Estimation of Three-dimensional Volumetric Errors of Machine Tools by a Laser Tracker

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The importance of the evaluation of three-dimensional volumetric accuracy of machine tools has been more widely recognized in recent years. A laser tracker is a laser interferometer with the mechanism to steer the laser direction to follow the target. Based on the triangulation principle, it estimates the three-dimensional position of the target, attached to the machine's spindle, by using four laser measurements from different tracker locations. This paper presents its application to the measurement of three-dimensional volumetric accuracy of a machining center. To improve its estimation accuracy, its major error sources are discussed.

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1. Introduction

In ISO standards (e.g. ISO 230-1), the motion accuracy of a feed drive of a machine tool is basically evaluated in the axis-to-axis basis; the linear positioning error and straightness errors are separately measured for each axis, and the squareness error between two axes is then measured. Linear positioning errors are typically measured by using a laser interferometer. Straightness and squareness errors are often measured by using a linear displacement sensor and an artifact such as a straight edge or a square edge. Since the measurement is one-dimensional, an operator must change the setup of a sensor and an artifact every time for the measurement of each different error component. For orthogonal three-axis machines, 3 linear displacement errors, 6 straightness errors and 3 squareness errors must be measured by different setups. Furthermore, the artifact must have geometric accuracies guaranteed to be higher than the accuracy of the measured machine. Such measurements are time-consuming, and require higher cost for artifacts of higher accuracy.

Error calibration for a coordinate measuring machine (CMM) described in ISO 10360 series contains tests with a different concept. By using an artefact such as a ball plate, all the three-dimensional position error components (in X, Y, and Z) for the given reference location are directly measured over the entire workspace. The importance of the evaluation of such volumetric errors has been recently recognized also by many machine tool builders. Currently, a technical committee in ISO (TC39) is working on the standardization of the definition of volumetric accuracy for machine tools [1].

A laser tracker is a laser interferometer with the mechanism to steer the laser direction to follow the target. The majority of commercially available laser trackers (e.g. FARO Technologies Inc.) measures the 3D position of the target from the displacement and the orientation of the laser beam to the target [2]. In this type, measurement uncertainties of its orientation angles crucially influence the measurement uncertainty of the target's position, and it is thus practically quite difficult to obtain measurement accuracy sufficiently high to be applied to machine tool error calibration.

The multilateration measurement of the target's 3D position only use the distance to the target from different tracker locations based on the triangulation principle. Since it does not require angular measurement, it is expectedly easier to obtain higher accuracy. Research works on laser trackers based on this principle have been reported in the literature [3,4] and some lately commercialized it (Etalon AG).

This paper demonstrates the application of a laser tracker based on the multilateration principle to the calibration of volumetric errors of a machining center. The laser tracker developed by a group in National Institute of Advanced Industrial Science and Technology [5] is used in our study. Error causes in the laser tracker system that must be addressed to further improve its estimation accuracy will be discussed.

2. Three-dimensional Position Measurement by Multilateration Principle

2.1 Configuration of Laser Tracker

Figure 1 illustrates the configuration of the laser tracker [6]. Figure 2 shows an outlook of the laser tracker used in this study [6]. It consists of a steering mirror to control the laser direction and a quad-detector to locate the laser spot returned from the target. When the laser beam reaches a corner cube, a target attached to the machine's spindle, the beam reflects back to the tracker. The location of the returned laser spot is measured by the quad-detector, and the orientation of steering mirror is regulated such that the laser beam follows the target.

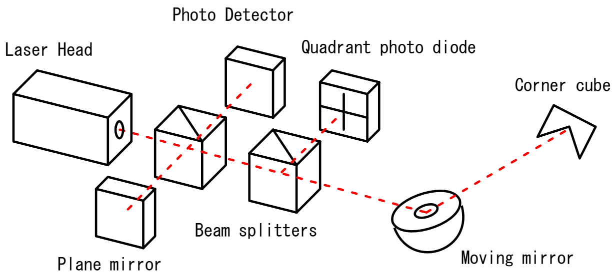


Fig. 1 Configuration of a laser tracker [6]

