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# Geometric-error analysis of three-axis machine tools using displacement information relative to single location

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**Abstract**

To achieve rapid and automatic analysis of linear-positioning and squareness errors of three-axis machines, a method requiring a single tracking interferometer placed at a single location is proposed. A kinematic model of a three-axis machine was first devised. Subsequently, an optimization algorithm was applied to solve the inverse kinematic problem by defining reasonable initial and boundary conditions. Simulation parameters included geometric errors of the machine, instrument locations, and repeatability of measurement results (definition derived from the ISO 230-1 standard). Results obtained via simulations demonstrate that considering a repeatability of 4 µm, the maximum differences in linear-positioning and squareness are observed to be -0.9 µm/m and 0.2 arcs, respectively, whereas the corresponding maximum standard deviations are 0.28 µm/m and 0.01 arcs. The method has further been verified using a coordinate-measuring machine. Experimental results demonstrate that analyzed parameters show reasonable agreement with simulation results, wherein maximum differences in linear positioning and squareness errors were observed to be 0.7 µm/m and 0.3 arcs, respectively. The total measuring time of a thrice-divided spatial grid was approximately 10 min. The results of the study demonstrate the feasibility of the proposed method in rapidly analyzing geometric errors in three-axis machines.

Geometric error, geometric modelling, machine tool, optimization

## 1. Introduction

Machine tools and coordinate-measurement machines (CMMs) are constructed using three linear kinematic chains, which comprise 21 error terms. To increase the efficiency and capability of a production line, geometric errors must be well evaluated and compensated for. Several methods have been employed to evaluate such geometric errors as those incurred when using artificial objects [1], ball-bars [2], and laser interferometers [3–4].

In geometric error analysis, the use of a tracking laser interferometer with the multilateration method provides maximum precision, which is traceable up to the wavelength standard. This, however, requires use of either four instruments to perform target measurements simultaneously or a sequential method to complete the entire measurement, the former involves in incurring capital expenses and the latter increase time costs. Research teams of the Physikalisch-Technische Bundesanstalt (PTB) and National Physical Laboratory (NPL) constructed a kinematic model of machines and solved for error motions using a best-fit algorithm with sequential measurements at different locations [5]. Another method [6] employed the multilateration technique to obtain 3D coordinates, thereby combining parallel trajectories to extract parametric errors of pitch, yaw, and roll. The method proposed in [6], however, involves complex procedures that is difficult to implement in automation processes.

The proposed study presents a novel method to accomplish rapid and automatic analysis of geometric errors in three-axis machines. The method requires only one tracking interferometer placed at a single location. By measuring the displacement at numerous target points, linear-positioning and squareness errors could be analyzed.

## 2. Methods

### *2.1. Kinematic model*

The kinematic model used in the proposed study was built using homogeneous transformation. Figure 1 depicts a schematic of the machine structure and reference coordinates of the kinematic model. The model can be mathematically expressed in terms of the following equation, using which the location of the machine terminus (origin of the O4 coordinate system) relative to the O1 coordinate system can be derived.

$$O_4 = O_1 T_x R_{z2} T_y R_{x3} R_{y3} T_z \tag{1}$$

where $T_x = L_x x_c$, with $x_c$ denoting the position command of the machine along the x-axis direction; $L_x$ denotes the scale factor to represent the linear positioning error. Similar expressions could be used to represent $T_y$ and $T_z$.

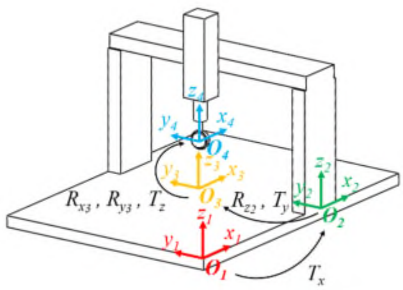


**Figure 1.** Kinematic model of the three-axis machine.

The mathematical model employed accounts only for linear-positioning ($L_x$, $L_y$, $L_z$) and squareness ($R_{z2}$, $R_{x3}$, $R_{y3}$) errors. Nonlinear errors, such as straightness and rotation (pitch, yaw, roll) were assumed not to be significant and were, therefore, regarded as residuals when solving inverse kinematic problems.

### 2.2. Inverse kinematic

During simulation, the machine terminus moved to the specified location within a spatial grid segmented into three parts along each axis, as depicted in Fig. 2. Therefore, 27 measurements were performed in one analytical procedure.

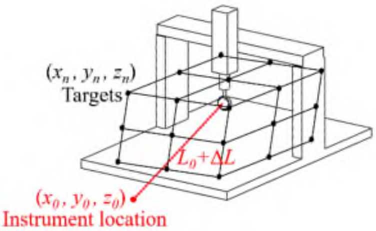


**Figure 2.** Distortion of a spatial grid.

Equation (2) below was provided as the objective function. Initial values of the instrument location ($x_0$, $y_0$, $z_0$) and the initial distance $L_0$ were derived using the method of reference [7]. Values of other parameters, such as linear-positioning and squareness errors, were set as 1 (scale factor) and 0 arcs, respectively. For boundary conditions, scale factors of linear-positioning errors were specified as 1 ± 0.00005 (± 50 µm/m) and squareness errorss were set to ± 50 arcs. In addition, coordinates $x_0$, $y_0$, $z_0$, and initial length $L_0$ were constraint at ±3 mm with respect to their initial values.

$$\min \sum_{n=1}^{N}\left[\sqrt{(x_n-x_0)^2+(y_n-y_0)^2+(z_n-z_0)^2}-(L_0+\Delta L)\right]^2 \qquad (2)$$

## 3. Results and Discussion

### 3.1. Simulation of geometric error analysis

Table 1 lists parameter values obtained via simulation along with optimized results. Parametric values obtained via simulation include instrument location ($x_0$, $y_0$, $z_0$) and geometric errors. To simplify the content, the authors decided to change the scale factor concerning linear-positioning errors ($L_x$, $L_y$, $L_z$) to µm/m ($L_X$, $L_Y$, $L_Z$). The repeatability of measurements was simulated in the form of a normal distribution with standard deviation of 1 µm (4-µm repeatability based on the ISO 230-1 standard) and the effect of backlash was neglected by employing a well-designed trajectory. Subsequently, an optimization algorithm was employed to solve the equation in over 30 iterations with different length-measurement errors in order to verify its stability.

