [mm]

CMM Measuring Volume	700×700×600
Laser tracker evaluation range	330×330×330
Ball plate evaluation range	332×332×332

4.1 Kinematic parameter estimation

For example, the positioning and pitching error in x-axis are shown in Fig.3 and Fig.4 respectively, and yawing and rolling error in y-axis are shown in Fig.5 and Fig6 respectively. In these figures solid lines show the estimations using the laser tracker, and dotted lines show the estimations using the ball plate. These results of the estimation by using the ball plate and the laser tracker showed good agreement. Maximum difference of the estimation between the laser tracker and the ball plate is about 1.0 μm and . Therefore the measurement strategy we proposed is considered reasonable for CMM calibration.

4.2 Verification of CMM calibration method

Figure 7 shows the indication error of object CMM actually measured by the laser tracker. Above mentioned the results of kinematic parameters estimation can be used for compensation of the CMM, If the CMM has reproducibility in positioning.

Figure 8 shows the residual between the raw data shown in Figure 7 and the results of 21 parameters estimation.

The maximum indication error in Fig.7 is about 4 μm, but after the compensation, the residual error became less than 0.5 μm as shown in Fig.8. According to those results, the calibration method we proposed may be considered to be effective. This also means that the error model we assumed is considered reasonable.

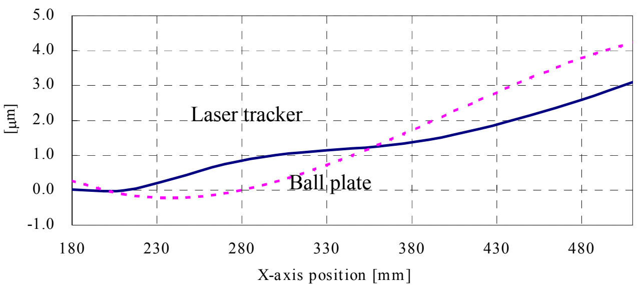


Fig.3 Positioning error in X axis

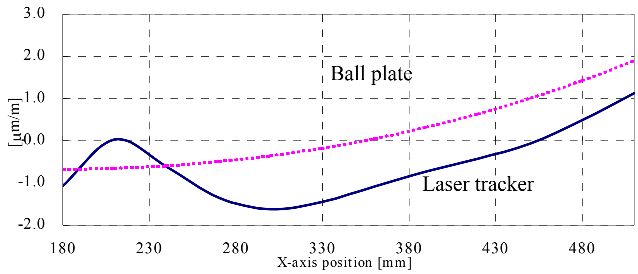


Fig.4 Picting error in X axis

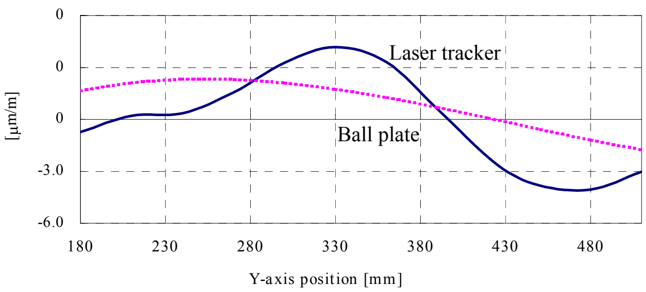


Fig.5 Yawing error in Y axis

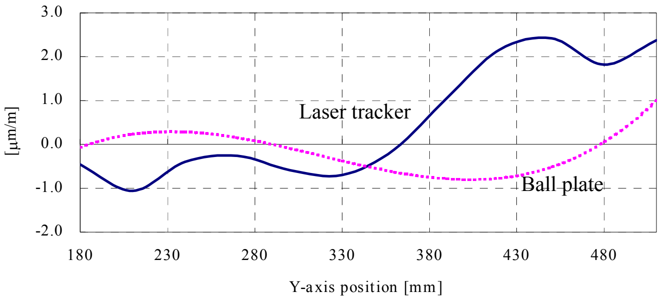


Fig.6 Rolling error in Y axis

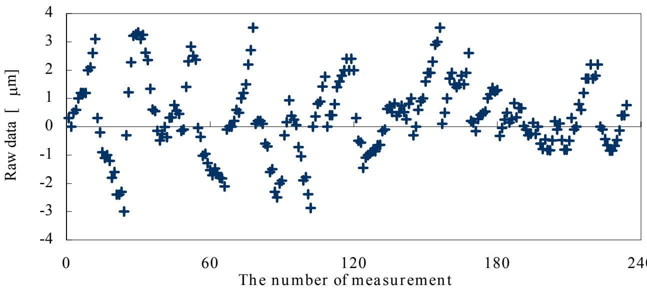


Fig.7 Indication error of object CMM

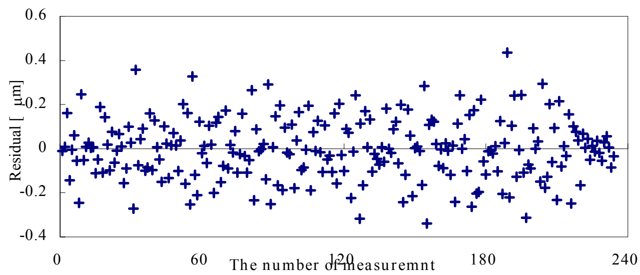


Fig.8 Compensated data of object CMM

5. CALIBRATION USING TWO LASER TRACKERS

To realize the calibration strategy mentioned above on middle size CMM, trilateration principle is not suitable because the measuring volume is restricted to be small. To avoid this physical limitation we propose a new method that makes use of two laser trackers. Although this method can expand the measuring volume, only two lengths are observed when the coordinate P_i is measured as shown in Fig.9. Therefore additional redundancy is required to estimate the three-dimensional coordinate. To realize this, the retroreflector is attached to the ram with an offset and the orientation of the offset is changed at each coordinate P_i as shown in Fig.9. Using the redundancy produced by this offset, unknown system parameters p_1, q_1, r_1, p_2, q_2, r_2, P_x, P_y and P_z are identified. This algorithm is well-known as a self calibration algorithm.

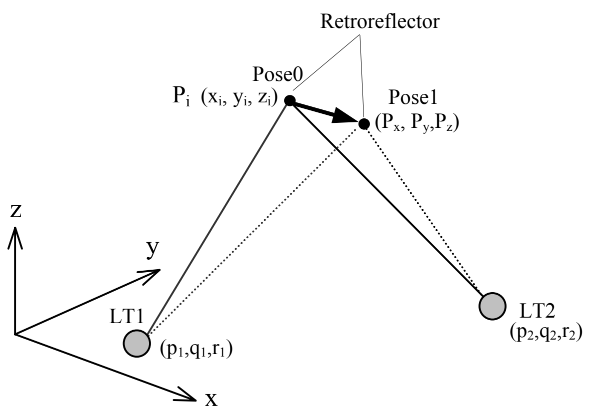


Fig.9 New approach using two-laser trackers calibration

6. CONCLUSIONS

The twenty-one kinematic parameters are estimated using only one laser tracker. The results of the estimation by using the ball plate and the laser tracker showed good agreement.

It indicates the measurement strategy proposed here can be used for calibration.

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