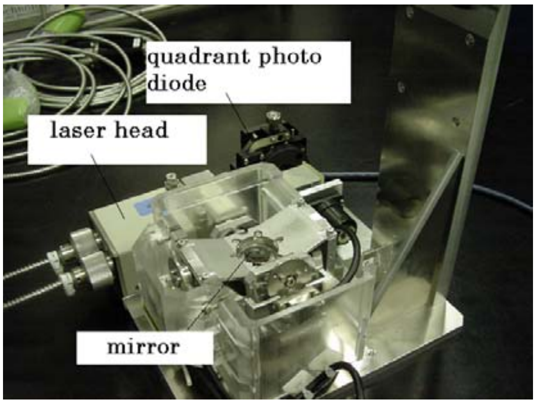


Fig. 2 An outlook of laser tracker [6]

Table 1 Major specifications of the machining center

Travel	X:610mm, Y:510mm, Z:460mm
Drive type	Ball screw
Guideway	Roller guideway
Positioning resolution	1 μm (X, Y, Z)

2.2 Algorithm to Calculate Target Position

The position of the target can be calculated by measuring the distance to it from three different tracker locations based on the triangulation principle, when each tracker location is exactly known. In practice, however, it is not possible to measure the exact position of the tracker. To address this issue, tracker locations are typically self-calibrated by using an abundant measurement from the fourth location of laser tracker. This section briefly review an algorithm to calculate the target position from four measurements from different tracker locations. More details can be found in [5].

The coordinate system is defined such that four tracker locations are given by $\mathbf{U}_1 = [0\ 0\ 0]^T$, $\mathbf{U}_2 = [U_2\ 0\ 0]^T$, $\mathbf{U}_3 = [U_3\ V_3\ 0]^T$, and $\mathbf{U}_4 = [U_4 V_4 W_4]^T$. Suppose that target locations are given by $\mathbf{u}_i = [u_i\ v_i\ w_i]^T, (i = 1,2,\ldots,m)$, where m represents the number of locations. The laser displacement, d_{ij}, measured by the j-th tracker to the i-th target location, is given by:

$$\mathbf{d} - \mathbf{f} = \mathbf{0}$$

$$\begin{cases} \mathbf{d} = [d_{11}\, d_{21} \cdots d_{3m}\, d_{4m}]^T \\ \mathbf{f} = [f_{11}\ f_{21} \cdots f_{3m}\ f_{4m}]^T,\ f_{ij} = \left(\left\| \mathbf{u}_i - \mathbf{U}_j \right\| - \left\| \mathbf{u}_1 - \mathbf{U}_j \right\| \right) \end{cases} \tag{1}$$

The equation above contains 6+3m unknown parameters. Define the vector, p, that contains all the unknown parameters. Notice that the number of laser measurements is 4m. Therefore, when m>6, the number of measurements exceeds the number of unknown parameters.

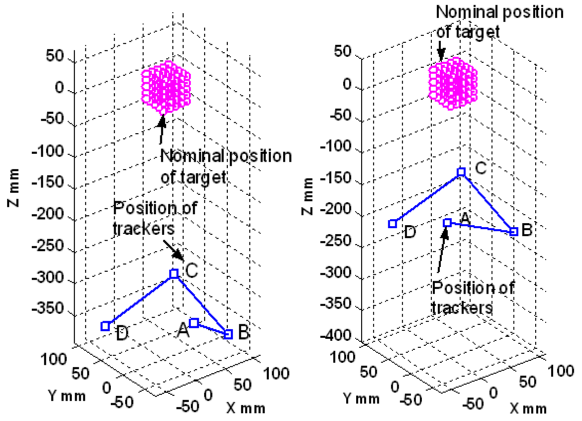
p can be identified by applying the Newton method with linearizing the function **f**. At the k-th step, define:

$$\Delta\mathbf{d}^{(k)} = \mathbf{d} - \mathbf{f}(\mathbf{p}^{(k)}),\ \Delta\mathbf{p}^{(k)} = \mathbf{p} - \mathbf{p}^{(k)},\ A^{(k)} = \left.\frac{\partial \mathbf{f}}{\partial \mathbf{p}}\right|_{\mathbf{p} = \mathbf{p}^{(k)}} \tag{2}$$

Then we have:

$$\mathbf{p}^{(k+1)} = \mathbf{p}^{(k)} + \Delta\mathbf{p}^{(k)} = \mathbf{p}^{(k)} + (A^{(k)T} A^{(k)}) A^{(k)T} \Delta\mathbf{d}^{(k)} \tag{3}$$

In practice, we employ an alternating approach to identify 1) parameters representing target locations and 2) parameters representing tracker locations in a recursive manner for better convergence.