It can be realized from Table 1 that maximum differences between simulation and solved values of linear-positioning and squareness errors were of the order of -0.9 µm/m and 0.2 arcs, respectively, while corresponding maximum standard deviations were 0.28 µm/m and 0.01 arcs. Average solved values demonstrated good agreement with the approximated ideal value, whereas the standard deviation of solved values was found to be sufficiently small to identify the errors.

**Table 1** Optimization results for simulated measurements (30 iterations)

| Parameter | Simulation value | Solved value | |
|---|---|---|---|
| | | Average | Standard deviation |
| $x_0$ (mm) | **-150** | -149.999 | $1.2 \times 10^{-4}$ |
| $y_0$ (mm) | **200** | 200.000 | $2.3 \times 10^{-5}$ |
| $z_0$ (mm) | **230** | 230.000 | $1.5 \times 10^{-4}$ |
| $L_X$ (µm/m) | **7** | 7.2 | $5.1 \times 10^{-8}$ |
| $L_Y$ (µm/m) | **9** | 8.7 | $1.1 \times 10^{-7}$ |
| $L_Z$ (µm/m) | **5** | 4.1 | $2.8 \times 10^{-7}$ |
| $R_{Z2}$ (″) | **9** | 9.0 | $8.5 \times 10^{-3}$ |
| $R_{X3}$ (″) | **5** | 5.1 | $1.0 \times 10^{-2}$ |
| $R_{Y3}$ (″) | **7** | -7.2 | $1.0 \times 10^{-2}$ |

### 3.2. Experimental results on CMM

The proposed method was verified on CMM (Leitz PMM-C), and an eTALON LaserTRACER was used to measure the displacements. The trajectory was designed to avoid backlash. Experiments involved performing initial measurements on the CMM with an ordinary pathway, defined as a baseline, and subsequent measurement of the error pathway that was defined based on simulation values listed in Table 2. Variation values listed in Table 2 represent differences between parameters corresponding to ordinary and error pathways.

Results demonstrate that the difference between simulation and solved values were of the order of 0.7 µm/m and 0.3 arcs in terms of linear positioning and squareness errors, respectively. In addition, each measurement was performed in approximately 10 min. This implies that such measurements serve to reduce the downtime of machines and become the means of quality assurance for diagnosing and compensating for the machine tool.

**Table 2** Experimental results of given parameters and variation between baseline and error-simulation cases.

| | Experiment 1 | | Experiment 2 | |
|---|---|---|---|---|
| | Simulation value | Variation value | Simulation value | Variation value |
| $L_X$ (µm/m) | **7** | 6.9 | **7** | 6.9 |
| $L_Y$ (µm/m) | **9** | 8.3 | **-9** | -8.4 |
| $L_Z$ (µm/m) | **5** | 5.2 | **-5** | -5.6 |
| $R_{Z2}$ (″) | **9** | 8.9 | **-9** | -8.9 |
| $R_{X3}$ (″) | **5** | 4.9 | **-5** | -4.9 |
| $R_{Y3}$ (″) | **7** | 7.0 | **7** | 6.7 |

## 4. Conclusion

The proposed study presents a method that requires only a single tracking interferometer placed at a single location to evaluate linear-positioning and squareness errors induced in three-axis machines. A kinematic model was built to simulate the positioning error of a machine, and subsequently, an optimization algorithm was used to solve the inverse kinematic problem. Usability of the proposed method was then simulated and subsequently verified using CMM. Results demonstrate that occurrence of errors were of the order of a few micrometers and arcseconds and the total operation time was approximately 10 min. The authors intend to perform a future study focusing on different simulation configurations to obtain more accurate solutions. Moreover, utility of the present method would be improved to analyze the remaining 15 geometric errors in order to compensate for the nonlinear behavior of machines.

## References


[1] Trapet E and Wäldele F 1991 A reference object based method to determine the parametric error components of coordinate measuring machines and machine tools *J. Measurement* **9** 17-22

[2] Pahk H J, Kim Y S and Moon J H 1997 A new technique for volumetric error assessment of CNC machine tools incorporating ball bar measurement and 3D volumetric error model *J. Mach. Tool Manu.* **37** 1583-96

[3] Chen G Q, Yuan J X and Ni J 2001 A displacement measurement approach for machine geometric error assessment *J. Mach. Tool Manu.* **41** 149-61

[4] Wang C and Liotto G 2003 A theoretical analysis of 4 body diagonal displacement measurement and sequential step diagonal measurement *WIT Trans. Eng. Sci.* **44**

[5] Schwenke H, Franke M, Hannaford J and Kunzmann H 2005 Error mapping of CMMs and machine tools by a single tracking interferometer *CIRP Annals - Manu. Tech* **54** 475-78.

[6] Camboulives M, Lartigue M, Bourdet P and Salgado J 2016 Calibration of a 3D working space by multilateration *J. Pre. Eng.* **44** 163-170

[7] Wang J D, Guo J J, Zhang G X, Guo B A and Wang H J 2012 The technical method of geometric error measurement for multi-axis NC machine tool by laser tracker. J. Mea. Sci. Tech. **23**