(a) Setup #1 (b) Setup #2

Fig. 3 Location of target and laser trackers

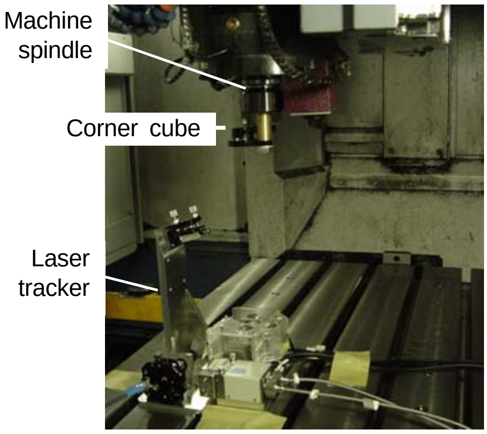


Fig. 4 An outlook of experiment.

3. Experiments

3.1 Experimental Setup

Experiments to evaluate the performance of the laser tracker used in our study were conducted. The volumetric accuracy of a vertical machining center of major specifications shown in Table 1 was measured by using the laser tracker.

A corner cube is attached to the machine's spindle as the target. It is located at the following total 125 points by driving the machine's X, Y, and Z axes:

$$[x\ \ y\ \ z]^t = [10 \cdot i\ \ \ 10 \cdot j\ \ \ 10 \cdot k]^t \tag{3}$$

where i, j, k=0~4. Nominal target positions are shown in Fig. 3. Since only one laser tracker is available at this stage, it is set in different four positions on the machine table, and laser displacements from each tracker location to total 125 target locations above are measured. Two different setups of laser tracker are tested. In Setup #2 (Fig. 3(b)), four tracker locations are set closer in the Z direction to target locations by about 150 mm than Setup #1 (Fig. 3(a)).

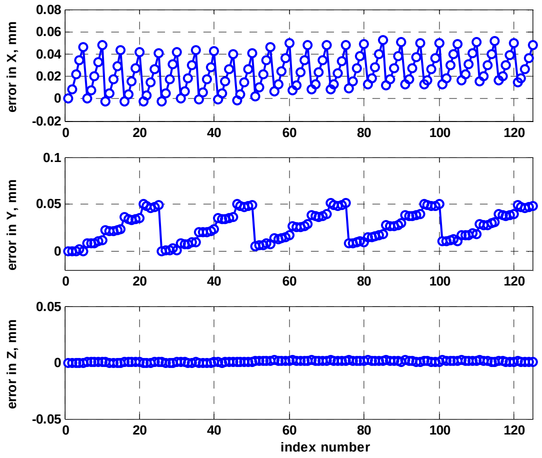
Furthermore, two different corner cubes were tested. Corner cube #1 is a typical commercial corner cube; it is a glass cube with mirror attached on its faces. Corner cube #2 is a hollow-type, with mirror attached to each other without a glass cube. The following three tests were conducted:

Test 1: Tracker locations: Setup #1, Target: Corner cube #1.

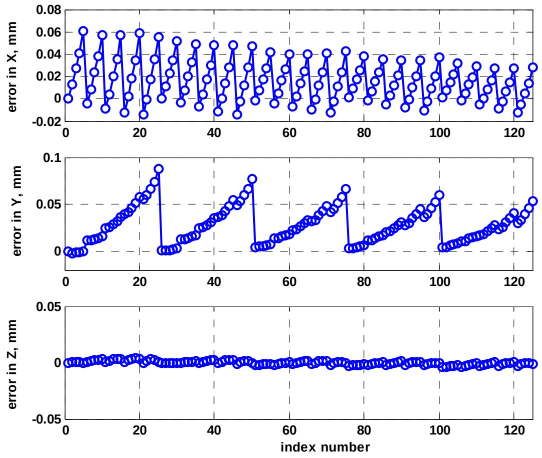
Test 2: Tracker locations: Setup #2, Target: Corner cube #1.

Test 3: Tracker locations: Setup #2, Target: Corner cube #2

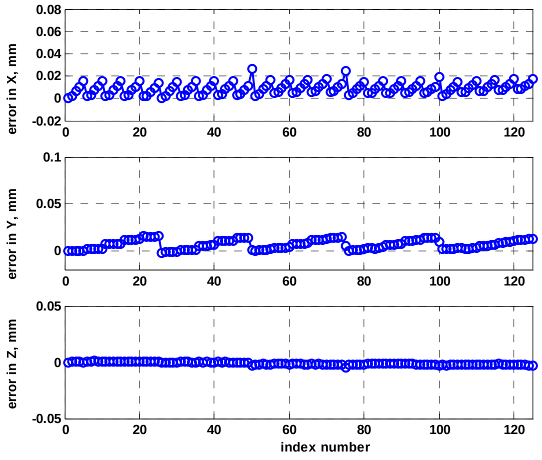
Figure 4 shows a photograph of experimental setup.



(a) Test 1 (Setup #1, Corner cube #1)

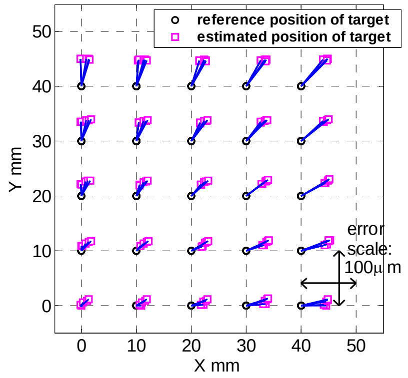


(b) Test 2 (Setup #2 Corner cube #1)

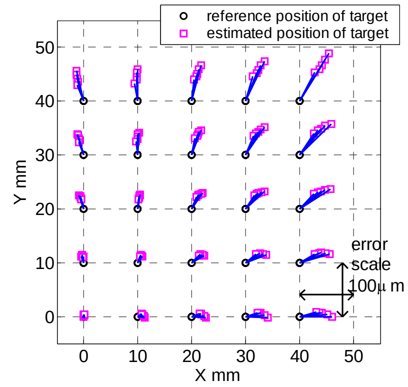


(c) Test 3 (Setup #2 Corner cube #2)

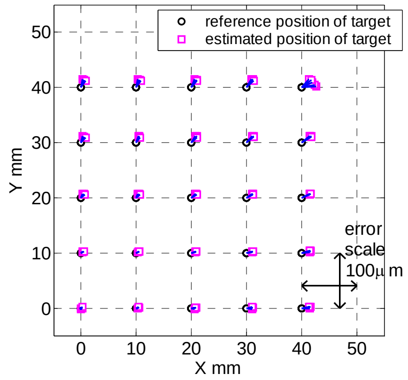
Fig. 5 Estimation errors of target position in x, y, and z directions



(a) Test 1 (Setup #1, Corner cube #1)



(b) Test 2 (Setup #2, Corner cube #1)



(c) Test 3 (Setup #2, Corner cube #2)

Fig. 6 Estimated target position projected on XY plane.

3.2 Experimental Results

For each reference target location given in Eq.(3), the actual target location is estimated from laser displacements by applying the algorithm presented in Section 2.2. Figure 5 shows an error in X, Y, and Z directions between the estimated target position and its reference position. In Fig. 5, the horizontal axis represents the index number of reference point. Figure 6 shows estimated target positions projected on the XY plane. The error is magnified by 100 times.

Although the target's actual position was not measured by other more reliable measurement device for the comparison, the volumetric error of the measured machine tool in the region 40 mm×40 mm×40 mm must be at most several micrometers. Compared to the estimation uncertainty of the present laser tracker, the machine tool's volumetric error can be assumed to be sufficiently small.

In Test 1, the maximum error between estimated target positions and their reference positions are 52.7 μm (X), 51.1 μm (Y), and 2.3 μm (Z). In Test 2, it is 60.4 μm (X), 88.1 μm (Y), and 4.2 μm (Z). In Test 3, it is 26.4μm (X), 15.8 μm (Y), and 4.7 μm (Z).

4. Discussion

Although Test 3 results in the smallest estimation errors, estimation errors are still significantly larger than expected volumetric errors of the measured machining center. This section discusses potential error causes of the experimental laser tracker and future studies to improve its estimation accuracy.

4.1 Difference of Nominal and Measured Laser Displacements

Assuming that the positioning error of the measured machine is negligibly small, the position of the laser tracker at A~D can be identified from the target's nominal positions and laser displacements in an analogous manner as shown in Section 2.2. From identified tracker positions, the nominal laser displacement can be computed to reach each nominal position of the target. The difference of nominal and measured laser displacement for each reference point in Tests 2 and 3 is plotted in Fig. 7(a) and (b), respectively.

Considering the expected positioning accuracy of the measured machine, it can be said that the error shown in Fig. 7 is mostly attributable to the measurement error associated with the laser tracker.

4.2 Potential Error Sources

As some of the authors has discussed in [7], the estimation uncertainty by multilateral principle is dependent on the location of laser trackers relative to target locations. From the condition number of the Jacobian matrix $A^{(k)}$ in Eq. (2), it can be shown that Setup #2 (Fig. 3(b)) is less sensitive to a measurement error in laser displacement than Setup #1 (Fig. 3(a)). From experimental results shown in Figs. 4 and 5, however, this difference is not clear.

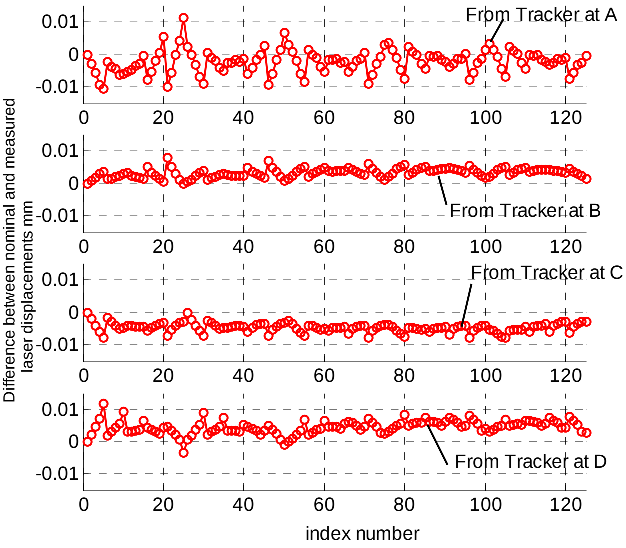
The rotation range of the X-axis of the laser tracker is about 11°~20° in Setup #1, and 16°~35° in Setup #2 (the vertical direction is defined as 0°). A larger rotation range would reduce the condition number, which may further improve the estimation accuracy. Due to a technical problem with the tracker, we did not test a setup that requires larger rotation range of the tracker. The technical problem must be addressed soon.

By comparing Test 2 (Fig. 5(b)) and Test 3 (Fig. 5(c)), it is clear that the high-accuracy hollow-type Corner cube #2 resulted in significant improvement of estimation accuracy of target position. It can be also observed by comparing Fig. 7(a) and (b). Although the estimation accuracy under Test 3 is still not satisfactory, it indicates a significant influence of the characteristics of corner cube on the laser tracker's estimation accuracy.

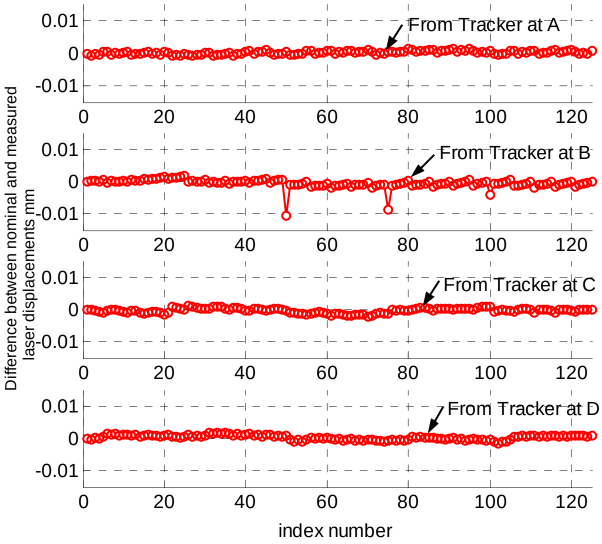
Further study will be conducted to clarify and remove error sources associated with the laser tracker measurement to achieve estimation accuracy sufficiently high to be applied to the error calibration of a commercial machining center.

5. Conclusion

A laser tracker can measure the position of a target in the three-dimensional space based on the multilateration principle. It can be potentially applied to the direct measurement of three-dimensional volumetric errors of a machine tool over a large workspace. In this paper, we tested a laser tracker developed by a group in National Institute of Advanced Industrial Science and Technology [5]. The estimation error of a corner cube position, attached on a spindle of a machining center, was not sufficiently small compared to the positioning error of the measured machine tool. Experimental study suggested that the characteristics of corner cube has a significant influence on the laser tracker's estimation accuracy. We will continue our study to improve its estimation accuracy sufficiently high to be applied to the error calibration of a commercial machining center.



(a) Test 2 (Setup #2, Corner cube #1)



(b) Test 3 (Setup #2, Corner cube #2)

Fig. 7 Difference between the nominal laser displacement and the measured laser displacement (Test 2)

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